THE UNIVERSITY OF QUEENSLAND

AUSTRALIA

Predicting soccer penalty success: An optimality model

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Bachelor of Psychological Science (Honours)

Master of Organisational Psychology

A thesis submitted for the degree of Doctor of Philosophy at

The University of Queensland in 2018

School of Biological Sciences

ABSTRACT

The penalty shot in soccer is one of the most exciting one-on-one contests in sport, where a single kick of the ball can decide major tournaments and multimillion-dollar prizes. Successful shooters must use power and accuracy to kick the ball beyond the goalkeeper's reach and into the goal; conversely, goalkeepers must predict the shooter's intent and move accurately to intercept the ball. Each player's performance is constrained by biomechanical trade-offs, and success relies on selecting the best strategy to overcome these constraints in myriad situations. Thus, the soccer penalty provides an ideal study system to investigate how the strategies of two competing agents interact to determine success or failure.

The aim of this thesis was to quantify the trade-offs faced by shooters and goalkeepers during a soccer penalty, determine the strategies used to overcome them, and show how these strategies interact to affect the outcome. From these outcomes, I developed an optimality model that predicts the likelihood of success for different shooting strategies, accounting for the biomechanical trade-offs that constrain each player. The model can match individual shooters against individual goalkeepers to identify the shooting strategy with the best chance of success.

In Chapter 2, I quantified the trade-off between speed and accuracy when kicking a ball. As expected, shooting precision decreased as shot speed increased. I also found that the likely dispersion of shots around a target was dependent on target height, kick technique, and player left- or right-footedness. Aiming at a target off the ground decreased precision compared with a target on the ground, and kicks made with the side of the foot were more accurate, while those made with the top of the foot generated greater speeds. Right-footed players tended to miss above the target and to the right, or below the target and to the left, with the opposite true for left-footed players.

In Chapter 3, I identified a previously unknown trade-off between shot speed and unpredictability. Unpredictability is advantageous for a penalty-kicker because it makes the ball more difficult for the goalkeeper to defend. I found that goalkeepers were better able to predict the direction of fast side-foot shots compared with slow- or medium-paced side-foot shots. Furthermore, the direction of shots became easier to predict as the shooter's kicking action neared contact with the ball. During a penalty, goalkeepers generally start to move toward a side of the goal before the kicker contacts the ball—thus, moving earlier gives them more time to move to reach and intercept a shot, while moving later increases the likelihood that they move in the correct direction. Ultimately, the likelihood that a goalkeeper moved in the correction direction was determined by an interaction between when they began to move and the speed and technique used to kick the ball.

A penalty shooter selects where to aim and how fast to kick the ball, and a goalkeeper decides when to initiate movement relative to the shooter's kicking action. Yet each player can be deceptive, giving the impression of kicking or moving to one side of the goal while doing the opposite. In Chapter 4, I quantified the strategies used by both players, and identified elements of these strategies that interact to affect the outcome of penalty shots. I found that shooters usually aimed toward the lower extremities of the goal, kicking at sub-maximal speeds with a side-foot technique (mean = 23.5 ms^{-1}, SD = 1.9 ms^{-1}, min = 16 ms^{-1}, max = 30 ms^{-1})—suggesting that shooters prioritise accuracy over speed. Though shooters occasionally tried to be deceptive, goalkeepers were not susceptible to this strategy. Goalkeepers tended to move to either side of the goal, on average, 0.19 s (SD = 0.15 s) before the shooter kicked the ball, though certain individuals moved consistently earlier or later. Faster penalty shots elicited earlier movement in goalkeepers, and were harder to save, even when they were within reach. In contrast with shooters, goalkeepers rarely used a deceptive strategy.

In Chapter 5, I constructed a model based on trade-offs for shooters and goalkeepers that could be used to predict the likelihood of success for any shooter strategy. I parameterised the model with results from Chapters 2-4, and found that in general, faster shots aimed closer to the ground give the best chance of scoring. Importantly, the model can be used to compete individual shooters and goalkeepers to identify the best shooting strategy for that specific matchup. Therefore, a shooter matched against a goalkeeper who tends to move early should shoot toward the centre of the goal; if matched against a goalkeeper who tends to move late, shooting toward the extremities of the goal is the best strategy, with the optimal target location in the horizontal dimension dependent on shot speed and kick technique.

Taken together, the results of this thesis indicate the outcome of a penalty shot in soccer is determined by a complex interaction between the shooter and goalkeeper strategies. For a shooter, whatever strategy they choose is subject to the inherent error involved when kicking a ball. However, with knowledge of the goalkeeper's behaviour, they can select a strategy that directs the shot to regions of the goal unlikely to be defended.

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, financial support and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my higher degree by research candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Publications included in this thesis

Peer-reviewed papers

Hunter, A. H., Angilletta Jr, M. J., Pavlic, T., Lichtwark, G., & Wilson, R. S. (2018). Modeling the two-dimensional accuracy of soccer kicks. *Journal of Biomechanics*, 72, 159–166. doi:10.1016/j.jbiomech.2018.03.003.

Hunter, A. H., Murphy, S. C., Angilletta Jr, M. J., & Wilson, R. S. (2018). Anticipating the direction of soccer penalty shots depends on the speed and technique of the kick. *Sports,* 6(3), 73. doi:10.3390/sports6030073.

Hunter, A.H., Angilletta Jr, M. J., Wilson, R. S. (2018). Behaviors of shooter and goalkeeper interact to determine the outcome of soccer penalties. *Scandinavian Journal of Medicine & Science in Sports*, 28 (12), 2751-2759 . doi: 10.1111/sms.13276.

Submitted manuscripts included in this thesis

Hunter, A. H., Angilletta Jr, M. J., Pavlic, T., Lichtwark, G., & Wilson, R. S. (2018). Modeling the two-dimensional accuracy of soccer kicks. *Journal of Biomechanics*, *72*, 159–166. (Incorporated as Chapter 2).

Contributor	Statement of contribution
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Hunter, A. H., Murphy, S. C., Angilletta Jr, M. J., & Wilson, R. S. (2018). Anticipating the direction of soccer penalty shots depends on the speed and technique of the kick. *Sports*, 6(3), 73. (Incorporated as Chapter 3)

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Author RS Wilson	Conception and design (10%) Analysis and interpretation (10%) Writing and editing (10%)

Hunter, A.H., Angilletta Jr, M. J., Wilson, R. S. (2018). Behaviors of shooter and goalkeeper interact to determine the outcome of soccer penalties. *Scandinavian Journal of Medicine & Science in Sports*, 0 (0), 1-9. doi: 10.1111/sms.13276. (In Press) (Incorporated as Chapter 4 with minor changes)

Contributor	Statement of contribution
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	Analysis and interpretation (10%) Writing and editing (15%)

Other publications during candidature

Hunter, A. H., Angilletta Jr, M. J., Pavlic, T., Lichtwark, G., & Wilson, R. S. (2018). Modeling thetwo-dimensional accuracy of soccer kicks. *Journal of Biomechanics*, 72, 159–166. doi:10.1016/j.jbiomech.2018.03.003.

Hunter, A. H., Murphy, S. C., Angilletta Jr, M. J., & Wilson, R. S. (2018). Anticipating the direction of soccer penalty shots depends on the speed and technique of the kick. *Sports*, 6(3), 73. doi:10.3390/sports6030073.

Hunter, A.H., Angilletta Jr, M. J., Wilson, R. S. (2018). Behaviors of shooter and goalkeeper interact to determine the outcome of soccer penalties. *Scandinavian Journal of Medicine & Science in Sports*, 28 (12), 2751-2759 . doi: 10.1111/sms.13276.

Conference oral presentation abstracts

Hunter, A. H., Lichtwark, G., & Wilson, R. S. (2013). Can we improve a footballer's kicking performance using optimisation theory? *Society of Integrative and Comparative Biology* Conference. San Francisco, CA, USA.

Hunter, A. H., Angilletta Jr, M. J., Lichtwark, G., & Wilson, R. S. (2014). Identifying the Best Penalty Takers and their Optimal Strategy. *World Conference on Science and Soccer*. Portland, OR, USA.

Hunter, A. H., Angilletta Jr, M. J., Pavlic, T., Lichtwark, G., & Wilson, R. S. (2017). Building a model to identify the perfect soccer penalty through optimising the trade-off between speed and accuracy. *Society of Integrative and Comparative Biology* Conference. New Orleans, LA, USA.

Hunter, A. H., Angilletta Jr, M. J., Pavlic, T., Lichtwark, G., & Wilson, R. S. (2018). Optimising behavioural strategies between competing agents: Using the soccer penalty as a model system. *Australian Society of Animal Behavioiur* Conference. Brisbane, QLD, Australia.

Contributions by others to the thesis

Robbie Wilson contributed significantly to the conception of all aspects of this thesis through discussions with me. Mike Angilletta provided essential statistical input in all Chapters and provided writing assistance throughout. Ted Pavlic provided statistical input in Chapter 2 and was essential in developing the model in Chapter 5. Sean Murphy constructed the online survey in Chapter 3 and provided important assistance in the design of this study. Glen Lichtwark provided crucial advice in the conception and design of Chapter 2. Robbie Wilson provided critical reviewing of all thesis chapters.

Statement of parts of the thesis submitted to qualify for the award of another degree

No works submitted towards another degree have been included in this thesis

Research Involving Human or Animal Subjects

This project was approved by the Behavioural and Social Sciences Ethical Review Committee, University of Queensland (project ID – 2012001078).

Acknowledgements

First and foremost, I would like to thank my primary supervisor Robbie Wilson. You encouraged me to start this journey many years ago, convincing me it was my own idea, and have provided the exact support I needed throughout. After helping generate some initial ideas you allowed me the freedom to take them where I wanted, then provided the help I needed when those ideas got too big. You were free with advice and patient with my shortcomings. I may not be a better soccer player from this experience, but I'm definitely a better scientist. I would also like to thank my advisory team, Glen Lichtwark, Bill von Hippel and Daniel Ortiz-Barrientos for all your advice throughout my candidature.

To Mike Angilletta and Ted Pavlic – I couldn't have done this without you guys. Thank you! Thank you! Thank you! You took all our crazy ideas and turned them into modelling gold. I learned more about statistics drinking Margaritas with you two than I had in my whole university career. Thankyou to Sean Murphy for taking time out of your own Phd to collaborate. You were invaluable. Thankyou also to Chris Clemente. When I was struggling with some methodological issues you pointed me in the right direction. An unmemorable 10 minute conversation for you saved my Phd.

To the Wilson Lab – thank you for your support over the years. It has been a pleasure working and playing with you all, something I hope to continue. In particular, thank you to Bec, Jaime, and Gwen for manning the cameras when I needed help collecting data. To all the guys from the University of Queensland Football Club who volunteered – thank you for being my lab rats. This Phd would not have happened without you.

Finally, thank you to Mum and Dad. You have been a constant source of encouragement and support throughout my life. I consider myself extremely lucky and grateful to have parents who think starting a Phd at the age of 33 is a fantastic idea.

Financial support

No financial support was provided to fund this research.

Keywords

soccer, penalty, kick, speed, accuracy, trade-offs, goalkeeper, anticipation, modelling

Australian and New Zealand Standard Research Classifications (ANZSRC)

ANZSRC code: 110601 Biomechanics, (30%)

ANZSRC code: 110699 Human Movement and Sports Science not elsewhere classified, (30%)

ANZSRC code: 010202, Biological Mathematics, (40%)

Fields of Research (FoR) Classification

FoR code: 1106 Human Movement and Sports Science (60%)

FoR code: 0102, Applied Mathematics, 40%

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List of Abbreviations used in the thesis

σ - standard deviation

μ - mean

∞ - infinity

bs – ball speed

lt – leave-time

lt_{min} – minimum leave-time

lt_{max} – maximum leave-time

P_{AA} - proportion of side-foot and instep kicks shots aimed in the air that go in the air

P_{AG} - proportion of side-foot and instep kicks shots aimed in the air that go on the ground

$P_{GA\ side}$ - proportion of side-foot shots aimed along the ground that go in the air

$P_{GA\ instep}$ - proportion of instep shots aimed along the ground that go in the air

$P_{GG\ side}$ - proportion of side-foot shots aimed along the ground that go on the ground

$P_{GG\ instep}$ - proportion of instep shots aimed along the ground that go on the ground

t_x – target position in the horizontal dimension

t_y – target position in the vertical dimension

CHAPTER 1

GENERAL INTRODUCTION

The penalty shot in soccer is one of the most enthralling spectacles in world sport, whereby a single kick of the ball can determine the outcome of major tournaments. Since 1986, 39% of knockout matches in the FIFA World Cup Finals involved a penalty kick or were decided by a penalty shootout, and the multi-million dollar UEFA Champions League is routinely won on penalties. Fundamentally, the penalty shot is a one-on-one competition between a shooter and a goalkeeper: the ball is placed on a designated spot 11 metres from the centre of the goal, the shooter attempts to kick the ball into the goal, the goalkeeper attempts to block the shot. Each player can be successful by selecting from a range of different strategies. Because the performance of each player is constrained by biomechanical trade-offs, penalty-taking is an ideal study system to investigate how competing agents manage these trade-offs to optimise performance.

The ability to perform complex motor tasks is constrained by various biomechanical trade-offs. For example, to change direction while running, a player must decelerate and make postural and gait changes to overcome their body's inertial forces—resulting in a trade-off between speed and agility (Besier, Lloyd, Ackland, & Cochrane, 2001; Jindrich, Besier, & Lloyd, 2006; Wheeler & Sayers, 2010). A similar trade-off exists between speed and accuracy. According to Fitt's Law (1954), the time taken to accurately move a limb toward a target is greater when the target is smaller or farther away, so that increasing movement speed decreases precision. A central assumption of this law is that continuous, feedback-based corrections are made during movement to correct the limb's trajectory toward the target (Fitts, 1954; Fitts & Peterson, 1964). However, movement time is often less than sensory feedback time, in which case corrections cannot be made.

Taking another perspective, Impulse-Variability Theory (Schmidt, Zelaznik, Hawkins, Frank, & Quinn Jr, 1979) seeks to explain variation in rapid limb movements where corrections toward the target cannot be made. In such cases the limb is propelled through space by the initial activation of multiple muscles. Variation in the forces produced by the activating muscles leads to variation in the trajectory of the limb. This applies to actions such as throwing or kicking as these tasks are characterised by an initial accelerative impulse (Schmidt et al., 1979; Urbin, Stodden, Fischman, & Weimar, 2011). Importantly, like Fitt's Law (1954), Impulse Variability Theory predicts movement becomes less precise when limbs travel further to reach a target (Schmidt et al., 1979). As athletes must increase their range of motion when kicking a ball for example (Browder, 1991; Lees & Nolan, 2002), the position and direction of force applied to the ball by the foot will vary more as shot speed increases. This reduces the precision of the kick – a trade-off between speed and accuracy.

To ensure success, individuals must select strategies that account for these trade-offs, and which are appropriate to the demands of the task. When throwing or kicking a ball at a static target, for example, athletes reduce speed to prioritise accuracy (Lees & Nolan, 2002; Roland Van Den Tillaar & Ettema, 2003). However, many sports—including soccer—require the interaction of two or more competing players, and success is not as straightforward. In soccer, the speed and accuracy of a kick both increase the likelihood that a penalty shot will move past the goalkeeper and into the goal. The best strategy to use in this case is unclear.

The aim of this thesis was to develop a predictive model that identifies the optimal strategy when two competing agents are each constrained by biomechanical trade-offs. I used soccer penalty shots as a study system because the rules of the game ensure a controlled environment yet both players are free to select from a variety of strategies. Furthermore, the outcome of the attempt is easily defined. The shooter is successful if the ball enters the goal, and the goalkeeper is successful if they block the shot or the ball misses the goal. Here, I quantified the biomechanical trade-offs experienced by shooters and goalkeepers and measured the effectiveness of strategies used to overcome them, ultimately identifying strategies leading to success.

Soccer Penalty Shots

To successfully kick the ball past the goalkeeper, shooters have a variety of available strategies based on where they choose to aim and how fast they kick the ball. How these variables interact greatly impacts the outcome of any penalty. The closer the ball goes to either goal-post when it enters the goal, the further the goalkeeper must move to intercept it, and the faster the shot, the less time available for the goalkeeper to move. Therefore, it appears that aiming close to the goal-post and kicking the ball as fast as possible would give a player the best chance of scoring a goal. But because faster shots are less accurate, (Andersen & Dorge, 2011; Kawamoto, Miyagi, Ohashi, & Fukashiro, 2006; Lees & Nolan, 2002), a player must also consider the likelihood of missing the goal with this strategy. Should the shooter aim close to the goal-post but kick more slowly to increase precision, or aim further inside the post and kick a fast shot? Reducing shot speed will give the goalkeeper more time to move and intercept the ball. Maintaining a high shot speed but aiming further inside the post means the goalkeeper has less distance to travel to block the shot. No strategy has clear advantages over others, yet shooters must choose one they believe gives them the best chance of success.

Shooters can kick the ball in excess of 25 ms^{-1} (Lees & Nolan, 2002). To have any chance of saving shots that take less than 0.5 s to reach the goal, goalkeepers position themselves in the middle of the goal and generally start to move before the ball is kicked (Dicks, Davids, & Button, 2010; G. J. P. Savelsbergh, Van der Kamp, Williams, & Ward, 2005). Because they choose a direction to dive (left or right) before the shooter has made contact with the ball, they must interpret cues presented by the shooter's body to form a prediction of shot direction (G. J. P. Savelsbergh et al., 2005). Such cues include the angle of the run-up, angle of the hips, and the placement of the non-kicking foot (Dicks, Button, & Davids, 2010a; Franks & Hanvey, 1997; Terry McMorris & Colenso, 1996; G. J. P. Savelsbergh et al., 2005; A. M. Williams & Burwitz, 1993; M. Williams & Griffiths, 2002). As these cues become more predictive closer to ball contact, the longer goalkeepers wait before moving, the more likely they correctly anticipate the shot's direction (Smeeton & Williams, 2012). However, this delay in movement reduces the time available to move across the goal to block a shot. Goalkeepers must consider this trade-off, and their strategy can be defined by when they choose to move relative to ball contact.

A goalkeeper's direction of movement during a penalty has a large impact on the outcome; if they select the wrong direction, the result will almost certainly be a goal unless the shooter has committed a large error. As a result, shooters sometimes use strategies intended to provoke goalkeepers to move in the wrong direction. As they approach the ball, shooters can watch the goalkeeper and wait until they start to move in one direction before shooting to the other side of the goal. This is a "keeper-dependent" strategy and is effective if the goalkeeper moves early in the shooter's approach (Botwell, King, & Pain, 2009; Kuhn, 1988; Morya, Ranvaud, & Pinheiro, 2003; Van der Kamp, 2006). However, if the keeper moves closer to ball contact, the shooter does not have enough time to alter shot direction, and their accuracy may be compromised (Van der Kamp, 2006; Wood & Wilson, 2010b). Shooters can manipulate their body cues, appearing to kick toward one side of the goal while actually kicking toward the other, and increasing the likelihood that goalkeepers move toward the wrong side of the goal. (Dicks, Button, et al., 2010a; Dicks, Davids, et al., 2010; Smeeton & Williams, 2012; Tay, Chow, Koh, & Button, 2012). This deceptive strategy only works, though, if goalkeepers move well before ball contact (Smeeton & Williams, 2012).

The outcome of a penalty is determined by an interaction between shooter and goalkeeper, each using strategies based on biomechanical constraints. In this thesis, I quantify these trade-offs and build a model for predicting the optimal strategy for scoring a penalty.

Shooter Trade-offs

To determine the efficacy of any shooting strategy, we must be able to estimate the error structure of the shot, or where the ball is likely to go. The speed of a shot will affect this error structure, due to the trade-off between speed and accuracy (Andersen & Dorge, 2011; Kawamoto et al., 2006; Lees & Nolan, 2002). Though previous research shows that players reduce kicking speed when asked to prioritise accuracy, no study has yet shown how shooting error changes over the range of kicking speeds and kicking techniques (side-foot and instep) used in soccer (Andersen & Dorge, 2011; Kawamoto et al., 2006; Lees & Nolan, 2002; Sterzing, Lange, Wächtler, Müller, & Milani, 2009). Therefore, shot accuracy must be quantified across a range of shot speeds, target locations and kick techniques to describe the likely dispersion of shots for a given shooting strategy. With this, one could determine the likelihood of success for any given strategy (Figure 1.1).

Shot speed may also trade off with unpredictability in penalty shots. Unpredictability is desirable, because shooters are more likely to succeed if they can disguise the direction of their shot (Dicks, Button, et al., 2010a). However, shooters must increase their range of motion to generate more speed (Browder, 1991; Lees & Nolan, 2002), so their intent may be easier to predict compared with slower shots with less range of motion. One study of soccer penalties manipulated the amplitude of the shooter's movement, and found that goalkeepers more likely to predict shot direction when shooters exaggerated their kicking action; however, the authors did not measure or manipulate shot speed (Smeeton & Williams, 2012). The trade-off between speed and unpredictability when kicking a ball is yet to be tested. If such a trade- exists, it will greatly influence penalty success by changing the likelihood that goalkeepers move in the correct direction toward the ball (Figure 1.1).

Goalkeeper Trade-offs

To prevent a goal, a goalkeeper must correctly predict the direction of the shot and move to intercept the ball before it enters the goal. Here, they face a clear trade-off, as earlier movement decreases the likelihood that they will assess the direction of the shot correctly (G. J. P. Savelsbergh et al., 2005; Smeeton & Williams, 2012). However, previous work in this area has been limited by experimental designs that allow participants to self-select the time of prediction (G. J. P. Savelsbergh et al., 2005), or use an insufficient number of shooters to encompass the natural variation in kicking styles (Smeeton & Williams, 2012). Furthermore, the likelihood of success depends on when the goalkeeper chooses to move, or their leave-time—while goalkeepers vary in leave-time (Dicks, Davids, et al., 2010; G. J. P. Savelsbergh et al., 2005), no study has assessed its variation within or among players .

Moving in the correct direction is not sufficient to block a penalty shot—the goalkeeper must move part of their body into the trajectory of the ball, preventing it from entering the goal. Because faster shots require greater force to alter their trajectory, the goalkeeper's movements must be accurate to ensure success. For example, a fast shot that hits only the goalkeeper's fingers is likely to continue into the goal, while a slower shot might be deflected outside the goal. Because faster shots give the goalkeeper less time to move accurately (Fitts, 1954), it is likely that blocking shots will become more difficult as shot speed increases (Figure 1.1), though no study has yet investigated this phenomenon in the context of a penalty shot.

Shooter and Goalkeeper Interactions

During a penalty, shooters and goalkeepers each select a strategy that they believe will lead to success. However, as each player can observe the other's behaviour prior to the ball being kicked, their strategies are not always independent (Van der Kamp, 2006; Weigelt, Memmert, & Schack, 2012). For example, if a goalkeeper takes a position slightly to one side of the goal, shooters tend to aim to the larger side of the goal (Weigelt et al., 2012). Goalkeepers can therefore use their starting position as a form of deception, influencing the shooter's strategy, and increasing the likelihood that they will predict shot direction (Figure 1.1). In a similar way, shooters can use deception to increase the likelihood that goalkeepers move in the wrong direction (Figure 1.1). While deceptive strategies are effective under experimental conditions, for both shooters and goalkeepers (Smeeton & Williams, 2012; Van der Kamp, 2006; Weigelt et al., 2012), little is known about their prevalence or effectiveness in match-like conditions (Kuhn, 1988).

Lastly, goalkeepers are likely to select a leave-time based on shot speed (Figure 1.1). Goalkeepers likely use cues presented by the shooter to estimate shot speed before the ball is kicked, such as the speed of their approach to the ball (Lees & Nolan, 2002). Moving earlier on faster shots increases a goalkeeper's probability of moving across the goal in time to block a shot. No previous study has investigated this relationship.

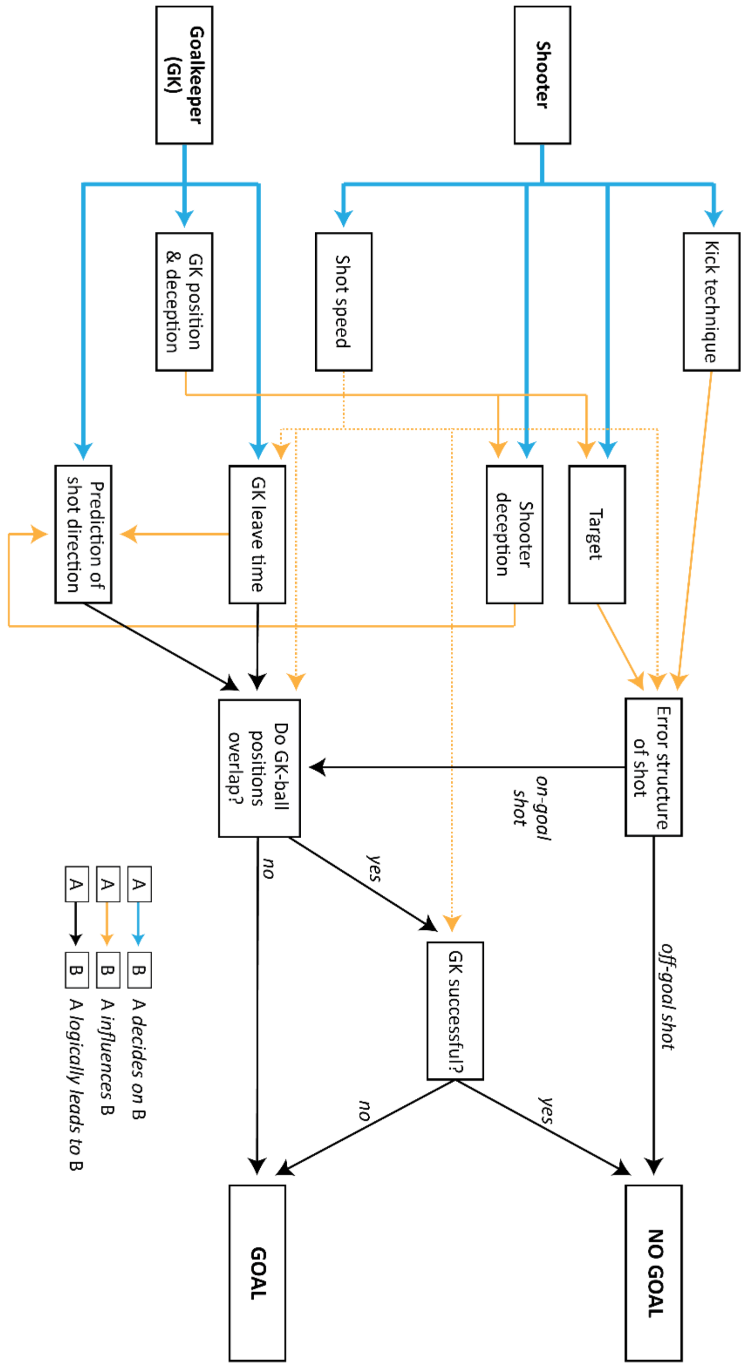

Figure 1.1: Flowchart describing how the shooter's strategy and goalkeeper's strategy interact to determine the outcome of a soccer penalty. Blue arrows describe the decisions made by shooters and goalkeepers to formulate an overall strategy. Yellow arrows show where one variable influences another. Black arrows show logical steps. For example, shooters select a target, shot speed, and kick technique, which determines the error structure of the shot (accuracy). If the shot is very inaccurate and misses the goal, the result is no goal.

Thesis Aims

The overall aim of my thesis was to build a predictive model that identifies the shooting strategy with the greatest chance of success in a soccer penalty. To achieve this, I needed to: quantify the trade-offs experienced by shooters and goalkeepers; determine the strategies used by both players to overcome these trade-offs; and determine how these strategies interact to influence the outcome of penalties.

To estimate the efficacy of different shooting strategies, I needed to quantify how speed affects the accuracy and unpredictability of shots. Therefore, the first aim of my thesis (Chapter 2) was to quantify the trade-off between speed and accuracy when taking a penalty shot for all shot speeds and kick techniques used in games. With this I could estimate where the ball is likely to go for any shooting strategy. The second aim (Chapter 3) was to determine if the shooting strategy affects the likelihood the goalkeeper predicts the direction of the shot – namely, identify if a trade-off exists between shot speed and unpredictability.

Next, I needed to determine what factors lead to goalkeeper success or failure. Goalkeepers must first move in the correct direction to have any chance of blocking a shot. Therefore, the third aim of my thesis (Chapter 3) was to quantify the relationship between goalkeeper leave-time and predicting shot direction. I also needed to describe the variation in leave-time within and among goalkeepers, which was my fourth aim (Chapter 4). If goalkeepers move correctly they still need to effectively block the shot. Determining if this becomes more difficult as shot speed increases was my fifth aim (Chapter 4).

I also needed to quantify elements of the shooter's and goalkeeper's strategies that interact. Both players can use deceptive strategies to influence each other's behaviour. The sixth aim of my thesis (Chapter 4) was to determine the prevalence and effectiveness of deceptive strategies for both players. Lastly, the seventh aim of my thesis (Chapter 4) was to determine the effect of shot speed on goalkeeper leave-time.

With the data collected in Chapters 2-4, I parameterised a predictive model that estimates the likelihood of success for any strategy a shooter might use (Chapter 5). In simple terms, the model matches a specific shooting strategy against all strategies a goalkeeper might use, considering the likelihood that each goalkeeper strategy might occur. Previous models of penalty shot success ignore shot speed and accuracy as elements of any shooting strategy, and/or ignore the timing of goalkeeper movement and the likelihood they predict shot direction (Azar & Bar-Eli, 2011; Bar-Eli, Azar, Ritov, Keidar-Levin, & Schein, 2007; Chiappori, Levitt, & Groseclose, 2002; Leela & Comissiong, 2009). My model therefore surpasses previous models of shooting success by 1) incorporating an error structure that changes with shot speed, target, and shooter footedness, 2) incorporating a distribution of goalkeeper leave-time that influences the likelihood the goalkeeper predicts shot direction and, 3) accounting for elements of each players strategy that interact to affect the outcome.

Structure of the Thesis

This thesis comprises three experimental (Chapters 2, 3, & 4) and one theoretical chapter (Chapter 5) that investigate how a shooter’s strategy and goalkeeper’s strategy interact to determine the outcome of soccer penalty shots. Chapters 2, 3, and 4 have been published and Chapter 5 will be submitted to a scientific journal in due course. Therefore, each chapter is structured with an Abstract, Introduction, Methods, Results, and Discussion. The final chapter (Chapter 6) provides a general discussion of the results and directions for future research.

CHAPTER 2

MODELING THE TWO-DIMENSIONAL ACCURACY OF SOCCER KICKS

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 & Dorge, 2011; Etnyre, 1998; Freeston & 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 & Dorge, 2011; Asami, Togari, & Kikuchi, 1976; Kawamoto et al., 2006; Lees & 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 & Nolan, 2002; Stoner & 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, Slomka, & Latash, 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 & 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 & 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 & 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 (Figure 2.1). 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 Figure 2.1). 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.

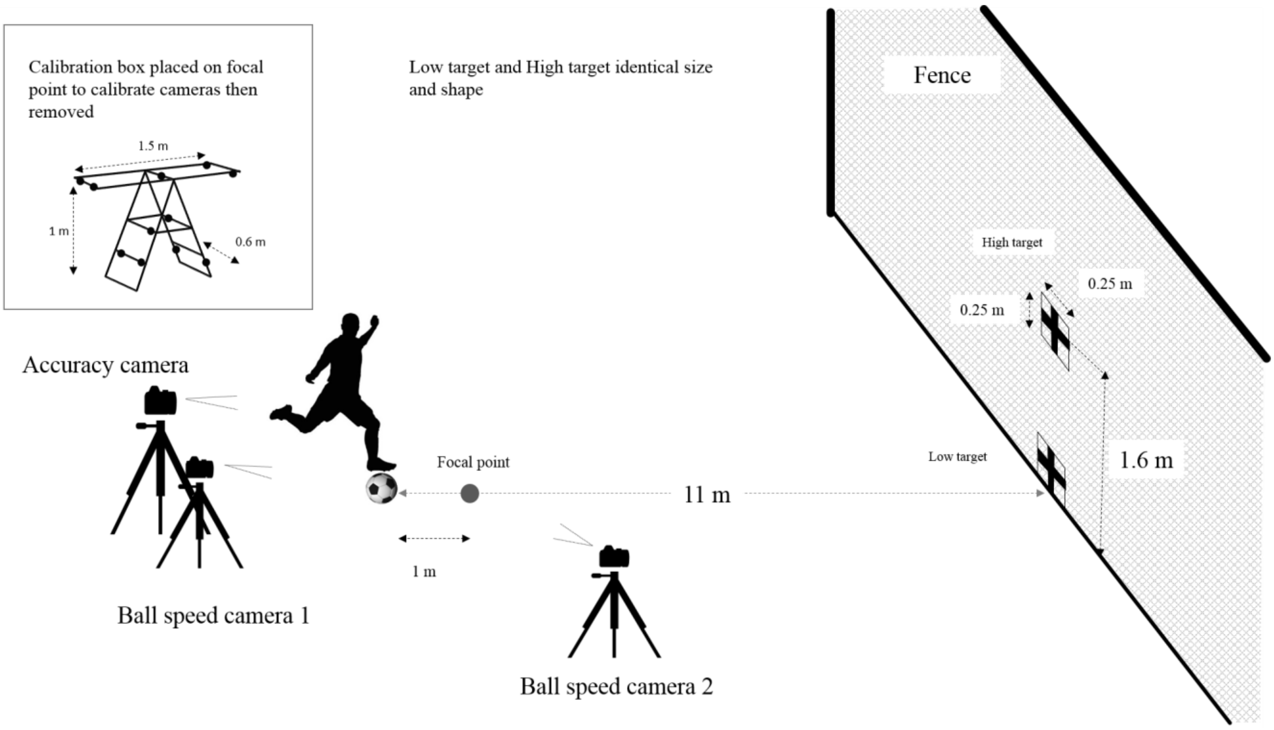

Figure 2.1: Graphical representation of experimental setup

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 2.1 and 2.2). We also modelled the residual variance separately for different targets and techniques. Models were fit with the nlme library (Pinheiro, Bates, DebRoy, Sarkar, & R Core Team, 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 2.3 & 2.4).

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.

Table 2.1: 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) · speed$^{2\delta}$	22	16804.38	0.00	0.86
(technique * target) · $e^{speed*2\delta}$	22	16807.99	3.61	0.14
technique · speed$^{2\delta}$	20	16831.57	27.19	< 0.01
(technique + target) · speed$^{2\delta}$	21	16831.93	27.54	< 0.01
technique · $e^{speed*2\delta}$	20	16835.47	31.09	< 0.01
(technique + target) · $e^{speed*2\delta}$	21	16835.80	31.41	< 0.01
technique * target	21	16903.42	99.04	< 0.01
target · $e^{speed*2\delta}$	20	17395.39	591.01	< 0.01
target · speed$^{2\delta}$	20	17398.60	594.22	< 0.01

Table 2.2: 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) · speed$^{2\delta}$	22	10734.85	0.00	> 0.99
(technique * target) · $e^{\mathrm{speed}*2\delta}$	22	10825.87	91.02	< 0.01
(technique + target) · speed$^{2\delta}$	21	10847.77	112.92	< 0.01
(technique + target) · $e^{\mathrm{speed}*2\delta}$	21	10937.28	202.43	< 0.01
target · speed$^{2\delta}$	20	11058.36	323.51	< 0.01
target · $e^{\mathrm{speed}*2\delta}$	20	11138.71	403.85	< 0.01
technique * target	21	11984.71	1249.86	< 0.01
technique · speed$^{2\delta}$	20	12168.36	1433.51	< 0.01
technique · $e^{\mathrm{speed}*2\delta}$	20	12228.14	1493.29	< 0.01

Table 2.3: 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).

Parameter	Estimate	SE	df	t	p
intercept (left-footed, low target, instep kick)	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 2.4 : 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					
(left-footed, low target, instep kick)	-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

Results

As predicted from biomechanical constraints, kicking speed and style influenced accuracy. Tables 2.3 and 2.4 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 (Figures 2.2 and 2.3, 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 Figures 2.2 and 2.3. 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 (Figure 2.2, 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 (Figure 2.2, top panels). Fast kicks were very likely to be inaccurate in the horizontal dimension even if they were accurate in the vertical dimension (Figure 2.3).

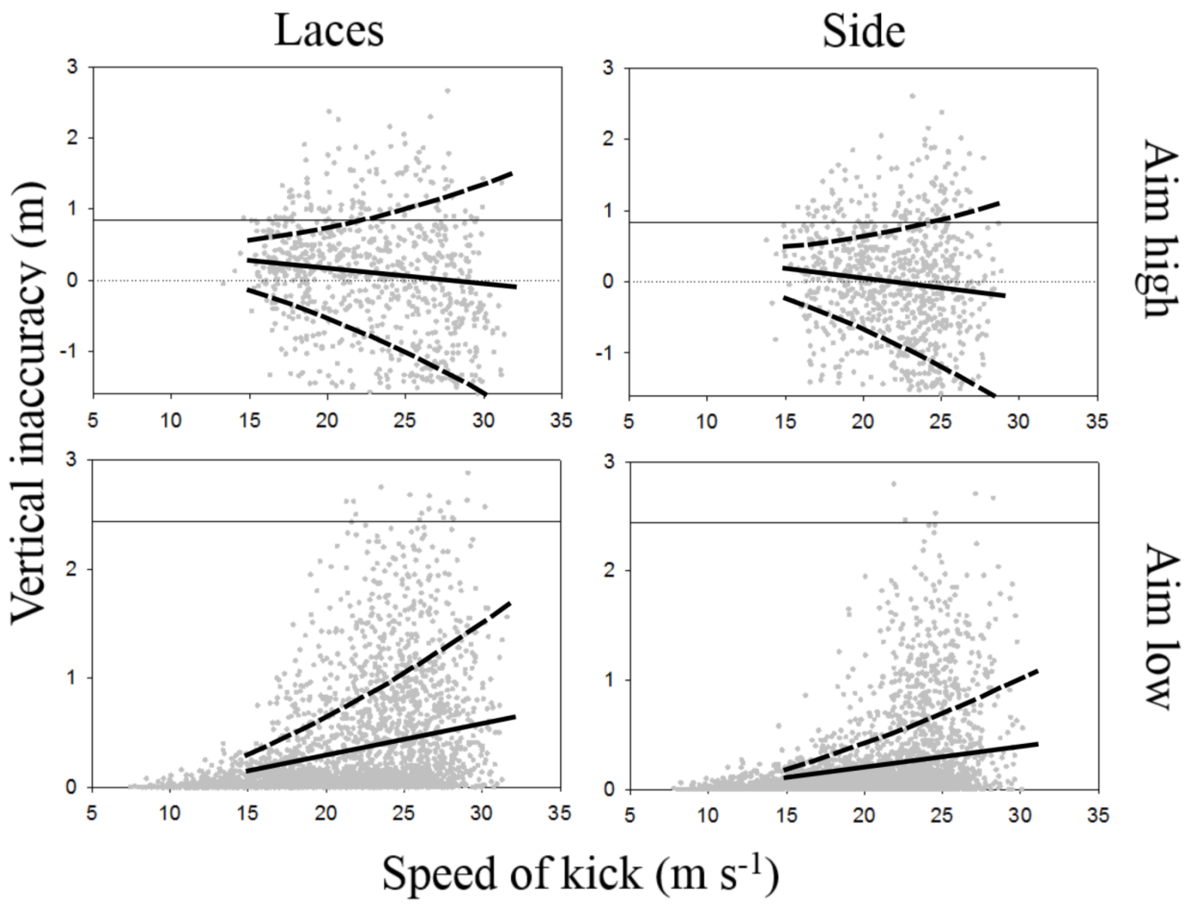

Figure 2.2: Raw data of effect of speed on inaccuracy of shots in the vertical dimension for side-foot and laces kicks aimed at low and high targets (right footed players only). Target is represented by dotted black line (top two panels) or y = 0 (bottom two panels) Solid black line represents height of crossbar in soccer goal. Solid black lines and dotted black lines represent mean miss and ± 1 SD respectively from statistical model.

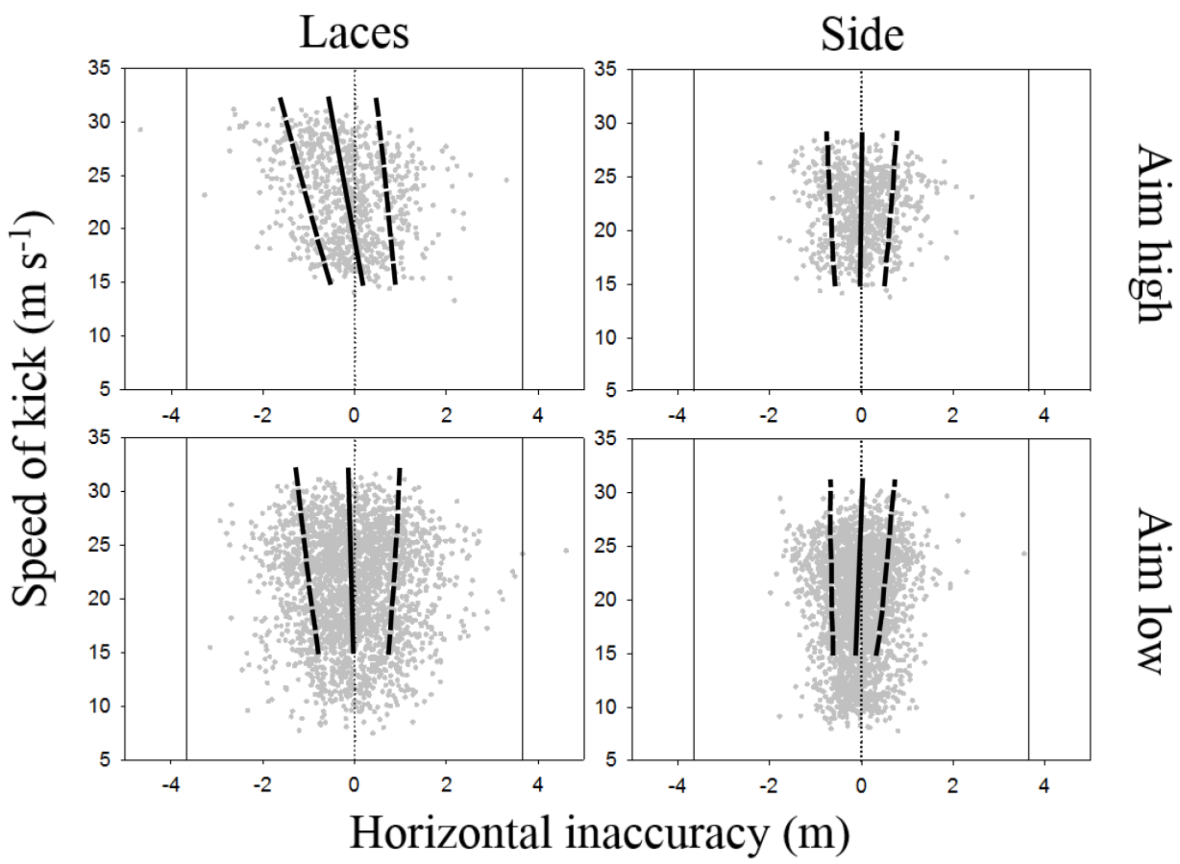

Figure 2.3: Raw data of effect of speed on inaccuracy of shots in the horizontal dimension for side-foot and laces kicks aimed at low and high targets (right footed players only). Target is represented by dotted black line. Solid black lines represent left and right goal-posts of soccer goal for target in the centre of goal. Solid black lines and dotted black lines represent mean miss and ± 1 SD respectively from statistical model.

Both speed and accuracy depended on the technique used to kick the ball. No player generated a speed above 30 $m{\cdot}s^{-1}$ when contacting the ball with the side-foot, but speeds as fast as 33 $m{\cdot}s^{-1}$ 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 Figures 2.2 and 2.3, 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 2.3 and 2.4). 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 (Figure 2.4). By contrast, left-footed kickers tended to miss high and left, or low and right (Figure 2.4). These distributions illustrate the greater spread of the ball when kicking in the air or with the laces of the shoe.

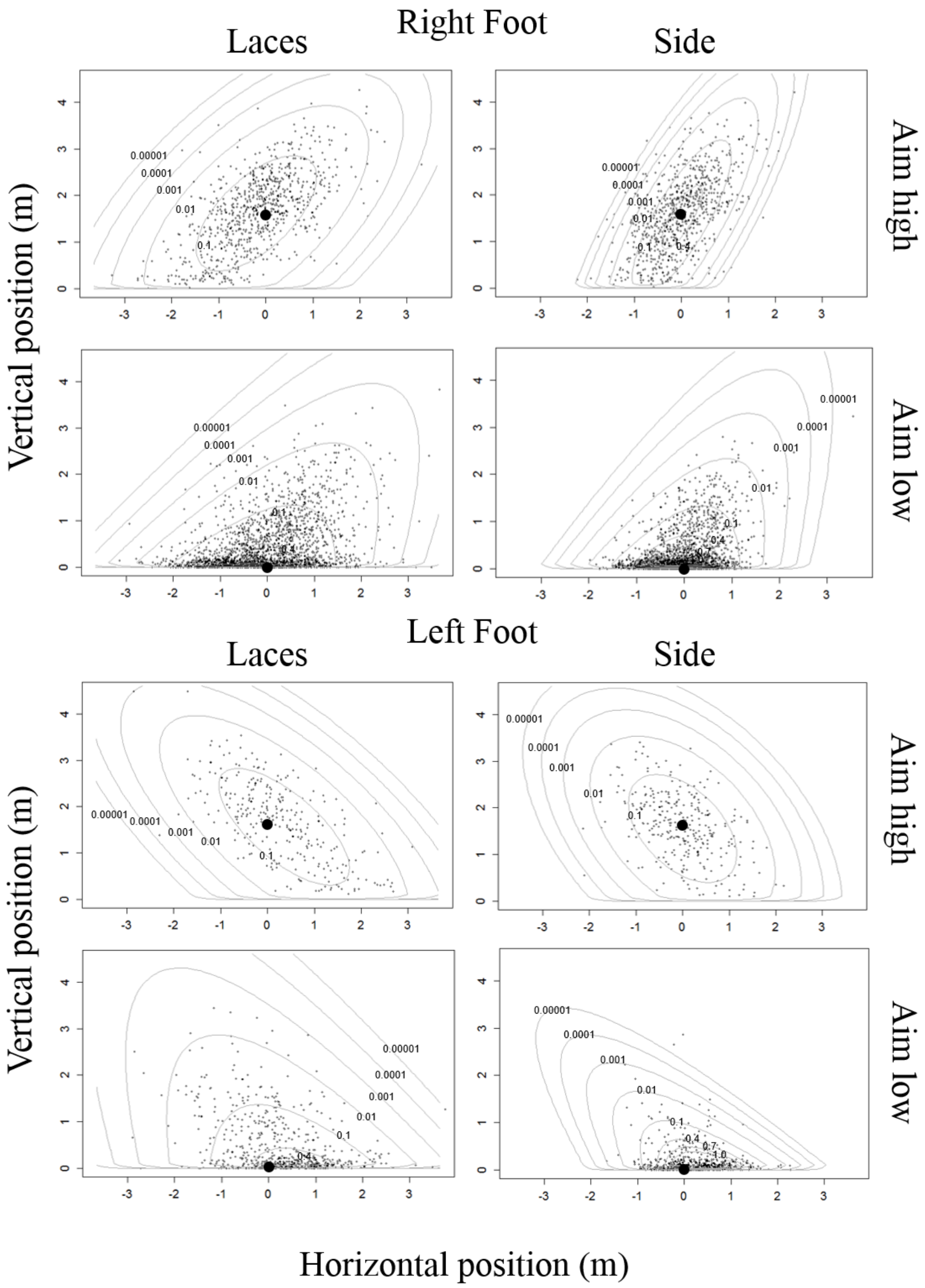

Figure 2.4: Bivariate distribution of kicks for right and left footed players shooting side-foot and laces at low and high target. Origin represents the ground and large black dots represent the target. Small dots are raw data for each condition. Contours shown are level curves of the joint density function of the best-fit truncated bivariate normal distribution, where the truncation occurs 0.1 m above the ground.

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 & Dorge, 2011; Asami et al., 1976; Lees & 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 & Asai, 2013; Shinkai, Nunome, Isokawa, & Ikegami, 2009; Tol, Slim, van Soest, & van Dijk, 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 & 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% (Figure 2.5). 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.

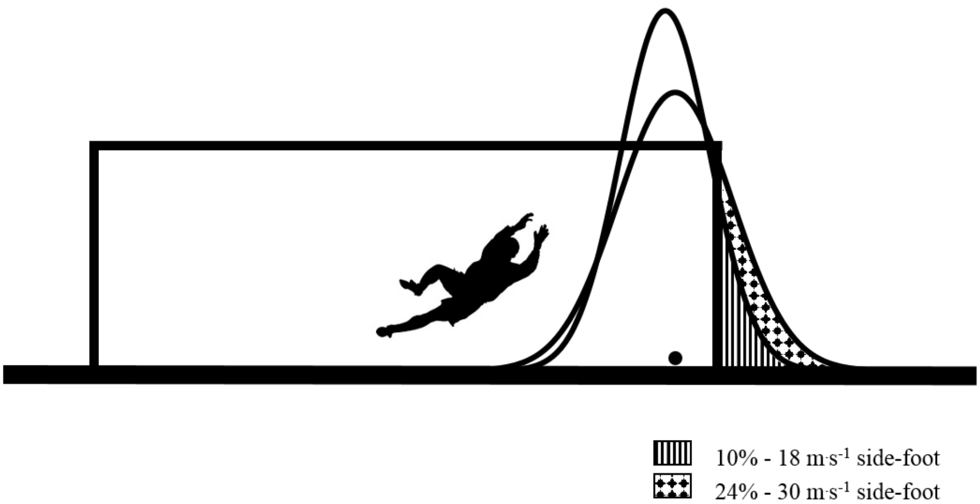

Figure 2.5: Proportion of shot distributions that will miss the goal in the horizontal dimension for side-foot shots of 18 ms-1 and 30 ms-1. Black dot represents target of 50cm inside the goal-post. Distributions generated from best-fit model.

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 $m \cdot s^{-1}$ (Figure 2.5), 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, Ferdinands, & Rooney, 2007; Freeston & Rooney, 2014; Indermill & Husak, 1984), or do not (Urbin, Stodden, Boros, & Shannon, 2012; R. Van Den Tillaar & 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.

CHAPTER 3

ANTICIPATING THE DIRECTION OF SOCCER PENALTY SHOTS DEPENDS ON THE SPEED AND TECHNIQUE OF THE KICK

Abstract

To succeed at a sport, athletes must manage the biomechanical trade-offs that constrain their performance. Here, we investigate a previously unknown trade-off in soccer: how the speed of a kick makes the outcome more predictable to an opponent. For this analysis, we focused on penalty kicks to build on previous models of factors that influence scoring. More than 700 participants completed an online survey, watching video of penalty shots from the perspective of a goalkeeper. Participants (ranging in soccer playing experience from never played to professional) watched 60 penalty kicks, each of which was occluded at a particular moment (-0.4 s to 0.0 s) before the kicker contacted the ball. For each kick, participants had to predict shot direction toward the goal (left or right). As expected, predictions became more accurate as time of occlusion approached ball contact. However, the effect of occlusion was more pronounced when players kicked with the side of the foot than when they kicked with the top of the foot (instep). For side-foot kicks, the direction of shots was predicted more accurately for faster kicks, especially when a large portion of the kicker's approach was presented. Given the trade-off between kicking speed and directional predictability, a penalty kicker might benefit from kicking below their maximal speed.

Introduction

Sport scientists commonly measure maximal performances such as fastest speed, highest leap, or farthest throw, because such parameters are thought to reflect performance in a game or event. However, increases in one kind of performance may be associated with decreases in another. For example, moving faster usually reduces agility (Jindrich, Besier, & Lloyd, 2006; Wheeler & Sayers, 2010) and accuracy (Fitts, 1954). Throwing darts (Etnyre, 1998), kicking soccer balls (Andersen & Dorge, 2011), and pitching in baseball or cricket (Freeston & Rooney, 2014) are all subject to a trade-off between speed and accuracy. Thus, sporting success does not rely simply on maximal performance but is affected by trade-offs that can be managed to optimise overall success.

In soccer, a potential trade-off between the speed and unpredictability of an action could influence success in penalty kicks. In this situation, unpredictability is advantageous, and soccer players are more likely to score on a penalty kick if they can disguise the direction of the kick (Dicks, Button, et al., 2010a). During penalties, goalkeepers use cues presented by the kicker to predict shot direction before the ball moves (Dicks, Button, & Davids, 2010b; Kim & Lee, 2006; Piras & Vickers, 2011). If a shooter kicks as fast as possible, their range of motion increases compared to a slower kick (Browder, 1991; Lees & Nolan, 2002), exaggerating visual cues used by the goalkeeper and improving their accuracy in predicting the direction of the shot (Smeeton & Williams, 2012).

The ability to anticipate ball direction has been studied in a range of sports, including badminton (Abernethy & Zawi, 2007), tennis (Smeeton & Huys, 2011), squash (Abernethy, Gill, Parks, & Packer, 2001), and soccer (Dicks, Button, et al., 2010b; T McMorris & Hauxwell, 1997; G. J. P. Savelsbergh et al., 2005). In most of these studies, a subject is shown a video in which a portion of the opponent's (shooter's) movement has been occluded. In this way, researchers can determine whether a shooter's movements reveal their placement of the ball. Not surprisingly, subjects predict direction more accurately when they have more visual information about a shot. Two studies manipulated movement amplitude, finding it influenced subjects' ability to predict shot direction in soccer (Smeeton & Williams, 2012) but not tennis (Smeeton & Huys, 2011). As these studies manipulated movement amplitude, not shot speed, the relationship between speed and unpredictability is unclear. A better understanding of this phenomenon could assist kickers in selecting (and training for) the shooting strategy that maximises their chance of scoring. While various factors contribute to the outcome of a penalty shot (Masters, Kamp, & Jackson, 2007; Terry McMorris & Colenso, 1996; Smeeton & Williams, 2012; Wood & Wilson, 2010b), understanding any variable that increases or decreases the likelihood of goalkeepers anticipating shot direction is beneficial for shooters.

In this study, we quantified the trade-off between speed and unpredictability using videos of soccer penalties. By manipulating the speed of a kick with human actors, we investigated the relationship between speed and unpredictability more rigorously than in previous studies of soccer or tennis. Controlling for footedness (Terry McMorris & Colenso, 1996) and approach angle (Franks & Hanvey, 1997; Terry McMorris & Colenso, 1996), soccer players were recorded from the perspective of a goalkeeper while shooting penalties at various speeds. These videos were presented to subjects in a computer-based survey in which participants guessed the direction of each kick. We were also interested in how the relationship between speed and unpredictability might be mediated by the amount of information observers receive, as shot direction is easier to predict when predictions are made closer to the shooter's foot contacting the ball (Dicks, Button, et al., 2010a; G. J. P. Savelsbergh et al., 2005; Smeeton & Williams, 2012). Therefore, we manipulated the endpoint of each video so that it varied from the point at which the shooter's foot contacted the ball to −0.4 s before contact. Shooters used both kick techniques seen in soccer: side-foot and instep kicks. We predicted participants would be more likely to guess the direction of faster shots compared to slower shots, and that predictions made closer to ball contact more likely to be correct than predictions made earlier in the shooter's kicking action.

Methods

The survey was an online-based community convenience sample constructed using Qualtrics (*Qualtrics*, 2015) and the video hosting site Vimeo. A link to the survey was distributed via email, Facebook, Twitter, and the University of Queensland online magazine. Informed consent was obtained and the methods and protocols for this experiment were approved by the Behavioural and Social Sciences Ethical Review Committee, University of Queensland (project ID-2012001078).

Prior to completing the survey, participants were asked their age, gender, soccer playing experience before the age of 18, soccer playing experience after the age of 18, and if their soccer playing experience was predominantly as a goalkeeper or outfield player (see Appendix).

Survey Task

Participants watched 60 videos of soccer players taking penalty shots. Each video was a single penalty shot filmed from the perspective of a goalkeeper. Each video commenced just prior to the start of the shooter's run-up and ended at various points up until the shooter's foot contacted the ball, thereby removing any information about the ball's trajectory. After viewing each video, participants were asked to decide whether the shot went to their left or their right. Instructions were provided at the beginning of the survey (see Appendix A), followed by 10 practice videos, then 60 test videos. Participants received feedback during the 10 practice videos informing them if their answer was correct. They did not receive feedback during the test phase.

Video Production

Ten right-footed soccer players from the University of Queensland Football Club were recruited to produce the video clips watched by participants. Video footage was captured on a camera (Panasonic Lumix DMC-TZ40, 50 fps, resolution 1920 × 1080, Panasonic, Kadoma, Japan) positioned 1.5 m off the ground in the middle of a soccer goal facing the penalty spot (Figure 3.1). A designated starting spot for all shooters was marked on the ground 4 metres behind the penalty spot at an angle of 22.5° (Figure 3.1). A line was drawn on the ground between the penalty spot and this mark. Players were instructed to execute shots to both sides of the goal aiming at a marker placed 1 metre inside either goal-post. Both side-foot and instep kicks were executed across a range of shot speeds (~50–100% of an individual's maximum kicking speed). Shooters were instructed to (1) commence their run-up from the designated starting spot and approach the ball along the drawn line, (2) not use any deception or try to conceal the direction they were shooting but concentrate on accuracy and shoot with a natural kicking motion, and (3) not look at their intended target for the period 2 s before they commenced their run-up until after they had completed their shot.

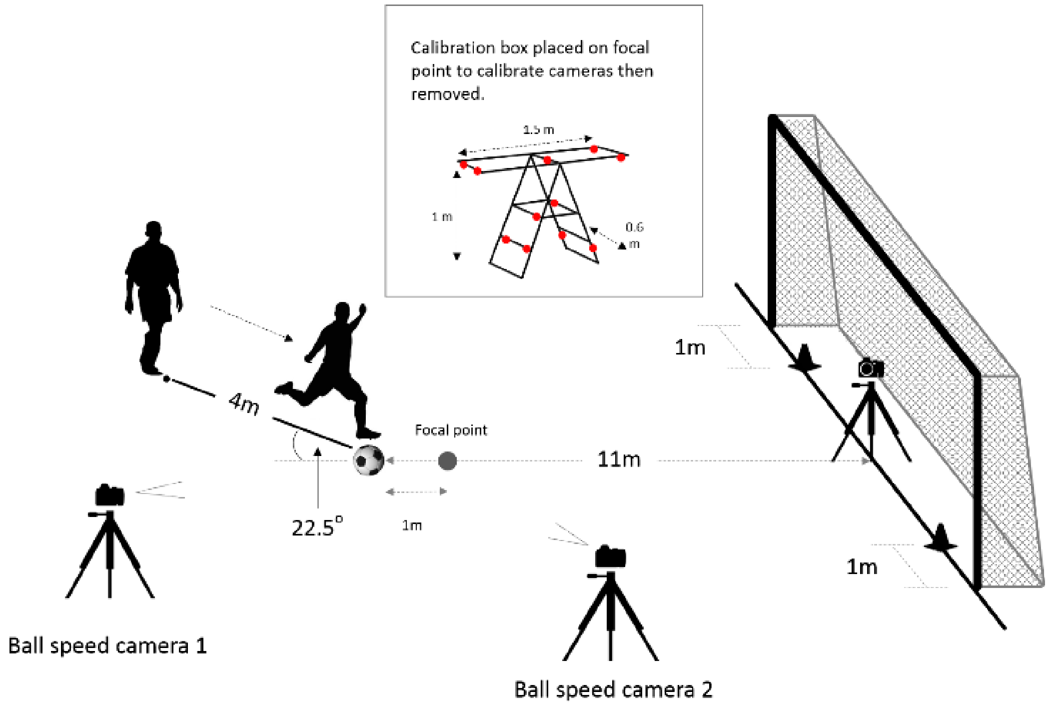

Figure 3.1: Graphical representation of experimental setup used to produce videos used in the survey.

Video Analysis

To measure ball speed, we used the DLTcal5 and DLTdv5 packages of MATLAB [24]. First, two high-speed cameras (Panasonic Lumix DMC-TZ40) were calibrated to a three-dimensional space. Then, coordinates (x,y,z) were extracted from subsequent footage taken with the calibrated cameras. To calibrate the cameras, an 'imaginary' focal point was designated at 1 m in front of the penalty spot (i.e., 10 m from the goal). An 11-point calibration box (1.5 m × 1 m × 0.6 m) was centred on the focal point, thereby filling the space through which the ball travelled (Figure 3.1). Two high-speed cameras, each on a 1 m tripod, were oriented 90 degrees from each other and facing the focal point. The first camera was positioned approximately 3 m behind the penalty spot and 3 m to the side to avoid impeding the kickers' approach. The second camera was placed 3 m in front of the penalty spot and 3 m to the side, perpendicular to the ball's trajectory. After positioning and filming the calibration box with both cameras, the box was removed. Each kick was then recorded on the cameras filming at identical frame rates (100 fps). In MATLAB, the ball's centre was extracted from six frames that spanned the first .06 s after the foot struck the ball. With these positional data the distance the ball travelled between each frame was first calculated. Then, knowing the frame rate, we calculated the speed of the ball between each frame. The average of these six velocities gave our measure of ball speed. For every player, the speed of each shot was converted to a percentage of their maximum speed for that side of the goal (left or right) and shooting technique (side-foot or instep).

Video Selection

For every player, twelve shots were selected to be in the survey—three shots for each combination of side aimed at and kicking technique (left and side-foot; right and side-foot; left and instep; right and instep). The three shots selected for each group were of varying speeds and categorised as slow, medium, or fast in order of increasing speed. The shot speeds used across all shooters for each kick technique were (Mean ± Standard Deviation): Slow side-foot, 64.9% ± 6.54%; medium side-foot, 84.8% ± 3.9%; fast side-foot, 99.5% ± 1%; slow instep, 62.4% ± 5.7%, medium instep, 83.7% ± 6%; fast instep, 99.6% ± 1.2%. The video of each shot was edited with the open-source software program Kinovea (v0.8.15, Kinovea, France). Original videos were converted to 30 frames per second to enable uploading to Vimeo. Each video was then edited to start 2 s before the shooter commenced their run-up toward the ball. The videos ended at one of 5 points in time (occlusion time): (1) At ball contact, (2) −0.1 s before ball contact, (3) −0.2 s before ball contact, (4) −0.3 s before ball contact, or (5) −0.4 s before ball contact. During the survey, the screen went blank after each video ended and participants were asked to infer the direction of the shot.

Combining the edited videos for 10 kickers yielded a pool of 600 videos. In designing the survey, we wanted to keep the following conditions consistent among participants: (1) An even spread of shots that went left or right, (2) an even spread of side-foot and instep shots, (3) an even spread of occlusion times, (4) an even spread of shot speeds, (5) shots randomized among kickers, and (6) not more than one occlusion of each original video. With this is in mind, ten groups of 60 videos were created that satisfied these conditions with no video repeated within or across groups. Participants were randomly assigned to watch one of these video groups with videos in random order. The 10 practice trials were produced from shots separate from those included in the test phase and included shots aimed left and right across a range of speeds, kick techniques, and occlusion times.

Post-Survey Feedback

At the completion of the survey, participants were given feedback on the number of shots they guessed correctly. This was broken down into 5 ‘difficulty’ levels corresponding with the 5 occlusion time conditions. The average number of correct guesses for each difficulty level from a pilot sample was also presented.

Penalty Shootout Analysis

Previous studies of penalty kicks report that goalkeepers dive at different times in matches (Kuhn, 1988; Edgard Morya et al., 2005) and under experimental conditions (Dicks, Davids, et al., 2010; G. J. P. Savelsbergh et al., 2005). However, no study presents a distribution describing the variance in time, relative to ball contact, goalkeepers choose to dive in matches. To estimate this distribution, we analysed 330 penalty shots from existing footage of 34 penalty shootouts from professional competitions (e.g., Fédération Internationale de Football Association {FIFA} World Cup, Union of European Football Associations {UEFA} Champions League, Africa Cup of Nations), with 41 countries or clubs represented in the sample. We sourced video of penalty shootouts from Youtube, and using Kinovea, two times were extracted from each penalty: (1) When the shooter’s foot contacted the ball and (2) when the goalkeeper initiated their dive to a side. Some goalkeepers make movements unrelated to their final dive direction during the shooter’s run-up (e.g., bobbing up and down, moving laterally side-to-side). These movements were ignored until the goalkeeper initiated their final dive. We then calculated the time goalkeepers first moved relative to ball contact (leave-time). The frequency distribution of leave-time is presented in Figure 3.2 ($M = -0.22$ s, $SD = 0.11$ s). From this distribution, the range of occlusion times we selected (-0.4 s to 0 s) represents the range of leave-times commonly used by professional goalkeepers in matches.

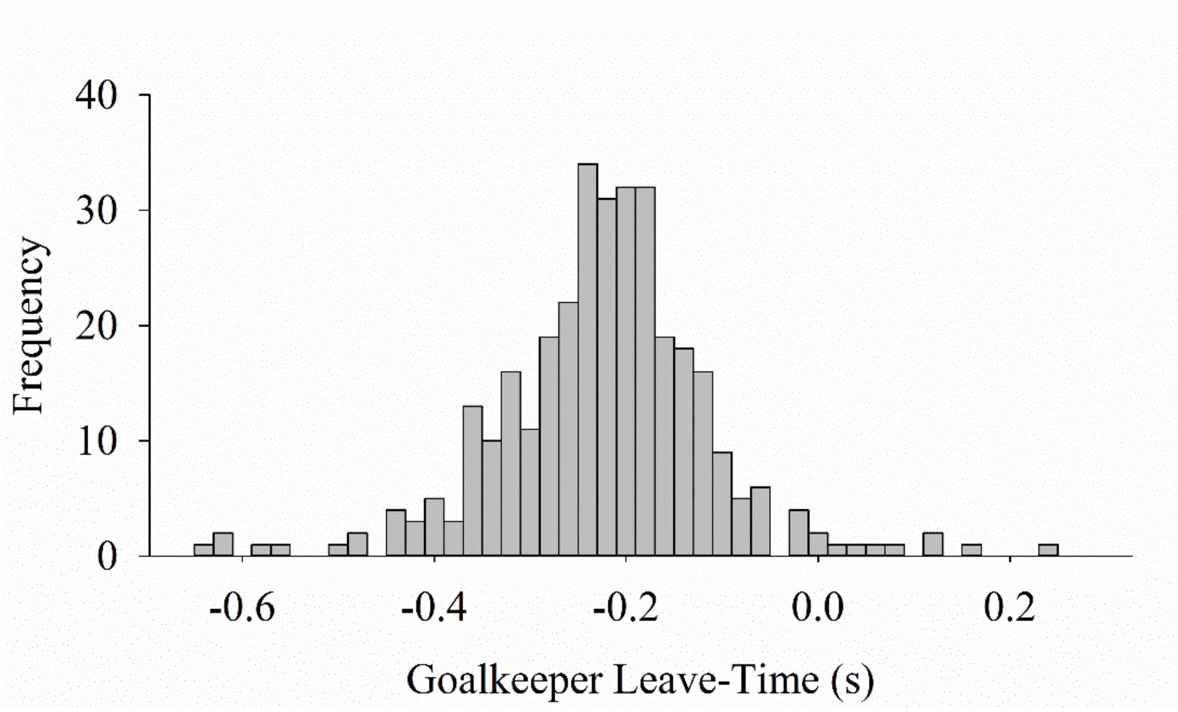

Figure 3.2: Frequency distribution of goalkeeper leave-time from 330 penalty kicks in professional/international matches. Negative values are before ball contact.

Statistical Analysis

Due to a low sample size (N = 3), participants classifying their soccer playing experience over the age of 18 as professional were removed from analysis. A one-way ANOVA and Tukey Honest Significant Difference (95% Confidence Intervals) (R Core Team, 2016) was initially used to detect significant effects of soccer playing experience over the age 18 on correctly guessing shot direction. A generalised linear model (GLM) with a binomial distribution (R Core Team, 2016) was used to relate the probability of correctly guessing a shot's direction to its speed (fast, medium, or slow), kick technique (side-foot or instep), and occlusion time (−0.4 s, −0.3 s, −0.2 s, −0.1 s, or 0.0 s before ball contact). To estimate the most likely effect of each variable in the GLM, we used multi-model inference based on information theory (Burnham & Anderson, 2002; Hunter, Angilletta Jr, Pavlic, Lichtwark, & Wilson, 2018). Initially, we estimated parameters from the full model containing all main effects and interactions. Then, we estimated the parameters of every sub-model, including the null model, using the MuMIn library of R (Bartoń, 2013). Based on the Akaike weight of each model, which gives the likelihood that a model best describes the data (Table 3.1), we calculated a weighted average value for each parameter among all models (Table 3.2). These values were then used to calculate the expected probability under each condition of the experiment. Multi-model inference estimates the effects of variables more accurately than null hypothesis testing, as all possible models (including the null) contribute to the most likely value of each parameter.

Table 3.1. Based on Akaike information criterion (AIC), we ranked statistical models of the probability of predicting the correct direction of a kick (left vs. right). Only models with a likelihood of > .001 are listed below. For each model, we report the difference between its AIC and the AIC of the most likely model (ΔAIC) and the likelihood that the model describes the data better than other models (*w*).

Model	df	AIC	ΔAIC	*w*
1) speed + technique + occlusion + (speed · technique) + (technique · occlusion)	14	-18615.58	0	0.78
2) speed + technique + occlusion + (speed · occlusion) + (speed · technique) + (technique · occlusion)	22	-18608.88	2.62	0.21

Table 3.2. Parameters of the most likely model of the probability of predicting the correct direction of a kick (left vs. right).

Parameter	Estimate	SE	z	P
intercept (fast speed, instep kick, 0 s occlusion)	1.350	0.068	19.91	<.001
medium speed	-0.057	0.068	0.83	0.41
low speed	0.091	0.102	0.89	0.37
side kick	0.821	0.081	10.17	<.001
-0.1 s occlusion	-0.445	0.083	5.39	<.001
-0.2 s occlusion	-0.470	0.084	5.60	<.001
-0.3 s occlusion	-0.678	0.093	7.28	<.001
-0.4 s occlusion	-0.809	0.069	11.75	<.001
medium speed · side kick	-0.151	0.063	2.40	0.02
low speed · side kick	-0.297	0.067	4.45	<.001
side kick · -0.1 s occlusion	-0.252	0.093	2.69	0.01
side kick · -0.2 s occlusion	-0.870	0.090	9.62	<.001
side kick · -0.3 s occlusion	-0.816	0.089	9.17	<.001
side kick · -0.4 s occlusion	-0.919	0.088	10.41	<.001
medium speed · -0.1 s occlusion	-0.029	0.076	0.38	0.70
low speed · -0.1 s occlusion	-0.051	0.110	0.46	0.65
medium speed · -0.2 s occlusion	-0.036	0.085	0.42	0.67
low speed · -0.2 s occlusion	-0.048	0.105	0.45	0.65
medium speed · -0.3 s occlusion	-0.035	0.083	0.42	0.67
low speed · -0.3 s occlusion	-0.073	0.147	0.49	0.62
medium speed · -0.4 s occlusion	-0.003	0.049	0.05	0.96
low speed · -0.4 s occlusion	-0.040	0.091	0.44	0.66
medium speed · side kick · -0.1 s occlusion	-0.001	0.023	0.05	0.96
low speed · side kick · -0.1 s occlusion	-0.002	0.029	0.06	0.95
medium speed · side kick · -0.2 s occlusion	0.000	0.016	0.02	0.98
low speed · side kick · -0.2 s occlusion	-0.002	0.035	0.06	0.95
medium speed · side kick · -0.3 s occlusion	0.000	0.015	0.02	0.98
low speed · side kick · -0.3 s occlusion	-0.001	0.024	0.05	0.96
medium speed · side kick · -0.4 s occlusion	0.000	0.015	0.01	0.99
low speed · side kick · -0.4 s occlusion	-0.001	0.026	0.06	0.96

Results

Of the 709 participants who completed the survey, 550 were male, 155 were female, and 4 participants did not define their gender. Their ages ranged from 6 to 70 years, with 37 participants being under the age of 18. To ensure that results were relevant, we excluded participants under the age of 18 years or who had never played soccer (Figure 3.3), leaving 521 participants (male = 435, female = 82) for analysis. As the included participants did not differ in the proportion of correct responses based on soccer playing experience over the age of 18 (Figure 3.3), this variable was not included in the GLM. Seventy-seven participants reported experience as a goalkeeper after the age of 18.

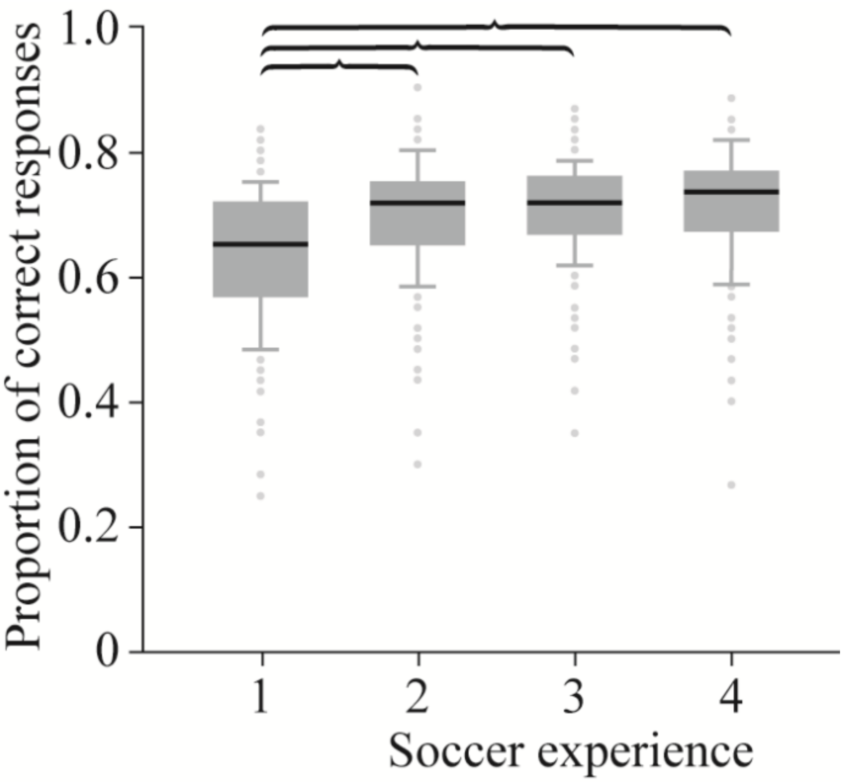

Figure 3.3. Success rates of participants grouped by over 18 soccer playing experience. 1) Never played, N=166. 2) Played socially, N=215. 3) Amateur player, N=213. 4) Semi-professional player, N=100. See Appendix A for full descriptions. Plotted are the median, 10^{th}, 25^{th}, 75^{th}, 90^{th} percentile and outliers. ANOVA revealed a significant difference among groups, $F(3,690) = 25.61$, $p < .001$. Braces show significant differences among groups identified by Tukey-HSD (95% CI). All significant differences are $p < 0.001$ (see Appendix Table A3.1 for further details).

As expected, participants were better at predicting the direction of shots at later occlusion times (Figure 3.4). At −0.4 s before ball contact, participants correctly guessed shot direction 55% to 64%

of the time, depending on the kick technique and speed of the shot (Figure 3.4). However, when shown ball contact, participants were successful ≈80% or ≈90% of the time for shots with instep or side-foot, respectively.

The effect of occlusion was greater for side-foot shots than instep shots, particularly for slow and medium-paced side-foot shots. At early occlusion times (−0.4 s, −0.3 s), participants predicted the direction of 55% to 61% of side-foot shots (slow and medium-paced), compared to 62% to 67% of instep shots (all speeds). As occlusion time approached ball contact, the predictability of side-foot shots increased at a greater rate than instep shots, with side-foot shots reaching a maximum of 90% at ball contact compared to 81% for instep shots (Figure 3.4).

Faster shots were easier to predict than medium and slow shots when shooters used a side-foot kicking technique. This effect was most pronounced at early occlusion times. For example, at −0.4 s before ball contact, participants correctly guessed 61% of fast shots compared to only 55% of slow shots and 56% of medium shots (Figure 3.4). This difference gradually reduced as occlusion time approached ball contact, at which point participants guessed 88% of slow and medium shots, compared to 90% of fast shots. We found similar patterns when only data from participants with goalkeeping experience were analysed (see Appendix Figure A3.1).

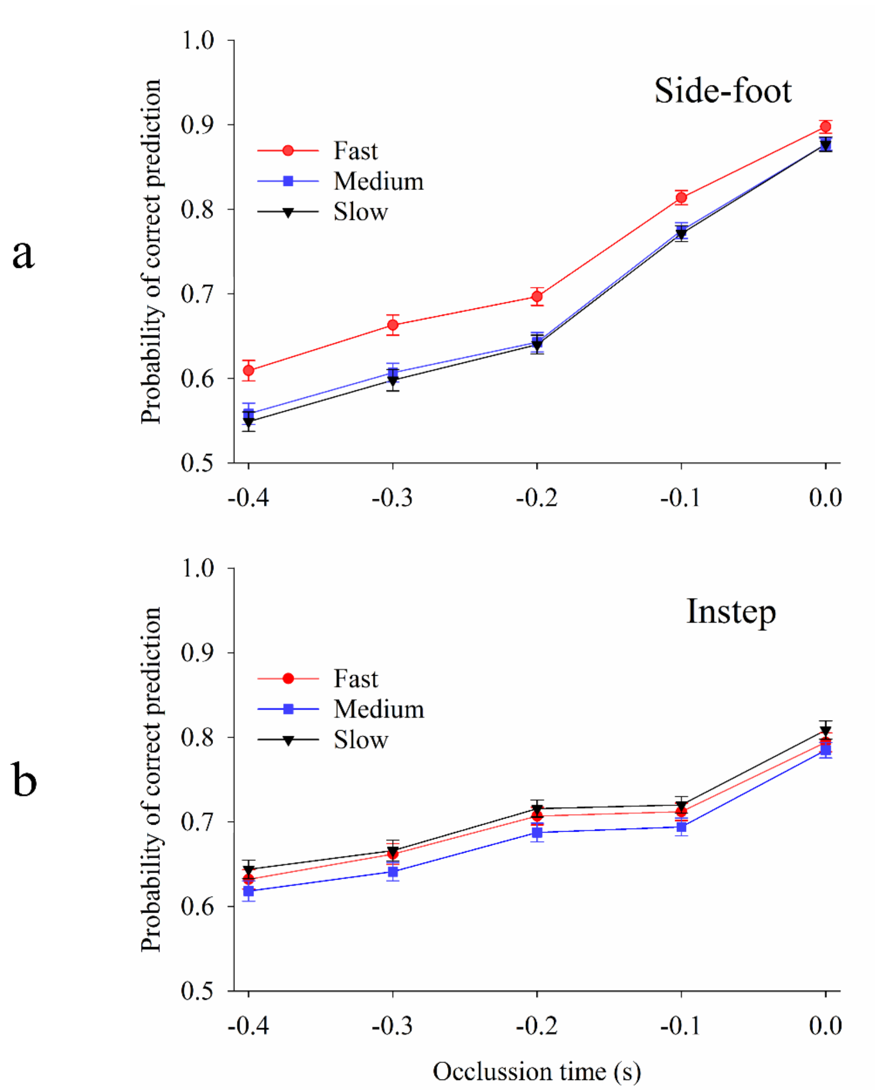

Figure 3.4: Probability of correctly guessing shot direction dependent on occlusion time and shot speed. Side-foot and instep shots are plotted separately. Probabilities and Standard Error bars calculated using averaged parameter estimates from statistical model. **a**) Side-foot shots. **b**) Instep shots.

Discussion

Goalkeepers face a clear trade-off between moving early and moving in the correct direction. To increase the chance of intercepting the ball, goalkeepers typically begin to move several hundred milliseconds before the ball moves (Dicks, Davids, et al., 2010; G. J. P. Savelsbergh et al., 2005). As with previous experiments, we confirm that earlier movements reduce the ability to predict shot direction. Under all conditions, participants in our study were better at predicting shot direction when given more video footage of the kicker's approach. The foot's final trajectory at contact is a reliable indicator of the ball's trajectory (Diaz, Fajen, & Phillips, 2012; A. M. Williams & Burwitz, 1993). Not surprisingly, participants who viewed a shot to the point of ball contact were likely to guess its direction correctly, regardless of kicking speed. In a match, keepers who delay their movement will receive more accurate information about shot direction, improving anticipation.

We show that the likelihood of goalkeepers moving in the correct direction depends on an interaction between the keeper's strategy (leave-time) and the shooter's strategy (technique, speed). If goalkeepers move late, instep shots of any speed are the least predictable. If goalkeepers move early, slow/medium side-foot shots reveal less about shot direction than all other shots. Considering the average leave-time for professional goalkeepers we identified (−0.22 s), slow/medium side-foot shots are the least predictable at this time (Figure 3.4). Previous studies show that kicking with the side of the foot (Hunter, Angilletta Jr, et al., 2018; Sterzing et al., 2009) and more slowly (Andersen & Dorge, 2011; Hunter, Angilletta Jr, et al., 2018), yields greater accuracy. Taken together, we show that kickers may use a slower shot with the side of the foot to improve accuracy as well as increase the chance that the keeper dives in the wrong direction.

Why is the direction of slower side-foot shots harder for goalkeepers to anticipate? From a goalkeeper's perspective, movements of the torso, hip, kicking and non-kicking legs, and angle of approach to the ball can all be used to indicate shot direction (Dicks, Button, et al., 2010a). Thus, comparing these cues between different types of shots should help us elucidate our results. In Figures 3.5 and 3.6, we present time-lapse images of shots with the side of the foot and the instep, respectively. For fast side-foot shots (Figure 3.5), the kicker orients the left arm, hips, and torso in the direction of the shot early in the kicking action. Differences in the shooter's posture are obvious −0.3 s before ball contact (compare panels C2 and D2 of Figure 3.5). Similar cues occur during early stages of shots with the instep, across all speeds (Figure 3.6). For slower side-foot shots, however, the kicker reveals much less information about the direction of the shot in the earlier stages of kicking (compare panels A2 and B2 of Figure 3.5). This absence of cues might explain why goalkeepers have more difficulty inferring the direction of slower side-foot shots.

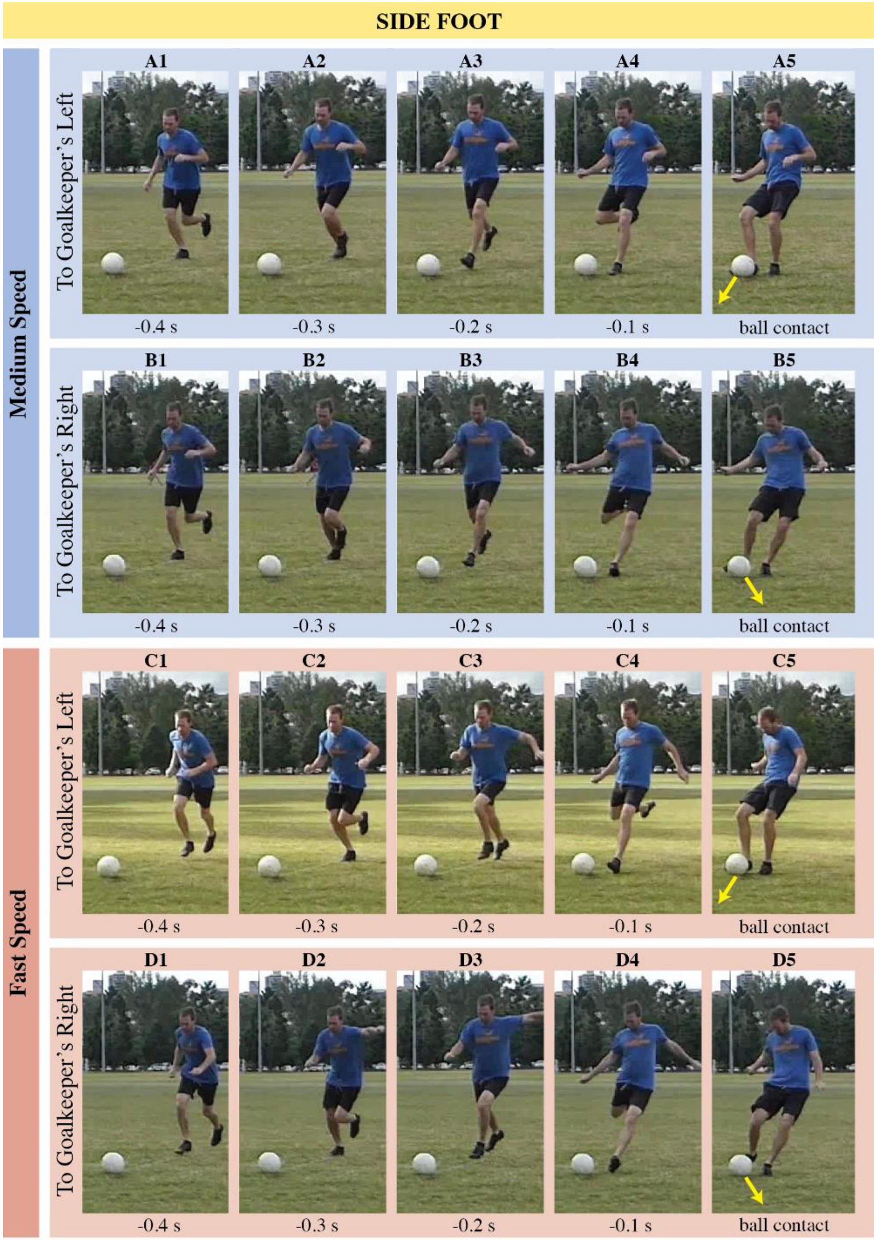

Figure 3.5: Images of four different shots taken with the side of the foot: medium speed aimed to the reader's left (panels A1 to A5); medium speed aimed right (panels B1 to B5); fast speed aimed left (panels C1 to C5); and fast speed aimed right (panels D1 to D5). Within each shot, five panels present the final frame of the video participants saw from each of the five occlusion time conditions (-0.4 s, -0.3 s, -0.2 s, -0.1 s, ball contact).

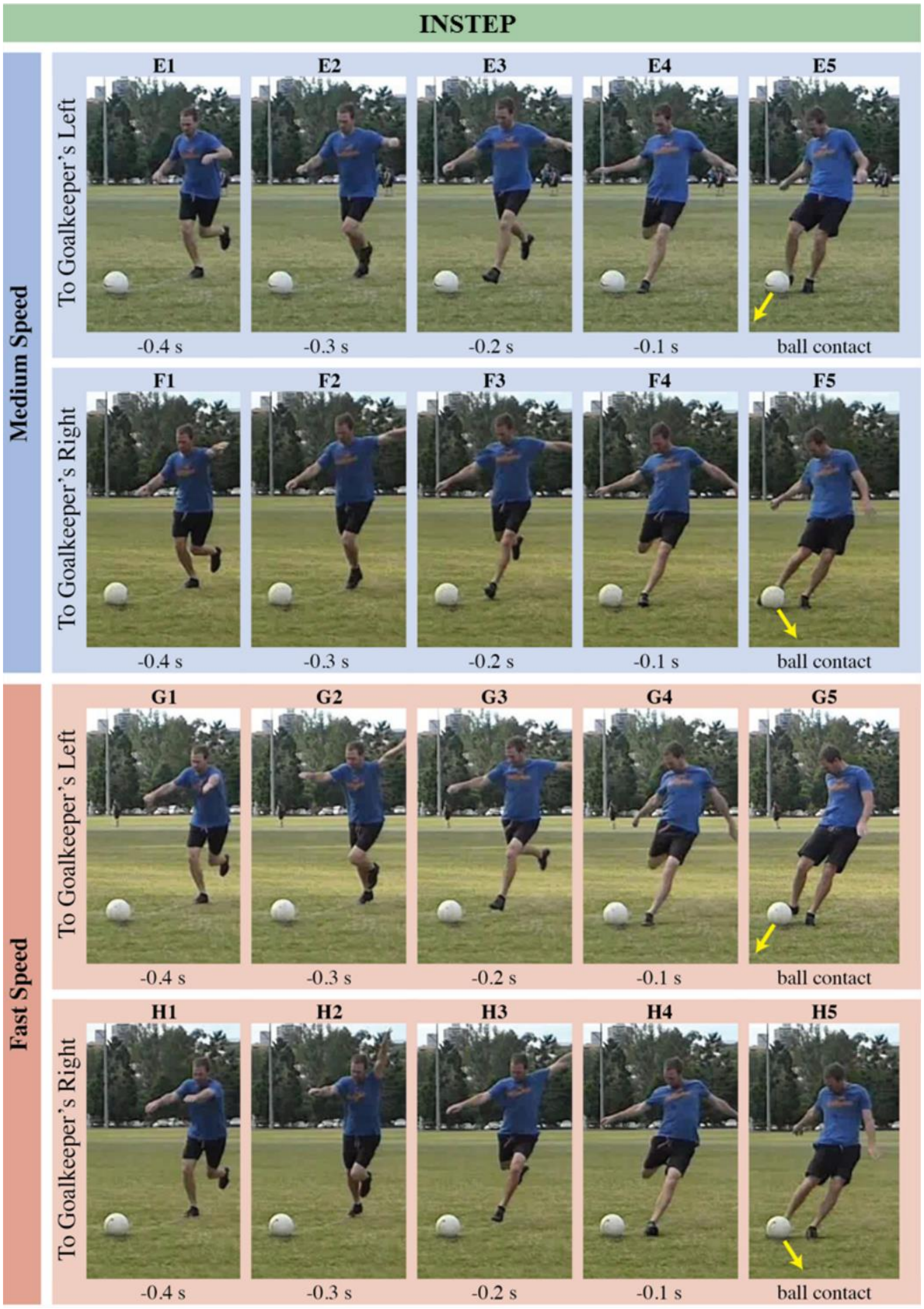

Figure 3.6: Images of four different shots taken with the instep: medium speed aimed to the reader's left (panels E1 to E5); medium speed aimed right (panels F1 to F5); fast speed aimed left (panels G1 to G5); and fast speed aimed right (panels H1 to H5). Within each shot, five panels present the final frame of the video participants saw from each of the five occlusion time conditions (-0.4 s, -0.3 s, -0.2 s, -0.1 s, ball contact).

Across all shot speeds, the direction of instep shots was less predictable than side-foot shots when participants were able to view most of the kicking action up until ball contact. Again, this difference likely relates to the orientation of the body. In Figure 3.7, we provide images from eight shots of the moment the shooter plants the non-kicking foot (≈−0.1 s before ball contact). At this point, the orientation of the kicker's hips and torso differ between shots to the left or right, and this difference is exaggerated for fast or side-foot kicks. At any speed, visual cues indicate shot direction more obviously for side-foot shots than instep shots. Furthermore, side-foot shots to the left require greater hip abduction, pointing the knee of the kicking leg toward the direction of the shot. This cue remains absent for instep shots. A goalkeeper could use this cue to predict the direction of a side-foot shot more accurately than the direction of an instep shot. Although our images show only one shooter, the qualitative patterns extend to other shooters in our experiment. A kinematic analysis of multiple shooters would confirm the cues that enable goalkeepers to predict the direction of a shot, and how these are affected by shot speed. The absence of kinematic analysis was a limitation of this study. Regardless, now that we have presented evidence for a trade-off between shot speed and unpredictability, examining the mechanism underlying this relationship should be the focus of future research.

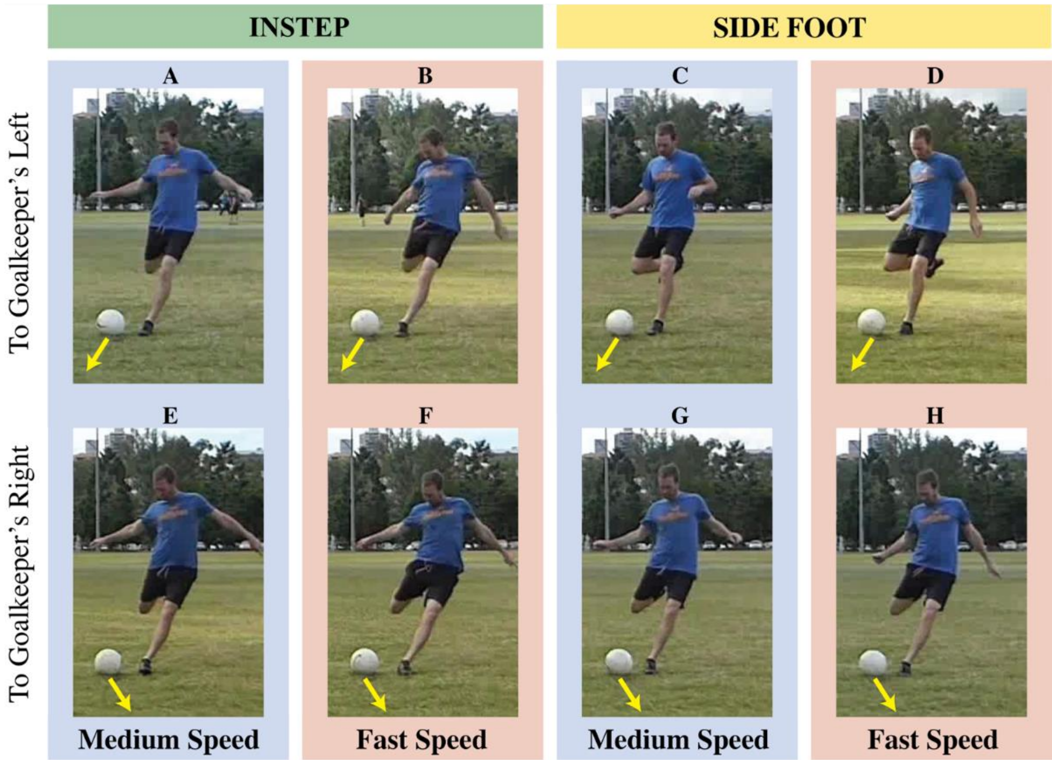

Figure 3.7 Images of eight shots, one for each combination of kick technique (side-foot {panels C,D,G,H} vs. instep {panels A,B,E,F}), shot speed (medium {panels A,C,E,G} vs. fast {B,D,F,H}), and kick direction (left {panels A,B,C,D} vs. right {E,F,G,H}). All images represent the same point in the shooter's kicking action, when the non-kicking foot is first planted on the ground.

The outcome of a penalty is determined by an interaction between the shooter's strategy and the goalkeeper's strategy. For example, shooters can use a "keeper-dependant" strategy, waiting for the goalkeeper to move to a side of the goal before kicking toward the opposite side (Kuhn, 1988).

Goalkeepers can choose when to dive (or not at all), which is affected by how quickly they can move (Dicks, Davids, et al., 2010). In this study, we investigated one aspect of the interaction between shooter and goalkeeper—the relationship between shot speed and unpredictability. While our findings progress the understanding of goalkeeper anticipation in soccer penalties, one must also consider factors such as goalkeeper movement (Weigelt, Memmert, & Schack, 2012), shooting accuracy (Hunter, Angilletta Jr, et al., 2018), and shooter deception (Dicks, Button, et al., 2010a; Smeeton & Williams, 2012) to determine the outcome of a penalty shot.

Our findings have implications across a variety of sports. A similar phenomenon as found here may occur in tennis with the direction of faster shots being easier to predict. While evidence exists that movement amplitude has no influence on predicting shot direction in tennis (Smeeton & Huys, 2011), experiments with human actors (rather than stick figures) are needed to further our understanding of anticipation in tennis. Overarm throwing sports such as baseball or handball could also benefit from replicating our research. Any changes in throwing action between different baseball pitches or intended targets in handball may become more pronounced as throwing speed increases, making their intent easier to read. Athletes in these sports may be less predictable when throwing at sub-maximal speeds. Sports involving evasive manoeuvres such as Rugby League, Rugby Union, Australian Rules Football, and American Football may also be interested in our findings. "Cutting", where attacking players sharply change running direction, can be a very effective manoeuvre across all football codes, but involves preparatory movements and changes of gait patterns (Besier, Lloyd, Ackland, & Cochrane, 2001; Jindrich et al., 2006; Wheeler & Sayers, 2010). There is evidence to suggest that the degree of postural and gait changes required to alter direction is dependent on movement speed (Hamill, Murphy, & Sussman, 1987; Jindrich et al., 2006). When defenders in football games are able to perceive and interpret gait changes in attackers and predict changes in direction (Sébastien Brault, Bideau, Kulpa, & Craig, 2009), they may better anticipate cutting manoeuvres as running speed increases and gait changes become more exaggerated. While the advantage of speed or a deceptive strategy (S. Brault, Bideau, Craig, & Kulpa, 2010) is not to be disregarded across the football codes, there may be situations where attackers benefit from running at sub-maximal speeds to increase both their agility and unpredictability.

Our study is the first to identify a trade-off between the speed of a kick and the predictability of its outcome. In the context of a soccer penalty, we have shown that both the kicker and keeper affect the predictability of a shot. If a keeper is known to dive early, a kicker can maximize unpredictability with a slow side-foot shot. However, if a keeper tends to dive late, a kicker must use the instep to maximize unpredictability, which necessarily reduces accuracy. Thus, the optimal strategy depends on the keeper's behaviour and the relative benefits of speed, accuracy, and unpredictability within each situation. A game theoretical perspective is needed to understand how these trade-offs determine the best strategies of each player.

CHAPTER 4

BEHAVIOURS OF SHOOTER AND GOALKEEPER INTERACT TO DETERMINE THE OUTCOME OF SOCCER PENALTIES

Abstract

During a soccer penalty, the shooter's strategy and the goalkeeper's strategy interact to determine the outcome. However, most models of penalty success overlook its interactive nature. Here, we quantified aspects of shooter and goalkeeper strategies that interact to influence the outcome of soccer penalties – namely, how the speed of the shot affects the goalkeeper's leave-time or shot-blocking success, and the effectiveness of deceptive strategies. We competed 7 goalkeepers and 17 shooters in a series of penalty shootout competitions with a total of 1278 shot taken. Each player was free to use any strategy within the rules of a penalty shot and game-like pressure was created via monetary incentive for goal-scoring (or blocking). We found that faster shots lead to earlier leave-times and were less likely blocked by goalkeepers, and—unlike most previous studies—that deceptive shooting strategies did not decrease the likelihood goalkeepers moved in the correct direction. To help identify optimal strategies for shooters and goalkeepers, we generated distributions and mathematical functions sport scientists can use to develop more comprehensive models of penalty success.

Introduction

A soccer penalty is a complex, interactive contest between a shooter and a goalkeeper. The shooter can direct the ball anywhere in the goal, kick at various speeds, and feign movement in the wrong direction to deceive the goalkeeper. In response, a goalkeeper can use these cues to predict the direction of the ball and to select the timing and movement most likely to block it. Understanding how goalkeepers perceive and respond to shooters' body angles, approaches, and shots is fundamental to optimising penalty success or prevention. However, most models of penalty success overlook the interactive nature of penalties and focus on a single, simplified strategy at a time(Azar & Bar-Eli, 2011; Bar-Eli et al., 2007; Botwell et al., 2009; Chiappori et al., 2002; Leela & Comissiong, 2009; Morya et al., 2003). This has limited the ability of sports scientists to predict (and train players for) the various interactions that may occur during soccer penalties.

For a goalkeeper, predicting the trajectory of the ball involves a trade-off between early prediction, which affords more time to move, and later prediction, which is more accurate(Botwell et al., 2009; Dicks, Button, et al., 2010a; G. J. P. Savelsbergh et al., 2005; Smeeton & Williams, 2012). Before the ball is even kicked a goalkeeper can use the shooter's angle of approach to predict where the shot will go (Terry McMorris & Colenso, 1996; M. Williams & Griffiths, 2002), but waiting to see the orientation of the non-kicking foot as it plants beside the ball is a far more reliable indicator of shot direction(Diaz et al., 2012; Franks & Hanvey, 1997). A major cost of waiting is that the goalkeeper may not have time to reach and block faster shots or shots toward distant parts of the goal. As they form judgements on shot direction before the ball is kicked, goalkeepers likely form predictions of shot speed as well based on the shooter's approach (Lees & Nolan, 2002). This may influence when a goalkeeper decides to move. To block a fast shot, they may initiate movement (i.e. leave-time) early to ensure they get to the ball in time to stop it; for a slower shot with longer flight time, they may choose to wait and prioritise accuracy. Furthermore, biomechanical trade-offs between speed and accuracy(Fitts, 1954) mean that faster shots, which give goalkeepers less time to respond, are likely to be defended less accurately—missed entirely, or deflecting off the goalkeeper into the goal. Yet the relationship between shot speed, leave-time, and blocking success is absent from existing penalty models.

Because penalty shots are interactive, a shooter can use deception to entice the goalkeeper to move in the wrong direction, improving the chances of scoring. Deception is a common strategy in soccer, and relies on placement of the body in a way that implies a particular action has occurred or will occur. For example, a penalty shooter may give the impression of shooting to one side of the goal, then kick toward the other. Evidence suggests that deception often succeeds in tricking goalkeepers, reducing the likelihood they move in the correct direction (Dicks, Button, et al., 2010a;

Dicks, Davids, et al., 2010; Smeeton & Williams, 2012), but these earlier studies were limited by using only one or two shooters, or were conducted in artificial experimental situations. Goalkeepers can also be deceptive, positioning themselves toward one side of the goal, or making movements or gestures before or during the shooter's run-up indicating the direction they will dive. The aim of these strategies is to influence where the shooter kicks the ball in a predictable way, increasing the likelihood the goalkeeper dives in the correct direction toward the ball. These strategies have been found effective under experimental conditions (Weigelt et al., 2012; Wood & Wilson, 2010a). Whether deception is prevalent or effective for either shooters or goalkeepers during penalty kicks is unclear for real game situations.

In this study, we investigated how the strategies of shooters and goalkeepers interact to influence the outcome of soccer penalties. Specifically, we quantified: 1) variation in goalkeeper leave-time, 2) the effect of shot speed on leave-time, 3) the prevalence and effectiveness of deceptive strategies, and 4) the effect of shot speed on the likelihood that goalkeepers block shots within reach. We conducted our study using game-realistic penalty shootouts between experienced outfield soccer players and goalkeepers, allowing both shooter and goalkeeper to use any strategy within the rules of a penalty shot. To simulate the pressure of a real game, we incentivised the contest, giving players more money the better they performed.

The simple mathematical functions we report here will allow sport scientists to predict, for a given shot speed and target location in the goal, the likelihood a goalkeeper will reach the ball before it crosses the goal-line and the likelihood they will effectively block the shot. This will enable sport scientists to develop more comprehensive models of optimal behaviour in soccer penalties, for both shooters and goalkeepers.

Methods

Participants

Seven goalkeepers and 17 shooters (age 18 – 42) were recruited from the University of Queensland Football Club, from competitive playing levels that included the Brisbane Premier League, Brisbane City League 1, Brisbane City League 3 and Brisbane Premier Under 20's. These subjects can be considered amateur/semi-professional players. Five of the shooters were left-footed. Informed consent was obtained and the methods and protocols for this experiment were approved by the Behavioural and Social Sciences Ethical Review Committee, University of Queensland.

Testing Sessions

In each session 1 or 2 shooters each took, on average, 39 (SD ± 13.6) penalty shots against 1 or 2 goalkeepers who each faced, on average, 47 (SD ± 10.4) shots. When multiple shooters and goalkeepers were available in a session, each goalkeeper faced an equal number of shots from all shooters, alternating between them. To ensure consistent performance across each session breaks were taken as needed to avoid fatigue (≈ every 10 penalties). Testing sessions were conducted over a 1 year period and, where possible, we paired goalkeepers with different shooters across sessions.

Task

A full-sized soccer goal was set up on a grassed oval with a soccer ball (size 5 inflated to 9 psi) placed on a designated penalty spot 11m from the centre of the goal-line (Figure 4.1). Shooters and goalkeepers were reminded of the IFAB rules for a penalty shootout("Laws of the Game," 2017). The shooter's aim was to score a goal, and the goalkeeper's aim was to prevent the ball from crossing the goal-line. To ensure that players were motivated and their scoring/saving strategies realistic, we offered a monetary incentive based on performance that was re-calculated for every 20 penalties an individual took part in. If the rate of goal-scoring was greater than 85%, the shooter received $20 and the goalkeeper received $5; if the rate of goal-scoring was between 70%-85%, the shooter and goalkeeper each received $10; and if the rate of goal-scoring was below 70%, the shooter received $5 and the goalkeeper received $20. The structure of the incentive was based on the success rate of penalty shootouts in major competitions, which range from ≈ 70%-85%(Jordet, Hartman, Visscher, & Lemmink, 2007).

Goalkeeper Leave-Time and Deception

To determine when the goalkeeper began to move relative to the ball being kicked (i.e. leave-time), a camera (Panasonic Lumix DMC-TZ40 filming at 50fps) on a 1m tripod was placed 4m behind the ball and slightly to one side to not impede the shooter (Figure 4.1). The leave-time camera was oriented to capture both the penalty spot and goalkeeper in its field of view. Using the software program Kinovea (*Kinovea*, 2011), two times were extracted from each penalty: 1) the moment the shooter's foot connected with the ball and 2) the moment the goalkeeper initiated movement to a particular side. Some goalkeepers move side-to-side or bob up and down as the shooter approaches the ball, but these actions were ignored until the goalkeeper initiated their movement to a side of the goal (Appendix A4.1 for further details). With these measurements, the time goalkeepers moved relative to ball contact was calculated. For example, if ball contact occurred at 0:00:06:24 and the goalkeeper initiated movement at 0:00:06:00, leave-time was -0.24 s. We also rated if a goalkeeper's movement during the shooter's run-up was deceptive, which was defined as making movements or gestures intended to influence where the shooter kicked the ball (Appendix A4.1 for further details).

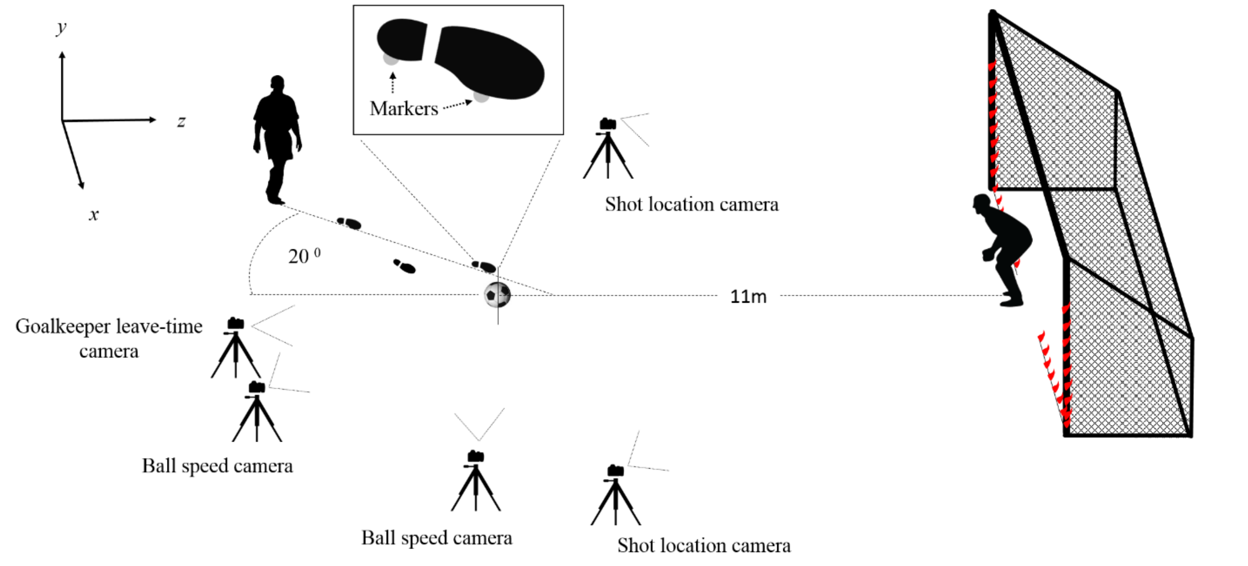

Figure 4.1: Graphical representation of experimental setup. Camera placement was mirrored for left-footed shooters.

Target

Before each penalty, shooters were asked to designate (in private) if their intended target was to their left, right, or to the centre of the goal and which kicking technique they would use, side-foot or instep (laces of the shoe). To correct for shooter footedness, we termed shooting "across the body" when a right-footed player shot to their left and vice versa for a left-footed player. Shots to the same side as footedness were termed shooting to the "open side". Shooters also indicated where they were aiming. To assist this, four wooden poles each 2.2 metres in length were fitted with bright markers at 0.20 m intervals. On each side of the goal, one pole was placed on the ground, in the goal, parallel to the goal-line. One end was level with the inside of the goal-post and the other end toward the centre of the goal (Figure 4.1). Another pole was attached to the inside of the goal-post with one end on the ground and the other approximately 0.2 m below the crossbar (Figure 4.1). Using these visual aids, shooters could estimate their intended target location defined as (x,y) coordinates. For example, before taking a penalty kick a shooter might say "I'll be kicking to the left with a side-foot shot, and I'll be aiming 60 cm inside the goal-post and 1 m off the ground." Shooters sometimes wait until the goalkeeper initiates a dive to a side of the goal, then kick toward the opposite side. This has been termed a "keeper-dependent" strategy (Kuhn, 1988; Van der Kamp, 2006). We advised shooters they were free to use this strategy or change target location during their shot in response to goalkeeper movement, but had to explain any change after they completed the shot. This allowed us to quantify when shooters used a keeper-dependent strategy.

Ball Speed

To measure ball-speed, we used the EasyWand5 and DLTdv5 packages of MATLAB(Hedrick, 2008; Lourakis & Argyros, 2009; Theriault et al., 2014). First, two high speed cameras (Panasonic Lumix DMC-TZ40 filming at 100fps), each on a 1m tripod, were calibrated to the three-dimensional space around the penalty spot. Then, coordinates (x,y,z) were extracted from subsequent footage taken with the calibrated cameras. One camera was placed 3m away from the penalty spot, perpendicular to the trajectory of the ball (Figure 4.1). The second camera was placed beside the leave-time camera (Figure 4.1). Both cameras were oriented with the penalty spot in the middle of their field of view. To calibrate, a 1m "wand" was systematically waved throughout the space around the penalty spot while filming with both cameras. The dimensions of the three-dimensional calibrated space were from the ground to 1m high in the *y*-axis, 2m either side of the ball in the *x*-axis, and 3m either side of the ball in the *z*-axis (the space before the ball was calibrated to measure the shooter's run-up angle described below). In MATLAB, the position of the centre of the ball was extracted from six frames that spanned the first 0.05s after the foot struck the ball. With these positional data the distance the ball travelled between each frame was first calculated. Then, knowing frame rate, we could calculate the speed of the ball between each frame. The average of these six velocities gave our measure of ball speed.

The EasyWand5 Matlab package provides a "wand score" which is a metric of the quality of calibration. A score of 1 indicates the standard deviation of the computed wand lengths is 1% of the total wand length. Generally, scores of 1 or less are considered good calibrations. Across 26 calibrations the average wand score was 1.24 (SD ± 0.58).

Penalty Outcome

Each penalty was recorded as a goal, save, or miss if the shot missed the goal completely. For goals, we also recorded if the ball touched the goalkeeper, did not touch them, or was not touched but within their reach. Shots were classed as not touched but within reach if the ball passed by the goal-keeper in a position they could reach with some part of their body but failed to move a body part to intercept the ball (see Appendix A4.1 for further details).

Shot Location

The location of each shot as it entered the goal was measured using the EasyWand5 and DLTdv5 packages of MATLAB, similar to the measure of ball speed (Hedrick, 2008; Lourakis & Argyros, 2009; Theriault et al., 2014). Two high speed cameras (Panasonic Lumix DMC-TZ40 filming at 100fps) were placed 2 m either side of the penalty spot, facing the goal (Figure 4.1). The dimensions of the space calibrated was from the ground to maximal reach of the researcher in the y-axis, 2 metres outside one goal-post to 2 metres outside the other goal-post in the x-axis, and 1 metre in front of the goal-line to 2 metre behind the goal-line in the z-axis. Each penalty shot was then recorded on both cameras. In MATLAB the x-axis was set as the goal-line (Figure 4.1). Then, the position of the centre of the ball (x,y,z) was extracted from 3 frames immediately before the ball crossed the goal-line and 3 frames immediately after. Using these data points, the ball's position as it entered the goal (x = 0) could be interpolated. For shots that were saved or hit the goalkeeper, coordinates of the centre of the ball were extracted from 6 frames immediately prior to the ball contacting the goalkeeper. Using these data points the position the ball would have entered the goal if not touched was extrapolated.

Deception

Before each shot, shooters (privately) reported if the run-up angle they intended to use was True, Neutral, or Deceptive relative to their desired target location. For example, if they planned to kick to their right-hand side of the goal, a True run-up angle for a right-footed player was likely to be greater than ~20 degrees (Figure 4.1), aligned to kick accurately to this side of the goal. A Neutral run-up angle would be slightly smaller, aligned to kick down the centre of the goal, and a Deceptive angle smaller again (eg. less than ~10 degrees) giving the impression of kicking to their left side of the goal. The opposite would be true for shots kicked to their left, with run-up angles greater than ~20 degrees likely being Deceptive, and angles less than ~10 degrees likely to be True. As shooters likely differ in what run-up angles they deem to be True, Neutral, or Deceptive, this self-report gave us the intent of individual shooters for each kick. We also measured the actual run-up angle of each shot, and the angle of the non-kicking foot at ball contact to confirm shooters were being Deceptive (or not) when intended, and determine the effectiveness of this strategy. Two markers were placed on the medial side of the shooter's non-kicking boot to help measure the angles of the shooter's run-up and non-kicking foot. On the outside of the boot, one marker was placed on the Sesamoid bone and the other on the middle of the Calcaneus bone. The two cameras measuring shot speed also captured the position of the non-kicking foot throughout the shooter's run-up and kicking action. Using Matlab, two coordinates were extracted from the film to measure the shooter's run-up angle: the position of the Calcaneus marker at ball contact, and the position of the Calcaneus marker when the foot was planted on the ground in the preceding stride (Figure 4.1). The angle of the non-kicking foot was calculated using the position of the Calcaneus and Sesamoid markers at ball contact. The run-up angle and non-kicking foot angle were separate measures used to quantify the amount of deception used by shooters, after considering which side of the goal the ball was kicked toward. For example, increasing run-up angle (Figure 4.1) for a right-footed player increases deception for shots aimed to their left, but decreases deception for shots aimed to their right. If manipulating run-up angle and/or non-kicking foot angle was effective at deceiving goalkeepers, one would expect goalkeepers less likely to move to the correct side of the goal when right-footed shooters use large angles shooting left, and small angles when shooting right.

Inter-Rater, Intra-Rater Reliability

All measures were extracted by a single researcher with over 30 years of experience as a soccer player and coach. To test the reliability of each measure, a subset of 100 penalties was re-extracted by the original rater and another rater (see Appendix A4.1).

Statistical Modelling

The statistical program R(R Core Team, 2016) was used for all analyses. To determine intra-rater and inter-rater reliability for our measures of ball speed, non-kicking foot angle, run-up angle, and goalkeeper leave time, intraclass correlation coefficient (ICC) estimates and 95% CI were calculated using the irr v0.84 package. Each analysis was based on single rating, agreement, two-way models (Koo & Li, 2016). To determine intra-rater and inter reliability for rating goalkeeper deception (yes, no) and penalty outcome (touched, not touched, within reach), Cohen's Kappa and 95% CI were calculated with the fmsb v0.6.3 package.

To determine the effect of shot speed on leave-time, a Linear Mixed Model from the lmerTest v2.0.33 package(Kuznetsova, Brockhoff, & Christensen, 2015) was used, with shot speed and kicking technique as fixed factors and the identities of each goalkeeper and shooter as random factors. Only the F-tests from the LMER results are presented (type III test with Satterthwaite approximation for degrees of freedom).

To estimate the effect of shot speed on the likelihood that goalkeepers blocked shots within their reach, shot speed was rounded to the nearest 1 ms^{-1} for all shots the goalkeepers saved, touched, or were within reach. Then, for shots of the same speed, the percentage of shots saved was calculated. A Linear Model estimated the relationship between shot speed and the percentage of shots saved.

Linear Mixed Models were used to confirm that shooters were being deceptive (or not) when intended. Including shooter ID as a random factor, separate models determined the effect of self-reported run-up angle (True, Neutral, or Deceptive) on actual run-up angle; and the angle of the non-kicking foot. Only side-foot kicks were included in the analysis as this was the preferred kicking technique, and shots to either side of the goal were modelled separately. Prior to analysis, actual run-up angle and foot angle were corrected for footedness.

A Generalised Linear Mixed Model with a binomial distribution in the lme4 v1.1.13 package of R(Bates, Mächler, Bolker, & Walker, 2015) was used to show whether the shooter's run-up angle and/or non-kicking foot angle were associated with the movement of the goalkeeper to the correct side of the goal. Goalkeeper leave-time was included as a fixed factor as it affects the likelihood of correct movement. Shot speed was also included as a fixed factor as it affects goalkeeper leave-time (see Results). Shots across the body and to the open side of the goal were modelled separately, only side-foot kicks were included, and data were corrected for shooter footedness before analyses. The fixed factors: shot speed (speed); goalkeeper leave-time (time); foot angle (foot) and; run-up angle (run-up) were each rescaled to a Mean of 0 and SD of 1 to better compare their relative effect on the dependent variable. Goalkeeper identity was included as a random factor to account for variation in ability to perceive and interpret visual cues presented by shooters. Shooter identity was also included as a random factor to account for variation in the visual cues presented by our shooters, beyond those measured. Initially, all main effects and interactions of interest were modelled (Table 4.1). Then, terms were removed from the model, starting with the highest order term, until the model with the lowest value of AIC was identified(Burnham & Anderson, 2002) (Table 4.1). The Akaike Information Criterion (AIC) estimates the quality of each model relative to each of the other models. It also provides an Akaike weight, which is the likelihood that model describes the data better than other models do. For each term in the full model, a weighted average of the parameter value for all models was calculated with the Akaike weights (Table 4.2 and Table 4.3)(Burnham & Anderson, 2002).

Table 4.1: Models of goal-keeper diving to correct side of the goal for shots across the body, and to the open side of the goal. Models were ranked according to their values of the Akaike information criterion (AIC) and the 10 most likely models are presented. For each model, the difference between its AIC and the AIC of the most likely model (ΔAIC) is reported. The Akaike weight (*w*) is the likelihood that a model describes the data better than other models. The terms included in each model are presented, referring to the following list which comprised the full model: *1*- foot, *2*- time, *3*- run-up, *4*- speed, *5*- foot:time, *6*- foot:speed, *7*- run-up:time *8*- speed:time, *9*- run-up:speed, *10*-foot:time:speed, *11*- run-up:time:speed.

	Across					Open				
Model	Terms	df	AIC	Δ*AIC*	*w*	Terms	df	AIC	Δ*AIC*	*w*
1	*2,3*	5	739.11	0.00	0.19	*2,3*	5	768.63	0.00	0.10
2	*1,2,3*	6	740.90	1.79	0.08	*2*	4	768.74	0.11	0.09
3	*2*	4	740.94	1.82	0.08	*1,2,3*	6	769.86	1.23	0.05
4	*2,3,7*	6	741.15	2.03	0.07	*2,3,4*	6	770.06	1.43	0.05
5	*2,3,4*	6	741.15	2.03	0.07	*2,3,4,9*	7	770.18	1.55	0.04
6	*1,2,3,5*	7	742.39	3.28	0.04	*1,2,3,4*	7	770.30	1.67	0.04
7	*2,3,4,8*	5	742.62	3.50	0.03	*2,3,7*	6	770.46	1.83	0.04
8	*1,2*	7	742.79	3.67	0.03	*2,4*	5	770.56	1.93	0.04
9	*1,2,3,4*	7	742.87	3.76	0.03	*1,2*	5	770.58	1.95	0.04
10	*2,3,4,9*	5	742.92	3.81	0.03	*1,2,3,4,9*	8	771.02	2.39	0.03

Table 4.2: Parameter estimates for model of goal-keeper diving to correct side of goal for shots aimed across the body. For each term, a weighted average of the parameter value for all models was calculated using Akaike weights.

Parameter	Estimate	SE	*z*	*P*	*Importance*
Intercept	0.569	0.305	1.860	0.062	
time	0.538	0.126	4.245	<.0001	1
run-up	0.214	0.162	1.324	0.1856	0.8
foot	-0.026	0.111	0.237	0.812	0.43
run-up:time	0.0001	0.052	0.003	0.998	0.22
speed	-0.004	0.081	0.048	0.962	0.47
foot:time	0.015	0.065	0.227	0.820	0.14
speed:time	-0.016	0.062	0.258	0.796	0.16
run-up:speed	-0.012	0.058	0.212	0.832	0.13
foot:speed	0.009	0.045	0.201	0.841	0.08
run-up:speed:time	-0.0002	0.009	0.026	0.979	< .01
foot:speed:time	0.0002	0.008	0.024	0.981	< .01

Table 4.3: Parameter estimates for model of goal-keeper diving to correct side of goal for shots aimed to the open side of the goal. For each term, a weighted average of the parameter value for all models was calculated using Akaike weights.

Parameter	Estimate	SE	*z*	*P*	*Importance*
Intercept	0.198	0.156	1.268	0.204	
time	0.326	0.109	2.997	0.003	0.99
run-up	-0.138	0.127	1.090	0.276	0.75
foot	0.059	0.103	0.571	0.568	0.5
speed	0.062	0.099	0.621	0.535	0.62
run-up:speed	0.035	0.082	0.421	0.674	0.26
run-up:time	0.0007	0.054	0.014	0.989	0.25
speed:time	-0.021	0.068	0.297	0.767	0.23
run-up:speed:time	0.018	0.078	0.234	0.815	0.06
foot:time	-0.003	0.043	0.079	0.937	0.14
foot:speed	0.003	0.027	0.099	0.921	0.1
foot:speed:time	< -.0001	0.007	0.014	0.989	<.01

Results

Intraclass correlation coefficient (ICC) and Cohen's Kappa estimates ranged from 0.77 to 1 indicating intra-rater and inter-rater reliability for all measures were good to excellent (Appendix Table A4.1) and Appendix Table A4.2). Of the 1278 penalty shots recorded, 72% resulted in a goal, 15% were saved by the goalkeeper, and 13% missed the goal. Of the goals, 90 (7%) were touched and 9 (<1%) were not touched but within the goalkeeper's reach. Shooters predominantly used a side-foot technique (83%), and the success rate of each kicking technique is presented in Appendix Table A4.3. The speed of side-foot shots and instep shots ranged from 16 ms-1 to 30 ms-1 (mean ± S.D, 23.5 ms-1 ± 1.9 ms-1), and 14 ms-1 to 32 ms-1 (26.5 ms-1 ± 2.6 ms-1), respectively (Appendix Table A4.4). Shooters kicked across the body on 50% of shots, to the open side on 46%, and down the centre of the goal on 4% of shots. Shooters used a keeper-dependent strategy on only 22 (2%) penalty shots in our study. While shooters predominantly chose a target near the ground, between 0.2 m and 1m inside either goal-post, the dispersion of shots due to shooting error was large (Figure 4.2).

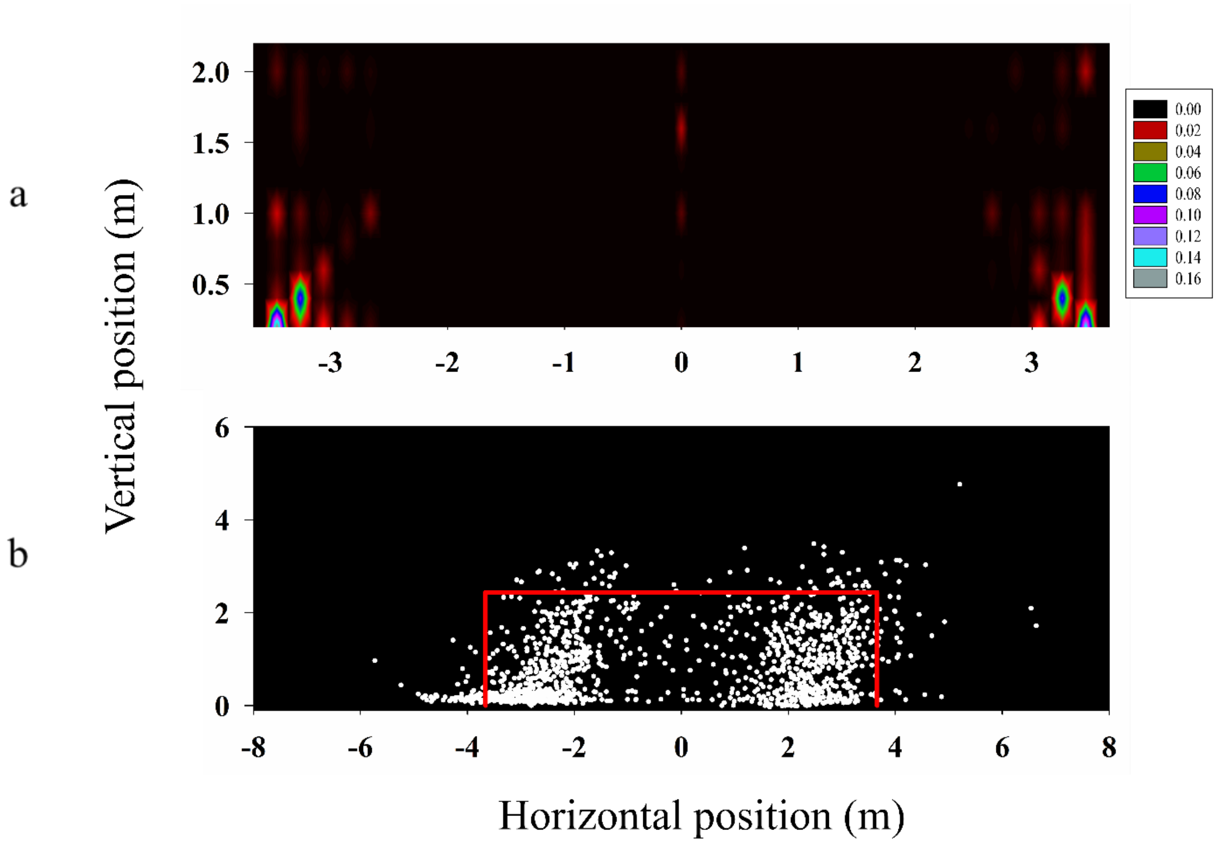

Figure 4.2: Comparison of shooter's targets and the position each shot crossed the goal-line. **a)** Heat map of the targets chosen by shooters. Contours represent the proportion of total shots (N = 1278). Black area represents the dimensions of a soccer goal (7.32 m x 2.44 m) **b)** Raw data of where each

shots crossed the goal-line (or where they would have crossed the goal-line if not deflected by the goalkeeper). Solid red lines represent the dimensions of a soccer goal. Both plots have been corrected for shooter footedness, with positive values on the x-axis being shots to the open side of the goal.

Goalkeeper Leave-Time and Deception

Goalkeeper leave-time ranged from -0.76 s (before ball contact) to 0.30 s (mean ± S.D, -0.19 s ± 0.145 s) (Appendix Figure A4.1). The average leave-time for individual goalkeepers ranged from -0.27 s to 0.04 s, and the standard deviation for individual goalkeepers ranged from 0.10 s to 0.15 s (Figure 4.3). Some goalkeepers tended to move consistently later (Goalkeepers 2 & 4) or earlier (Goalkeeper 3) than the average (Figure 4.3). On only 16 occasions (1%) did our goalkeepers use a deceptive strategy.

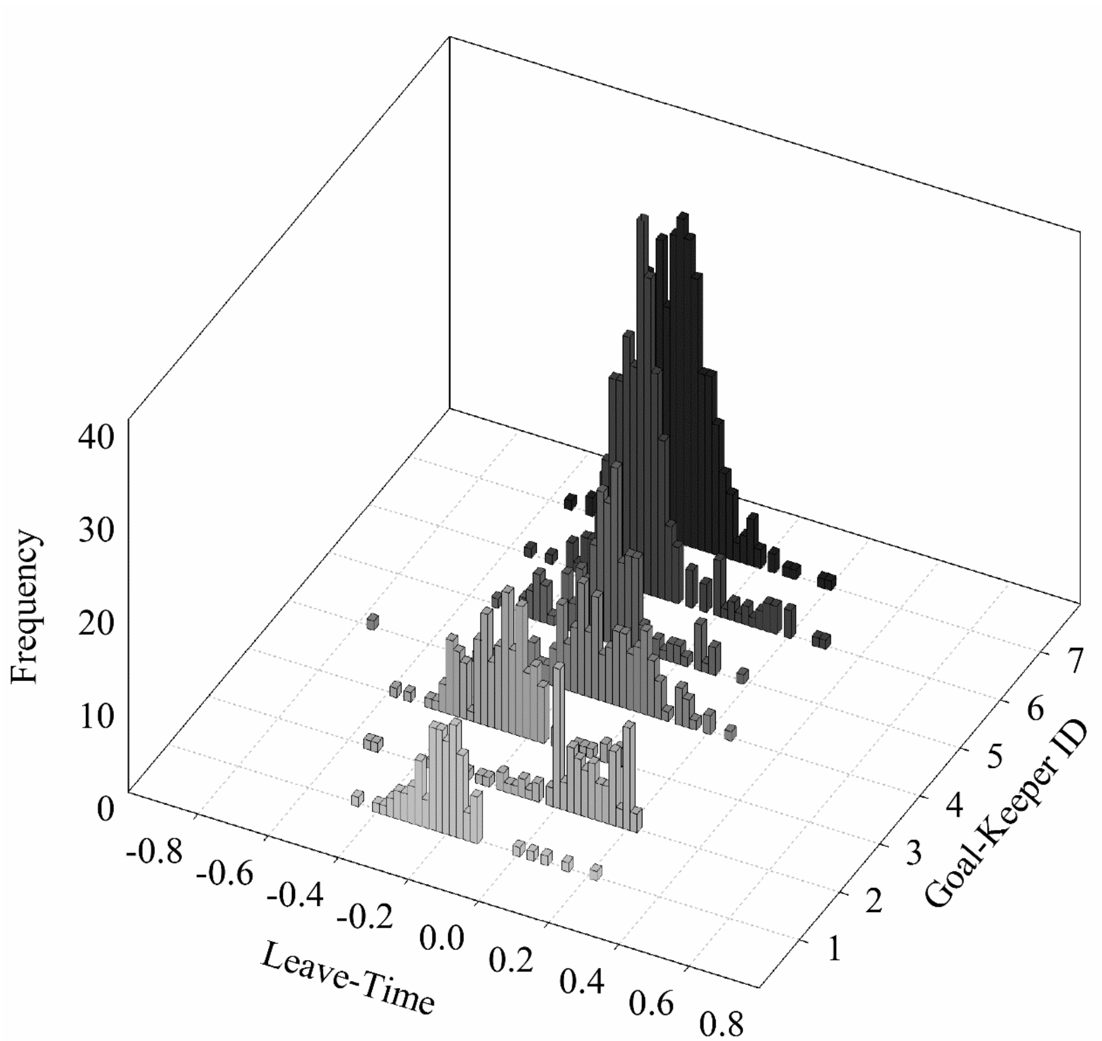

Figure 4.3: Frequency distribution of when goal-keepers moved relative to the shooter contacting the ball. Data is for individual Goal-Keepers. Positive time values are after ball contact.

Effect of Shot Speed on Leave-Time

When shot speed, kick technique, and their interaction were modelled, shot speed ($F_{(1,645)} = 18.835$, $p < 0.001$) and the interaction between shot speed and kick technique ($F_{(1,1203)} = 5.169$, $p < 0.05$) significantly affected goalkeeper leave-time. When the data were analysed separately for side-foot and instep kicks, shot speed had a significant, negative effect on leave-time for side-foot shots only ($F_{(1,199)}$) = 35.177, $p < .0001$, $\beta = -0.014$, 95% CI = [-0.009, -0.018]) (see Figure 4.4). Instep kicks were less frequently used (N = 214 of 1278 shots), which may have affected our ability to detect an effect (Figure 4.4).

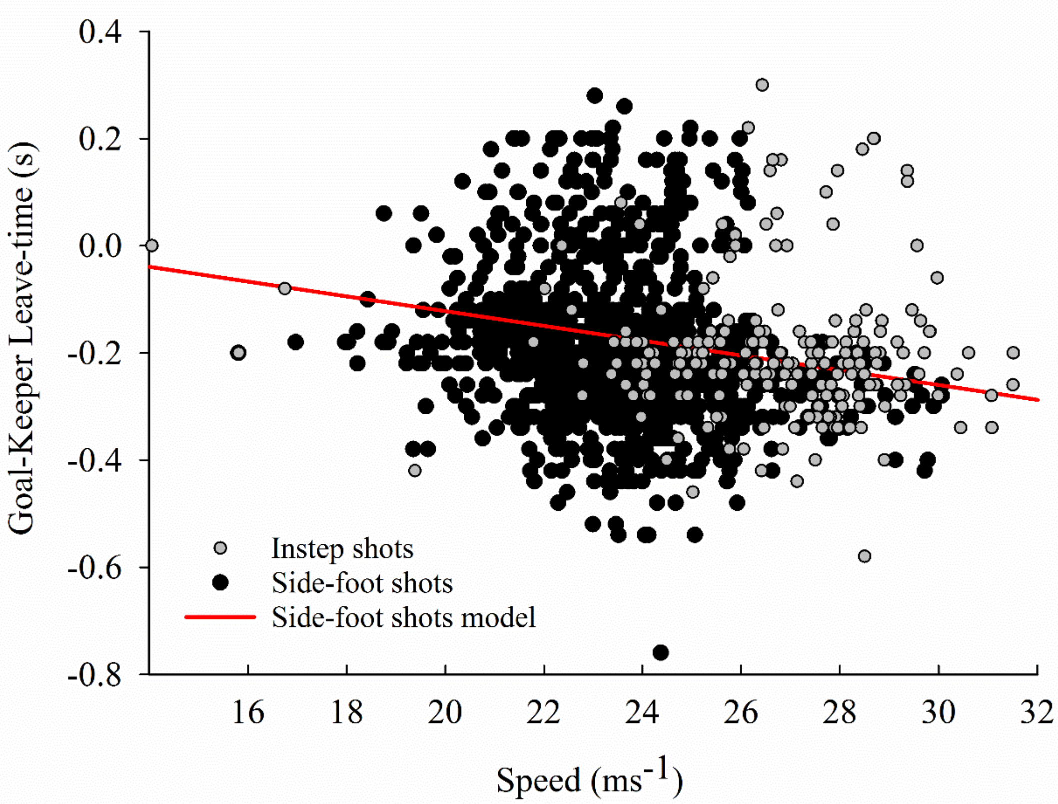

Figure 4.4: Relationship between shot speed and when goal-keepers moved relative to the shooter contacting the ball. Black dots are raw data from 1064 side-foot shots, grey dots are raw data from 214 instep shots. Positive time values are after ball contact. Black line is linear model from side-foot shots data only.

Probability of Blocking Shot

For shots within the goalkeeper's reach, faster shots were less likely to be blocked than slower shots (β = -0.045, 95% CI [-0.033, -0.056], p = <0.0001, adjusted R^2 = 0.82). An increase in shot speed from 20 ms^{-1} to 30 ms^{-1} decreased the likelihood the goalkeeper blocked the shot from 82% to 38% (Figure 4.5).

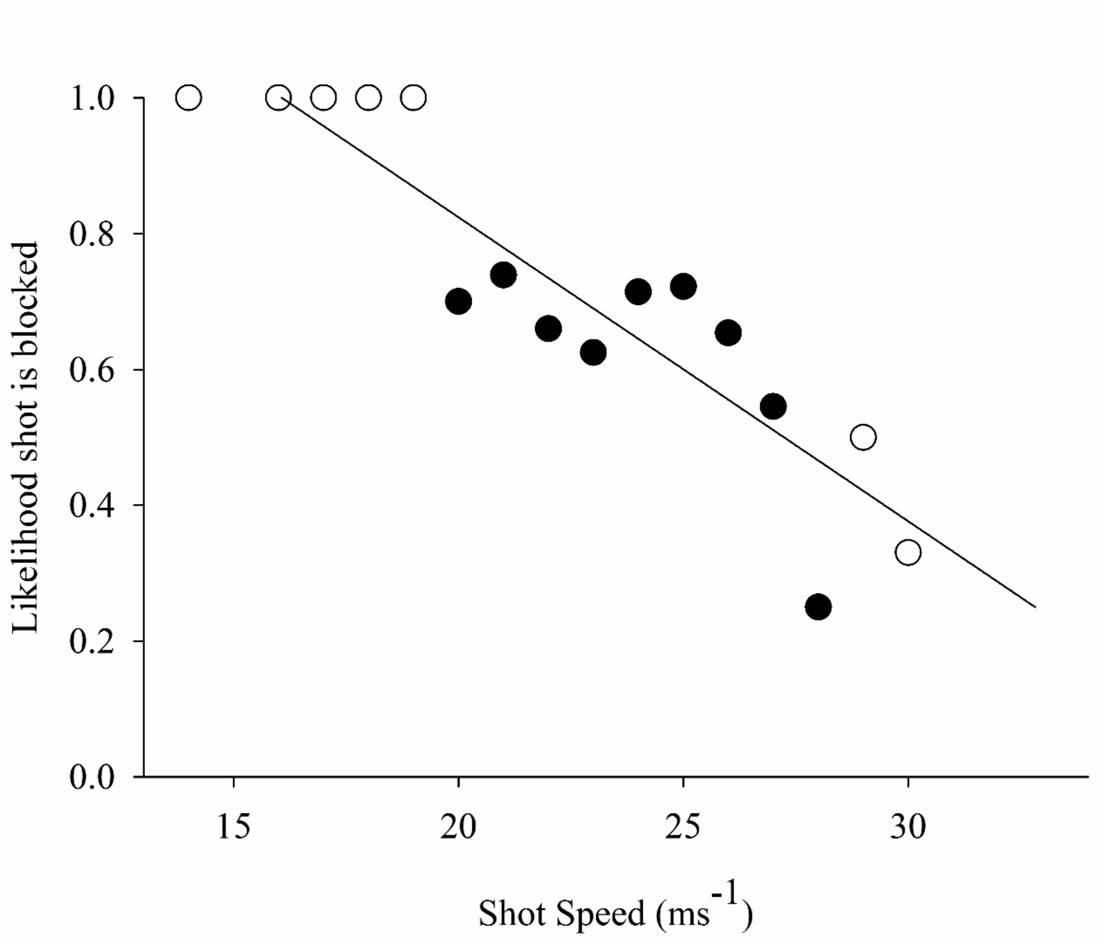

Figure 4.5: Relationship between shot speed and the probability the goal-keeper blocks a shot within reach. Black line is linear model. After rounding shot speed to the nearest ms-1 some speeds had less than 10 events with which to calculate the proportion of shots saved. These speeds are indicated by non-solid circles, while solid circles indicate speeds with 10 or greater events (Mean ± SD, 29.89 ± 16.37). All speeds were included in the statistical model.

Shooter Deception

When shooters were trying to be deceptive they changed their run-up angle and the angle of their non-kicking foot. This occurred for shots toward either side of the goal (Table 4.4). For example, players increased their run-up angle (Figure 4.1) if they were aiming across the body but trying to give the impression of shooting to the open side of the goal; when using a True (non-deceptive) run-up, this angle was significantly smaller for shots across the body. A Deceptive run-up was more likely to occur on shots across the body (66%) compared to shots to the open side (34%) (Appendix Table A4.5). Overall, however, shooters were more likely to use a True (22%) or Neutral (64%) run-up than a Deceptive one (14%) (Appendix Table A4.5).

Run-up angle and non-kicking foot angle did not affect the movement of the goalkeepers in the correct direction, for shots across the body (Table 4.2) or to the open side of the goal (Table 4.3). Only goalkeeper leave-time predicted goalkeeper movement, with earlier leave-times decreasing the likelihood goalkeepers moved in the correct direction for shots across the body (Table 4.2) and to the open side of the goal (Table 4.3).

Table 4.4: Summary statistics for Linear Model of nominated run-up angle predicting actual run-up angle and non-kicking foot angle, for shots across the body and to the open side of the goal.

Nominated run-up Angle		Estimate	SE	*t*	*P*
Across		*Run-up Angle*			
	Deceptive (Intercept)	32.005	2.142	14.945	< .0001
	Neutral	-14.041	0.814	-17.245	< .0001
	True	-11.070	1.113	-9.951	< .0001
		Foot Angle			
	Deceptive (Intercept)	11.131	2.014	5.528	< .0001
	Neutral	-5.069	0.722	-7.021	< .0001
	True	-2.888	0.987	-2.927	0.004
Open		*Run-up Angle*			
	Deceptive (Intercept)	11.752	2.561	4.588	0.0001
	Neutral	2.752	1.126	2.444	0.0149
	True	18.598	1.131	16.443	< .0001
		Foot Angle			
	Deceptive (Intercept)	18.050	1.718	10.509	< .0001
	Neutral	-0.247	0.957	-0.258	0.796
	True	6.047	0.962	6.286	< .0001

Discussion

The aim of our study was to show how the strategies of shooters and goalkeepers interact to influence the outcome of soccer penalties. We found that whether a goalkeeper moved in the correct direction and blocked the penalty was determined by their leave-time and the speed of the shot, respectively. However, to our surprise, goalkeeper success was not affected by the shooter's attempt at deception.

Previous studies indicated that shooters can use deceptive body positioning or movement to trick the goalkeeper into moving in the incorrect direction(Dicks, Button, et al., 2010a; Dicks, Davids, et al., 2010; Smeeton & Williams, 2012). Using a greater number of players and a testing protocol that closely resembled real game situations, we did not find this to be the case. We aimed to improve upon earlier methods by allowing shooters to decide for themselves their strategy—including deceptive ones—and players were offered a financial reward for scoring success. In previous studies, players were directed when and how to be deceptive, and told where to aim with no cost of being inaccurate as shots that missed the target region were retaken or removed from analysis. It is possible the focus on deception made their movements more exaggerated and obvious to goalkeepers. In a game situation, the shooter is likely to prioritise accuracy and goal-scoring, and attempts at deception may be subtler, and therefore less effective. Lastly, as previous studies used only one or two shooters caution must be taken when drawing conclusions from them(Dicks, Button, et al., 2010a; Dicks, Davids, et al., 2010; Smeeton & Williams, 2012).

Even with our improvements in protocol, it is difficult to study deception because there are many aspects to shooter movement that can be manipulated to deceive the goalkeeper(Smeeton & Williams, 2012). For example, a shooter's kicking leg and foot can take a trajectory normally resulting in a side-foot shot to the open side of the goal, but by altering the angle of the foot and contacting the side of the ball furthest from the shooter, the ball will go across the shooters body. Here, we quantified only the run-up angle and the angle of the non-kicking foot at ball contact, which likely underestimated the prevalence and effectiveness of deceptive strategies. Regardless, effective deception requires that a shooter wait as long as possible before altering their kick action from one direction to another, which increases variation in the trajectory of the kicking foot toward the ball and reduces precision (Asai, Carre, Akatsuka, & Haake, 2002; Carre, Asai, Akatsuka, & Haake, 2002). If so, shooters given the option to self-select technique may often decide the potential benefits of deception are not enough to outweigh its costs to accuracy, explaining the low prevalence of this strategy in our study. Future research should investigate if deceptive shots are less accurate than non-deceptive shots. Our shooters rarely used a keeper dependent strategy, a strategy frequently used by professional players (Kuhn, 1988) and under experimental conditions (Wood & Wilson, 2010b). Similar to deception, our shooters may have used this strategy so rarely due to the associated decrease in accuracy (Van der Kamp, 2006; Wood & Wilson, 2010b).

Goalkeepers are likely also aware that shooters sometimes use a deceptive strategy, and may anticipate shots based on whether or not they believe the shooter is trying to be deceptive. If they think the shooter is trying to deceive them, a goalkeeper will intentionally move to the 'wrong' side of the goal, having predicted a late change in shot direction. In this case, the shooter's attempt at deception is effective but the goalkeeper predicted their intent and chose to ignore the deceptive cues presented. Anecdotally, the most successful goalkeeper in our experiment reported assessing the shooter's personality to determine if they were likely to use a deceptive strategy. This highlights the difficulty in measuring the effectiveness of deception in game situations. Future research should collect more detailed data on goalkeeper strategies – i.e. "I predicted he was kicking left, but moved right because I also predicted he was trying to be deceptive." We saw very few instances of goalkeepers using deceptive strategies against shooters. This was surprising considering goalkeeper movement and gestures can predictably influence where the shooter kicks the ball (Weigelt et al., 2012; Wood & Wilson, 2010a). Professional goalkeepers may use deceptive strategies more often than our sample of players, with Petr Cech an example of a player often using deceptive movements. An analysis of professional players may yield different conclusions about the prevalence and effectiveness of deceptive strategies in match situations.

While our results indicate goalkeeper leave-time, but not shooter deception, affect the likelihood goalkeepers dive in the correct direction during penalties, further studies are required to develop mathematical functions describing these relationships. Regardless, if a goalkeeper moves in the correct direction, the distance they travel across the goal before the ball reaches the goal-line is determined by how fast they move and how much time is available to move (determined by shot speed and leave-time). For a 25ms^{-1} shot placed on the ground 3m from the middle of the goal (goalkeeper), the ball will travel 11.4m (distance $= \sqrt{(11\text{ m})^{2} + (3\text{ m})^{2}}$) and take 0.46s to reach the goal-line. If we assume that a goalkeeper moves at 4ms^{-1} (Dicks, Davids, et al., 2010), then to have enough time to move across the goal to block the shot, the goalkeeper must move at least 0.29 s before the ball is kicked (leave-time $= 0.46\text{ s} - \frac{3\text{ m}}{4\text{ ms}^{-1}}$). By calculating the proportion of our frequency distribution of leave-time (all goalkeepers) between -0.29 and -∞, one could estimate the likelihood a goalkeeper moves at this time or earlier, putting themselves in position to block the shot. This could also be applied to individual goalkeepers with their own frequency distribution of leave-time. For, example Goalkeeper 3 in our study is much more likely than Goalkeeper 2 to move early enough to block this shot (Figure 4.3).

Shot speed affected both goalkeeper leave time and their likelihood of missing the block. We found that goalkeepers tended to move earlier on faster shots, which decreased the likelihood they moved in the correct direction; however, early leave-times allowed them to move farther across the goal. Predictive models must include functions quantifying these relationships to estimate the effectiveness of any shooting strategy. For example, predictive models could use our function describing the relationship between shot speed and leave-time (Figure 4.4), to shift the Mean of the frequency distribution of leave-time for different shot speeds.

For shots within the goalkeeper's reach, faster shots were more likely to be missed or partially blocked than slower shots, resulting in a goal. This is not surprising as faster shots reduce the time available for goalkeepers to accurately move a body part (eg. arm or leg) to block the shot (Fitts, 1954), and even if they are within reach, they may not have time to do so. In fact, we found that increases in shot speed from 20 ms^{-1} to 30 ms^{-1} decreased the likelihood the shot was blocked from 80% to 40% – a considerable benefit for shooting near maximal speeds. However, because slower shots are more accurate(Andersen & Dorge, 2011; Hunter, Angilletta Jr, et al., 2018; Lees & Nolan, 2002), any benefits of faster shots must be weighed against the increased risk of missing the goal or placing the shot within the goalkeeper's reach. Simply put, a faster shot might be harder to save, but a slower, more accurate shot may more likely be out of the goalkeeper's reach. To evaluate the effectiveness of any shooting strategy, predictive models should include a function describing the relationship between shot speed and likelihood the goalkeeper blocks the shot, if within reach.

Lastly, previous research suggests shooters should kick to upper parts of the goal (Bar-Eli & Azar, 2009). This study observed existing footage of penalty shots from professional games. As such, the intent of shooters was unknown and shooting error immeasurable. In the present study, 6% of shots toward upper regions of the goal ($y > 1.6$ m) and 17% of shots below this height were saved, confirming shots high in the goal are difficult to defend. However, shooters predominantly aimed near to the ground (Figure 4.2), and while 265 shots went high in the goal, shooters chose a high target on only 94 shots. While professional players are likely more accurate kickers than players in the present study, we suggest shots high in the goal, while effective, are often the result of shooting error.

While many sports are a battle between competing agents, we often measure the skills and traits of individuals in isolation to determine what predicts success. We must also determine how the skills and strategies of competing athletes interact to influence the outcome of sporting activities. Here, using soccer players competing in game-realistic conditions, we identified elements of the shooter's strategy and goalkeeper's strategy that interact to affect the outcome of penalty shots. By generating mathematical functions quantifying these relationships, we can provide sport scientists with the tools to develop more sophisticated predictive models of penalty success. Many sports could benefit from a similar approach, particularly those where athletes vary the speed and timing of their actions to achieve different outcomes.

CHAPTER 5

A PREDICTIVE MODEL OF SOCCER PENALTY SUCCESS

Abstract

Success in a soccer penalty can be the difference between winning and losing matches, major tournaments, and multi-million dollar prizes. The outcome is determined by a complex interaction between the shooter and goalkeeper, whose performance are constrained by biomechanical trade-offs, such as that between speed and accuracy. 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-time), affecting the time available to move and the likelihood they move in the correct direction. Previous attempts to identify the optimal strategy for penalty success ignore the trade-offs faced by each player and how they interact to influence the outcome. Here, we present a model that predicts the likelihood of success for all shooting strategies, defined as any combination of shot speed, where the shooter aims, shooter footedness (left or right), and kicking technique (side-foot or instep). Each shooting strategy is matched against all leave-times the goalkeeper might use, considering the likelihood each leave-time is chosen, to estimate the likelihood of scoring success. This model can match individual shooters against individual goalkeepers to identify the optimal shooting strategy for that specific matchup. Generally, a fast kick aimed close to the ground has the greatest chance of success. Against a goalkeeper who tends to move early, aiming toward the centre of the goal is optimal. Against a goalkeeper who tends to move late, shooting to the extremities of the goal is the best strategy, with the optimal target in the horizontal dimension dependent on shot sped, kick technique, and footedness.

Introduction

A penalty shot in soccer is enthralling for spectators and can determine the outcome of matches and 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 a Video Assistant Referee system 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. In this one-on-one contest between shooter and goalkeeper, each player 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 simplistic strategies that do not account for the complex interaction between players (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 are trying 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 likelihood of scoring a goal. For example, if shooting near maximal speeds and aiming very close to one of the goal-posts, there is a reasonable chance the shot will miss the goal due to the inherent trade-off between speed and accuracy (Hunter, Angilletta Jr, et al., 2018). The shooter 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, the shooter could shift their target further inside the goal-post and kick at maximal speed. However, the goalkeeper doesn't need to move as far now to block 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. To determine the efficacy of any shooting strategy, predictive models must consider the trade-off between speed and accuracy.

Existing models of soccer penalty success were commonly 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 and 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). Further, shooting toward the top of the goal has a high chance of success as these shots are very difficult for goalkeepers to defend (Bar-Eli & Azar, 2009). These approaches simply suggest regions of the goal to kick toward. They ignore shot speed as an element of a shooter's strategy and assume the shot will always be accurate, despite the inherent error associated with kicking a ball (Hunter, Angilletta Jr, et al., 2018). Leela & Comissiong (2009) presented a model describing an optimal trajectory angle for shooters, including shot speed as a variable. They also included an "error margin" to account for inaccurate kicking but failed to empirically describe how shooting error changes as a function of shot speed. Evidently, to identify the optimal shooting strategy when taking a penalty shot, more comprehensive predictive models are required.

When facing a penalty shot, goal keepers 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 (G. J. P. 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, Angilletta, & Wilson, 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. Considering the influence leave-time has on the outcome of penalty shots, and the variation observed both within and among individuals (Hunter, Angilletta, & Wilson, 2018), it is surprising this variable has not been included in previous models (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 part of their body. This becomes more difficult as shot 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. Consequently, 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 harder to defend because it requires more force to alter their direction than slower shots. For example, a fast shot that hits the goalkeeper's outstretched fingers is likely to continue into the goal, while a slower shot might be deflected enough to miss the goal. In existing predictive models, the importance of this phenomenon has been overlooked.

Lastly, penalty shots are interactive, with the effectiveness of either player's strategy dependent on the strategy employed by the other. Additionally, 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 likelihood 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 likelihood 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 likelihood they dive in the correct direction and; accounts for elements of each players strategy that interact to affect the outcome of penalties. This model predicts the likelihood of scoring for all strategies available to shooters, identifying that with the greatest chance of success. First, we present a brief overview of the model. Then, we describe the shooter parameters and goalkeeper parameters and how these were obtained. We outline how these parameters are 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.

Method

Overview of Predictive Model

The predictive model was written in Matlab version 2017b (Mathworks, Inc, Massachusetts, United States). In the simplest terms, it competes a single shooting strategy against all strategies the goalkeeper might use, considering the likelihood of each goalkeeper strategy occurring. A shooter's strategy is defined as any combination of shot speed (ms^{-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)).

For a given shooting strategy, the model estimates (for all locations in the goal) the likelihood the shot will go to a specific location. After considering the likelihood of all leave-times the goalkeeper may choose and how this affects the likelihood they move in the correct direction toward the ball, the model also estimates the likelihood the goalkeeper's body will be blocking the same location as the ball when the ball reaches the goal-line. It then estimates the likelihood the goalkeeper successfully stops the ball, given the speed of the shot. With these likelihoods, the model estimates 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.

Shooter Parameters

Proportion of shots going along the ground or in the air

Shooters can select a target on or off the ground anywhere in the goal. If aiming on the ground, the shot may travel along the ground as desired or go in the air due to kicking error. Similarly, if aiming at a target off the ground, the shot may go in the air or along the ground. To estimate the error structure of any shooting strategy we must first determine the likelihood the shot goes on the ground or in the air.

For shots aimed on the ground, faster shots tend to go in the air more often than slow shots (Hunter, Angilletta Jr, et al., 2018). Using the data from Chapter 2 (Hunter, Angilletta Jr, et al., 2018), we generated linear functions describing the relationship between shot speed and the proportion of shots that went in the air, or along the ground, for side-foot and instep shots (see Supplementary Material).

$$P_{GA\ side} = (0.042 * bs) - 0.64 \tag{5.1}$$

$$P_{GA\ instep} = (0.04 * bs) - 0.5 \tag{5.2}$$

$$P_{GG\ side} = 1 - P_{GA\ side} \tag{5.3}$$

$$P_{GG\ instep} = 1 - P_{GA\ instep} \tag{5.4}$$

where $P_{GA\ side}$ and $P_{GA\ instep}$ are the proportion of shots aimed along the ground that go in the air for each kicking technique, $P_{GG\ side}$ and $P_{GG\ instep}$ are the proportion of shots aimed along the ground that go on the ground for each kicking technique, and *bs* is the ball speed (ms^{-1}).

For shots aimed in the air, target height likely affects the proportion of shots going on the ground or in the air. We heuristically generated a function describing this relationship (see Supplementary Material).

$$P_{AA} = 1 - 0.6908 * \exp(-1.527 * t_y) \tag{5.5}$$

$$P_{AG} = 1 - P_{AA} \tag{5.6}$$

where P_{AA} and P_{AG} are the proportion of side-foot and instep kicks shots aimed in the air that go in the air or along the ground, respectively, and t_y is the target height (m).

Bivariate distributions of shooting error

Next, we must estimate an error structure for each of the following situations: shots aimed along the ground that went on the ground (Ground-Ground); shots aimed along the ground that went in the air (Ground-Air); shots aimed in the air that went on the ground (Air-Ground); and shots aimed in the air that went in the air (Air-Air). To achieve this, we fit bivariate distributions of error (horizontal and vertical) to each situation using the kicking accuracy data from Chapter 2 (Hunter, Angilletta Jr, et al., 2018) (see Appendix for further details). We fit separate distributions for each combination of kicking technique (side-foot or instep) and footedness (left or right).To allow for a bouncing ball still considered as travelling along the ground, the ground was defined as anything below y = 0.1 m.

Distributions were fit across all shot speeds and shooters from Chapter 2 to yield bivariate distributions for the average speed in each situation. A summary of the bivariate distributions is presented in Table 5.1. While a normal distribution was almost always the most appropriate, we chose a generalised extreme value distribution to describe horizontal error for Air-Ground shots. The shape of this distribution changes as a function of target height. We did this because for a high target (t_y = 1.6 m), shots that go along the ground for right-footed players tend to miss left, with the opposite true for left footed players (Hunter, Angilletta Jr, et al., 2018). However, for a target height close to the ground this distribution is assumed to be normally distributed, like the Ground-Ground horizontal error. The generalised extreme value distribution allows us to model the shift from normal to left/right skewed as a function of target height and footedness.

Table 5.1: Summary of bivariate distributions of error (horizontal and vertical) for shots aimed along the ground that go along the ground (Ground-Ground) or in the air (Ground-Air), and shots aimed in the air that go along the ground (Air-Ground) or in the air (Air-Air)

	Horizontal Error Distribution	Vertical Error Distribution
Ground-Ground	normal	exponential, range = 0-0.1
Ground-Air	normal	truncated normal, range = 0.1 - ∞
Air-Ground	generalised extreme value	truncated normal, range = 0-0.1
Air-Air	normal	truncated normal, range = 0.1 - ∞

While these bivariate distributions describe an error structure for the average speed in each shooting condition (side-foot or instep kick; right or left footed), the mean and variance of shooting error are dependent on shot speed (Hunter, Angilletta Jr, et al., 2018). A statistical model was developed in Chapter 2 that estimates the mean and variance parameters for shots of any speed, for all combinations of kick technique (side-foot or instep), target height (t_y = 0 or t_y = 1.6 m), and footedness (left or right) (Hunter, Angilletta Jr, et al., 2018). We used this model to estimate the mean and variance parameters of our bivariate distributions for any shot speed. For Ground-Ground and Air-Ground shots, the statistical model was used to calculate the mean and variance parameters for horizontal error as a function of shot speed, while the parameters for vertical error were held constant across all speeds. For Ground-Air and Air-Air shots, the statistical model was used to calculate the mean and variance parameters for horizontal and vertical error. For Air-Air shots of the same speed, we assumed the mean and variance parameters were constant across all target heights. Shifting a target in the horizontal dimension was assumed to have no effect on the bivariate distributions.

Lastly, when kicking at a target, shots that miss above the target also tend to miss to the right for right-footed players, with the opposite true for left footed players (Hunter, Angilletta Jr, et al., 2018). In Chapter 2 (Hunter, Angilletta Jr, et al., 2018) the covariance between horizontal and vertical error was estimated for each combination of target height ($t_y = 0$ or $t_y = 1.6$ m) and footedness (left or right). We applied the appropriate covariance structure from Chapter 2 to the Ground-Air and Air-Air bivariate distributions to capture the pattern of miss for left and right-footed shooters.

Shooter probability densities

For a given shooting strategy (target location in the goal $\{t_x, t_y\}$, shot speed, kick technique, footedness), we can estimate the proportion of shots that will go on the ground, and the proportion of shots that will go in the air with expressions 5.1 to 5.6. Then, assigning parameters appropriate for that strategy, bivariate distributions describe where shots on the ground are likely to go, and where shots in the air are likely to go. Orienting these distributions relative to the target (t_x,t_y) generates a probability density describing where shots are likely to go in, or outside the goal for that shooting strategy. Figure 5.1 presents examples of probability densities for different shooting strategies. For any location in or outside the goal where the shot may go (shot {x, y}), calculating the area under the probability density gives the probability the shot will go to that specific location.

$$P(shot\ \{x,y\}) = \int_{x,y}^{x+dx,y+dy} f_{x,y}(x,y)\ dx,y \qquad 5.7$$

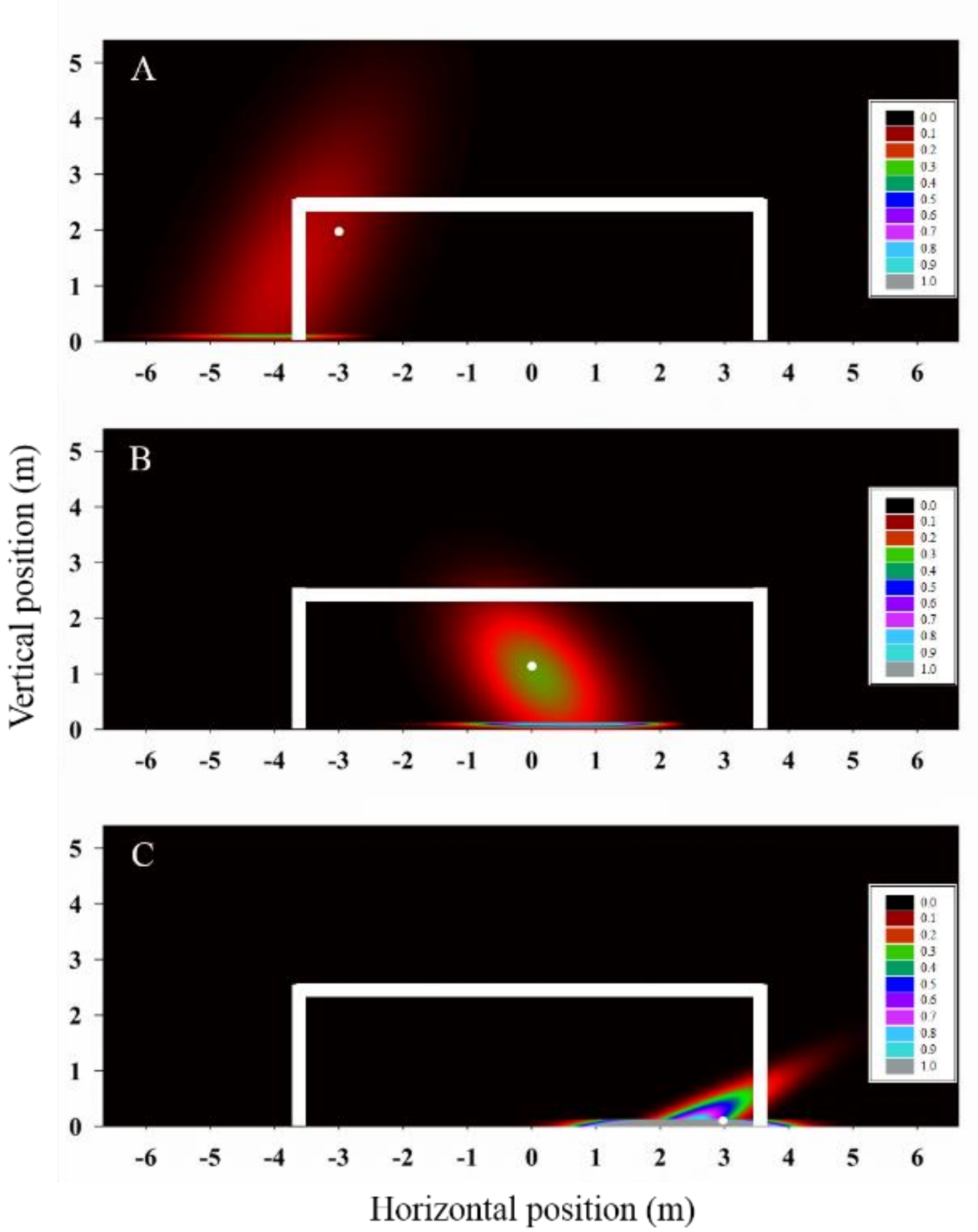

Figure 5.1: Probability densities describing where shots are likely to go for specific shooting strategies (target {t_x, t_y}; shot speed; kick technique; footedness). **A)** -3,2; 32 ms^{-1}; instep; right. **B)** 0,1.2; 24 ms^{-1}; side-foot; left. **C)** 3,0; 24ms^{-1}; side-foot; right. Solid white lines represent the dimensions of the goal and the white dot in each plot represents the target. The contour colours represent the probability density. These plots consider the likelihood the shot goes on the ground on in the air, dependent on target height (plots A and B) or shot speed (plot C). That is, within each plot, integrating under the ground and air distributions sums to 1.

Goalkeeper Parameters

Distribution of goalkeeper leave-time

Goalkeeper leave-time, together with shot speed, determines the time available for goalkeepers to move before the ball reaches the goal-line. There is variation within and among goalkeepers in when they choose to dive, best described by a normal distribution (Chapter 4, Figure 4.3). They also tend to move earlier on faster shots (Chapter 4, Figure 4.4). To describe when the "average" goalkeeper moves, the predictive model generates a leave-time distribution by estimating the mean with expression 5.7 (Chapter 4, Figure 4.4), and using a constant variance parameter (SD = 0.145 s) calculated from the combined data of all goalkeepers from Chapter 4 (Figure A4.1).

$$\text{Mean leave-time} = (-0.0138 * bs) + 0.1543 \qquad 5.8$$

where *bs* is ball speed

Goalkeeper Motion

Goalkeepers start in the middle of the goal in a crouched position. They generally move before ball contact, diving either left or right with their body parallel with and within reach of the ground. After diving, they can move their arms and legs to stop shots, but their body's trajectory is set. Thus, they tend to block the bottom portion of the goal, evidenced by shots high in the goal rarely being saved regardless of where they go in the horizontal dimension (Bar-Eli & Azar, 2009). Goalkeepers occasionally wait until after ball contact to initiate movement, and, having seen the ball's initial trajectory, move appropriately to intercept. As prediction is not perfect at ball contact (Chapter 3 Figure 3.4), the model sets a "recognition point" of 0.05 s after ball contact. For leave-times after this, it is assumed the goalkeeper has seen the trajectory of the ball and will move directly toward the location the ball enters the goal.

In the predictive model, the origin (x = 0, y = 0) is set in the middle of the goal on the ground. The goalkeeper is modelled as a circle with radius of 0.75 m, with its centre initially located at x = 0 m, y = 0.75 m (Figure 5.2). To represent a dive left or right initiated before the recognition point, the circle moves horizontally across the goal at 4 ms^{-1} (Dicks, Davids, et al., 2010). As it moves, the space it travels through, including its starting position, becomes "solid" representing the goalkeeper's body. This oblong shape grows to a length of 2.5 m and maintains a height of 1.5 m (Figure 5.2A). This represents the area considered to be within reach of the goalkeeper (imagine the total area a goalkeeper's body could block with their arms above their head or spread to either side, and by spreading their legs as wide as possible). The oblong continues moving horizontally through space at 4 ms^{-1} until the trailing point of oblong is 2.5 m from the goal-post. At this point the trailing edge stops moving but the leading edge continues to move horizontally until all regions of the goal below y = 1.5 m are blocked. Modelling the goalkeeper in this way assumes the goalkeeper does not dive past the goal-post, allowing their legs to block central regions of the goal regardless of leave-time. It also allows the goalkeeper to block all regions of the goal below y = 1.5 m at the goal-post. For leave-times after the recognition point, the goalkeeper again starts as a circle in the centre of the goal, but is then modelled as an expanding circle, with a radius increasing at 4 ms^{-1} (Figure 5.2B).

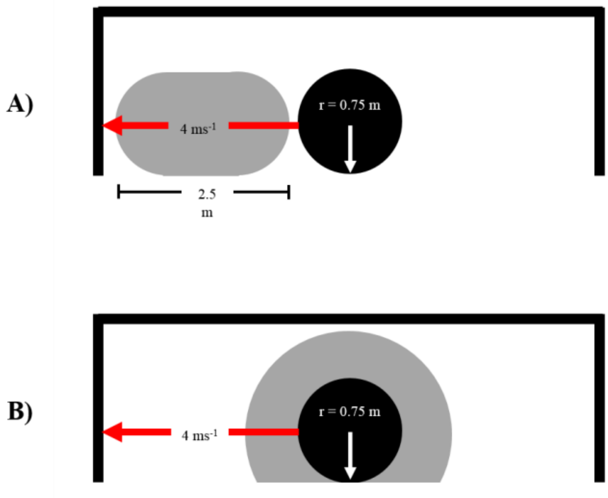

Figure 5.2: Graphical representation of how the goalkeeper's movement is modelled. Black circles represent the goalkeeper's starting position and grey areas depict movement. Black lines represent dimensions of goal (7.32 m x 2.44 m). **A)** Goalkeeper initiates movement before seeing the ball's trajectory. **B)** Goalkeeper initiates movement after seeing the ball's trajectory.

Likelihood of Correct Prediction

A major determinant in the outcome of a penalty is if the goalkeeper moves in the correct direction. If they move the wrong way the outcome is almost certainly a goal if the ball is on target. Using data from Chapter 3 (Hunter, Murphy, et al., 2018), we developed a linear function describing the relationship between goalkeeper leave-time and correctly predicting shot direction (See Supplementary Material for further details).

$$P_{correct\ prediction} = (0.584 * lt) + 0.819 \qquad 5.9$$

where *lt* is leave-time (s)

Likelihood of blocking shots within reach

If a goalkeeper moves appropriately to intercept the ball before it crosses the goal-line, the likelihood they successfully stop it entering the goal is dependent on the speed of the shot (Hunter, Angilletta, et al., 2018) (Chapter 4). Here, the linear function generated in Chapter 4 (Figure 4.5) is used to model this relationship.

$$P_{save} = (-0.0447 * bs) + 1.72 \qquad 5.10$$

where *bs* is ball speed

Goalkeeper probability densities

For any given shooting strategy, the model must estimate, for all locations within the goal, the likelihood some part of the goalkeeper is blocking that location when the ball reaches the goal-line. To achieve this, one must consider the distribution of goalkeeper leave-times. As an example, let us select one location and imagine a shot kicked at 25 ms^{-1} that enters the goal 3 m left of the goal's centre (0.66 m inside the goal-post), 0.75 m off the ground. This shot will travel 11.43 m ($\sqrt{(11\text{ m})^2 + (3\text{ m})^2 + (0.75\text{ m})^2}$) and take 0.46 s to reach the goal-line. The first step is to calculate the range of leave-times in which some part of the goalkeeper is blocking the location. To have enough time to move across the goal to block the shot, the goalkeeper must move at least -0.1 s before the ball is kicked ($0.46\text{ s} - \frac{3\text{ m}-0.75\text{ m}}{4\text{ ms}^{-1}}$). For all times after -0.1 s in the leave-time distribution, there is zero likelihood the goalkeeper blocks this location. As the goalkeeper does not move past the goal-post, some part of their body will block 0.66 m inside the goal-post for all leave-times before -0.1 s. For all leave times before -0.1 s, we must consider the likelihood the goalkeeper leaves at that time (5.11), and the likelihood they move in the correct direction, dependent on that leave-time (5.9). Thus, the probability the goalkeeper moves at -0.2 s (between -0.2 s and -0.201 s) and moves in the correct direction is 0.0019 ($P_{leave\text{-}time}$ * $P_{correct\ prediction}$ = 0.0027* 0.71).

$$P_{leave-time} = \frac{1}{\sigma\sqrt{2\pi}} \int_{lt}^{lt+dlt} e^{-\frac{(lt-\mu)^2}{2\sigma^2}} \qquad 5.11$$

μ = mean of leave-time distribution (expression 5.7); σ = standard deviation of leave-time distribution; lt = leave-time.

Repeating this across all leave-times before -0.1 s and summing the resultant probabilities gives the likelihood some part of the goalkeeper's body is blocking the location x = -3 m, y = 0.75 m when the ball reaches the goal-line. Lastly, with expression 5.10 (P_{save}) the model estimates the likelihood the goalkeeper successfully saves the shot, given shot speed. By repeating this across locations within the goal, a probability density can be generated describing the likelihood the goalkeeper will save a shot at any location in the goal, given its speed and intended target.

$$P(save|x, y) = P_{save} \ * \int_{lt_{min}}^{lt_{max}} P(block|lt, x, y)\, f_{lt}\,(lt)\, dlt \qquad 5.12$$

$lt_{min} - lt_{max}$ = range of leave-times for which the goalkeeper's body blocks location *x*,*y* when ball reaches the goal-line

As goalkeepers vary in when they choose to initiate movement (Chapter 4, Figure 4.3), probability densities can be customised to individuals. First, the difference between the mean leave-time for an individual and the mean leave-time for all goalkeepers combined from Chapter 4 (M = -0.19 s) is calculated. Then, assuming the effect of shot speed on leave-time is constant across all goalkeepers, the difference in means is added to the result of expression 5.7. This calculates the mean of the leave-time distribution for that individual goalkeeper, dependent on shot speed. A customised standard deviation for individuals can be used in expression 5.11 if appropriate. Figure 5.3 presents goalkeeper probability densities generated for the average of all goalkeepers from Chapter 4 and for the goalkeeper who tended to move latest (ΔMean = 0.23 s).

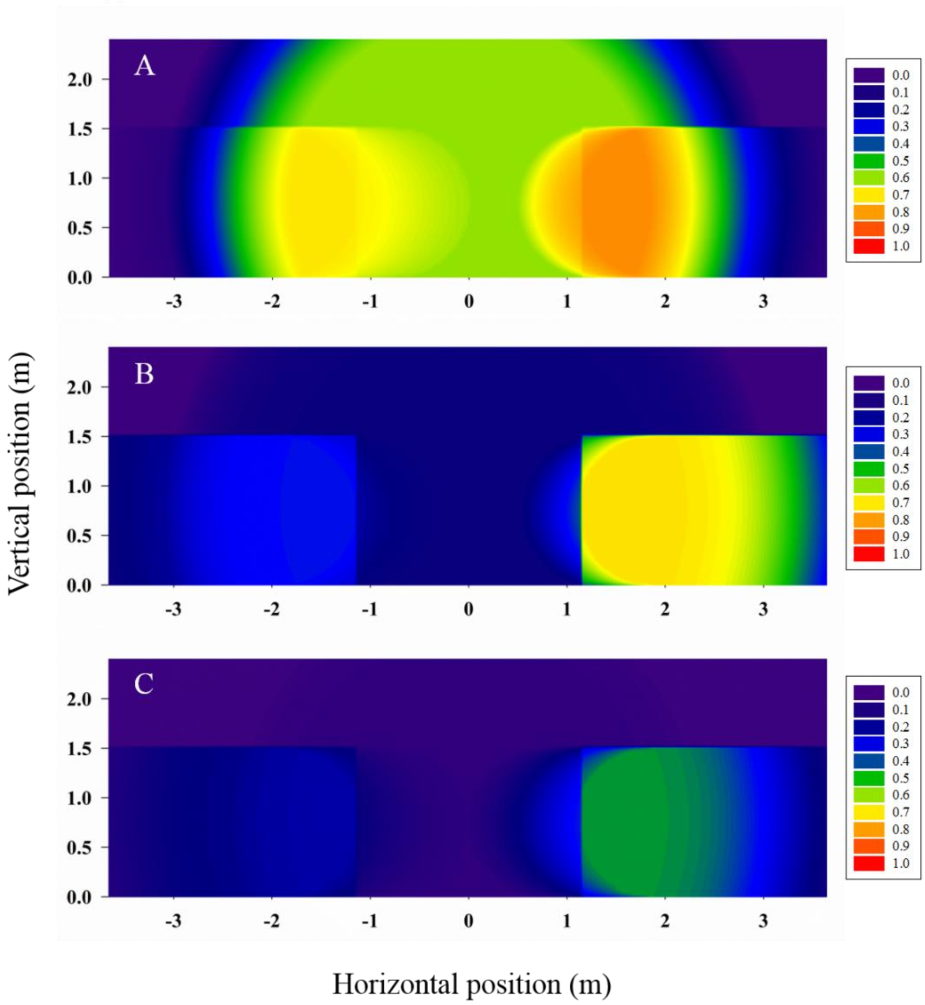

Figure 5.3: Probability densities describing the likelihood the goalkeeper will save a shot at any location within the goal, for a given distribution of leave-time (ΔMean, SD); shot speed (ms^{-1}) and; target (t_x, t_y) **A)** 0.230 s, 0.145 s; 18 ms^{-1}; 1, 1; **B)** 0 s, 0.145 s; 18 ms^{-1}, 1, 1; **C)** 0 s, 0.145 s; 24 ms^{-1}, 1, 1. The contour colours represent the probability density. These plots consider the likelihood the goalkeeper moves in the correct direction, and the likelihood the shot is saved dependent on shot speed.

Calculating the probability of a goal

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

$$P(goal) = \int_{-3.66,0}^{3.66,2.44} 1 - P(shot\ \{x, y\}\ P(save|x, y) \qquad 5.13$$

Note: dimensions of a soccer goal are 7.32 m x 2.44 m.

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 shooting strategies it competes against the goalkeeper. By holding constant all elements of the shooter's strategy except target location (t_x, t_y), we can generate a probability density for a shooting sub-strategy (shot speed, kick technique, footedness) that estimates the likelihood of a goal depending on the 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 Chapter 4 and a late moving goalkeeper (ΔMean = 0.23 s). From Chapter 4, shooters most often used a side-foot technique and kick at submaximal speeds (mean ≈ 24 ms^{-1}), a strategy that prioritises accuracy. When shooters choose a strategy that prioritises speed, they generally use an instep kicking technique and kick at maximal speeds (up to 32 ms^{-1}). A third general strategy sometimes used by shooters is to kick at low speeds and aim down the centre of the goal. 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.

Results

For a right-footed player shooting with a side-foot technique at 24 ms^{-1} against the "average" goalkeeper (see Chapter 4), the optimal strategy is to shoot close to the ground toward the centre of goal (Figure 5.4A). This is because the average goalkeeper tends to dive before ball contact (mean = -0.19 s), leaving the centre of the goal 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 strategy is to kick toward the right-hand side of the goal aiming close to the ground approximately 0.4 m inside the goal-post (Figure 5.4B). Because the central tendency for right-footed players is for the ball to go to the left of the target (Figure 5.1C), the optimal distance when shooting to the right-hand side of the goal ($t_x \approx 3.2$ m, Figure 5.4B) is closer to the goal-post than when shooting left ($t_x \approx -2.8$ m, Figure 5.4B). Thus, shots to the right for right footed players have a slightly greater chance of success because they can be aimed further away from the goalkeeper, with errors tending to remain within the bounds of the goal. This holds across varying shot speeds and kick techniques (eg. Figure 5.4C).

For a right-footed player shooting with an instep technique at 32 ms^{-1} against the average goalkeeper, the optimal strategy is to aim centrally, close to the ground (Figure 5.4C). Against a late moving goalkeeper, the optimal strategy is to kick to the right aiming close to the ground and the right-hand goal-post (Figure 5.4D). Against a late moving goalkeeper many target locations have a relatively high chance of success (Figure 5.4D). As the goalkeeper tends to move after ball contact (mean = 0.04 s) and the ball has a very short flight time, most of the goal remains undefended when the ball reaches the goal-line.

For a right-footed player shooting with a side-foot technique at 18 ms^{-1} against the average goalkeeper, the optimal strategy is to aim centrally (Figure 5.4E). However, compared to faster shot speeds aimed centrally, this strategy has a lower chance of success because slow shots are almost certainly saved if the goalkeeper reaches them, while faster shots are less likely defended accurately (Chapter 4, Figure 4.5). Against a late moving goalkeeper, the optimal strategy is to shoot higher in the goal toward either goal-post (Figure 5.4F). With the ball’s long flight time, even a late moving goalkeeper has enough time to move and block most parts of the goal. Aiming higher in the goal increases the distance a goalkeeper must travel, providing the best chance of success. The optimal target in the horizontal dimension is at the goal-post if aiming right or approximately 0.4 m inside the goal-post if aiming left (Figure 4.5F).

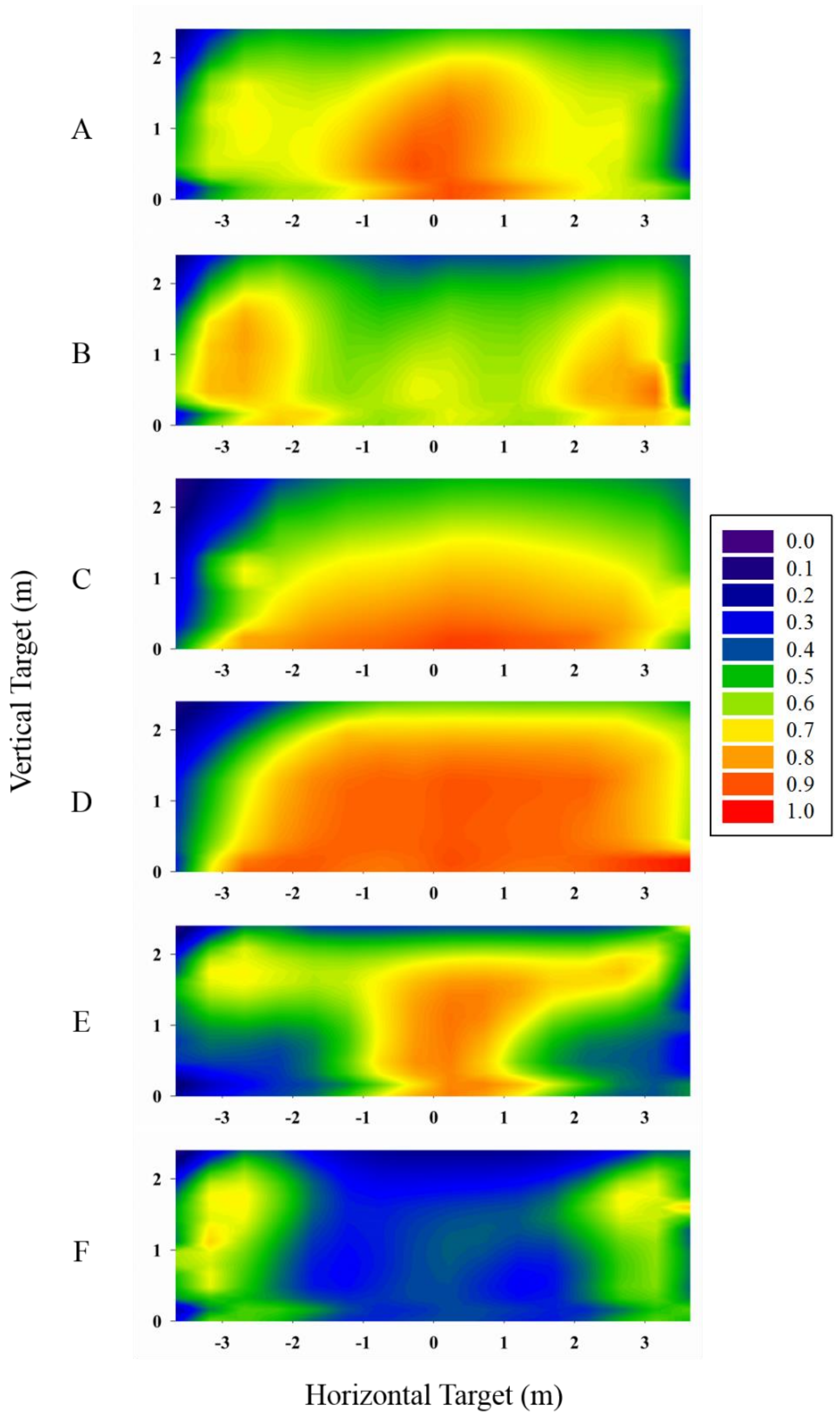

Figure 5.4: Probability densities describing likelihood of scoring a goal dependent on target (t_x, t_y), sub-strategy (shot speed, kick technique, footedness), and goalkeeper (average goalkeeper or late leaving). Each plot represents the dimensions of a goal. Contour colours are the probability density describing the relative likelihood of a goal depending on the target. Warmer colours (orange, yellow) have a greater chance of success than cooler colours (blue, green). **A)** shot speed = 24 ms^{-1}, technique = side-foot, footedness = right, goalkeeper = average; **B)** 24 ms^{-1}, side-foot, right, late; **C)** 32 ms^{-1},

instep, right, average; **D)** 32 ms^{-1}, instep, right, late; **E)** 18 ms^{-1}, side-foot, right, average; **F)** 18 ms^{-1}, side-foot, right, late.

Discussion

For scoring success, existing research suggests shooting down the centre of the goal (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 an early moving goalkeeper because the goalkeeper has moved to a side of the goal, leaving the middle undefended (Figure 5.4A, E). Conversely, shooting toward the edges of the goal is effective against a late leaving goalkeeper (Figure 5.4B, 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, if kicking at low speeds and aiming left, the optimal horizontal target is close to the goal-post (Figure 5.4F). However, as shot speed increases, the optimal horizontal target shifts further inside the goal-post accounting for greater error (Figure 5.4B). 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, in some situations aiming higher in the goal can increase the chance of success (Figure 5.4F).

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 Figure 5.4C, D a broad range of target locations have a high chance of success, against either a late or early moving goalkeeper. This is largely due to faster shots being more difficult to save – i.e. if the goalkeeper reaches the shot there is still only a 30% chance it will be successfully blocked (Chapter 4, Figure 4.5). Conversely, shooting slowly is only effective against an early moving goalkeeper and only when aiming down the centre of the goal (Figure 5.4 E,F). 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.

The model was parameterised using data from amateur/semi-professional shooters and goalkeepers. We expect the model's predictions to change depending on the skill level of players. For example, we assume the best outfield players in the world (e.g. Cristiano Ronaldo, Lionel Messi) to be very accurate shooters. This means professional players could aim closer to the goal-post than amateur players. Thus, the optimal target will be different for a professional player and have a greater chance of success as the shot is likely further from the goalkeeper. Goalkeepers vary in how fast they can move (Dicks, Davids, et al., 2010) and in their ability to predict shot direction (G. J. P. Savelsbergh et al., 2005; G. J. Savelsbergh, Williams, Kamp, & Ward, 2002). It is also likely they vary in their ability to block shots within reach. From Chapter 4, faster shots were less likely saved than slower shots if within the goalkeeper's reach. We expect this relationship to be less pronounced for professional goalkeepers, with them saving a higher proportion of fast shots. This would greatly alter the model's predictions for fast shots against better goalkeepers as shooters would get far less goals for "free" due to goalkeeper error.

Shooters sometimes use a keeper-dependent strategy, waiting until the goalkeeper moves to one side and then kicking toward the other (Kuhn, 1988). The efficacy of this strategy is contingent on goalkeeper leave-time (Botwell et al., 2009; Van der Kamp, 2006). If goalkeepers move very early, it is easy for shooters to alter kick direction. If goalkeepers move close to ball contact, shooters do not have enough time to change their kicking action to alter kick direction. Compared to the keeper-independent strategy (ignoring the goalkeeper's movement), this means the goalkeeper is less likely to predict shot direction for early leave-times if the shooter uses a keeper-dependent strategy, but this shooting advantage disappears as leave-time approaches ball contact. Currently, the Penalty Model focuses on the keeper-independent strategy only. However, to model the goalkeeper for a keeper-dependent strategy, one need only increase the slope of Expression 5.9. The keeper-dependent strategy also affects shooting accuracy (Van der Kamp, 2006; Wood & Wilson, 2010b), so one must also adjust the parameters of the shooter's bivariate distributions. However, how the keeper-dependent strategy affects shooting accuracy across a range of speeds is unclear from previous studies (Van der Kamp, 2006; Wood & Wilson, 2010b). Further studies are necessary to confidently model the efficacy of the keeper-dependent strategy.

Lastly, the likelihood goalkeepers predict shot direction is affected by shot speed, kick technique, and leave-time (Hunter, Murphy, et al., 2018). However, in the interest of model simplicity, we only included the effect of leave-time in the predictive model. One could generate predictions for different combinations of shot speed and kick technique by reanalysing the data from Chapter 3 including shot speed and kick technique as predictor variables, then appropriately altering the slope and intercept of Expression 5.9.

In conclusion, we have presented a predictive model that estimates the likelihood of scoring a soccer penalty for any strategy a shooter may choose, identifying the strategy with the greatest chance of success. This model can be customised to compete a specific shooter against a specific goalkeeper to identify the optimal strategy for that matchup. We surpass previous models by: including an error structure for shooters dependent on shot speed, kick technique, and footedness and; 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 likelihood the shot is saved if within the goalkeeper's reach.

CHAPTER 6

GENERAL DISCUSSION

Performing complex motor tasks at maximal speed has a cost, as an increase in this trait decreases performance in other traits such as accuracy (Fitts, 1954; Hunter, Angilletta Jr, et al., 2018), agility (Besier, Lloyd, Ackland, & Cochrane, 2001; Jindrich, Besier, & Lloyd, 2006; Wheeler & Sayers, 2010), or unpredictability (Chapter 3). Individuals must formulate and execute strategies that overcome such trade-offs to achieve desired outcomes. When two competing agents interact, each constrained by performance trade-offs, and each with a range of strategies to choose from, the outcome of each contest is determined by an interaction between the strategies chosen. In this thesis, using soccer penalty shots as a study system, I quantified the trade-offs constraining the performance of each competing agent and how these interact, and built a predictive model that identifies the optimal shooting strategy for scoring success.

Shooting Strategies

There is a clear trade-off between speed and accuracy when kicking a ball (Hunter, Angilletta Jr, et al., 2018). In Chapter 2, I found the dispersion of a penalty shot is dependent on shot speed, kick technique, target height, and player footedness. This builds on previous research identifying that shooters decrease shot speed when an accuracy demand is placed on the shot (Andersen & Dorge, 2011; R. Kawamoto et al., 2006; Lees & Nolan, 2002). To manage this trade-off, shooters in Chapter 4 most often used a side-foot shooting technique and kicked below their maximum speed. This suggests they commonly selected a strategy that prioritised accuracy over speed. Further, they generally selected a target near the ground and up to 1 m inside the goal-post to minimise the chance of missing above the goal or to the side (Chapter 4, Figure 4.2).

To help manage the trade-off between speed and accuracy shooters can use a deceptive or keeper-dependent strategy. Both strategies aim to increase the likelihood goalkeepers moves in the wrong direction (Botwell et al., 2009; Dicks, Button, et al., 2010a; Kuhn, 1988; Smeeton & Williams, 2012; Van der Kamp, 2006). If successful, the reliance on an accurate shot out of the goalkeeper's reach is greatly reduced. In Chapter 4, shooters used both strategies, but less than expected given the potential benefits. However, I likely underestimated the prevalence of deceptive strategies due to the limited number of kinematic variables measured. Regardless, using either of these strategies likely compromises shooting accuracy (Van der Kamp, 2006; Wood & Wilson, 2010b). As shooters in Chapter 4 tended to prioritise accuracy, the cost of using either deception or a keeper-dependent strategy may have outweighed the potential benefits.

Goalkeeper strategies

Goalkeepers have the more difficult task during a penalty, with over 75% of shots resulting in a goal (Jordet, Hartman, Visscher, & Lemmink, 2007). With relatively high shot speeds and little time to react, goalkeepers generally start moving before the ball is kicked to have any chance of blocking the shot (Dicks, Davids, et al., 2010; Edgard Morya et al., 2005). Thus, goalkeepers must try to predict shot direction based only on visual cues presented by the shooter, a task that becomes easier as the shooter's kicking action progresses (Smeeton & Williams, 2012). In choosing when to commit themselves to a dive to a side of the goal, they must balance the trade-off between moving in the correct direction and moving early enough to reach the shot. In Chapter 4 (Figure 4.3) individual goalkeepers varied their strategy, sometimes moving early and sometimes late. I also found some goalkeepers tend to move, on average, earlier or later than other goalkeepers. As expected, In Chapter 3 (Figure 3.4) and Chapter 4, the earlier goalkeepers predicted shot direction, the less likely they moved in the correct direction toward the ball. Goalkeepers can also use deception to influence where the shooter kicks the ball (Weigelt, Memmert, & Schack, 2012). However, the goalkeepers in Chapter 4 rarely used this strategy.

Interaction between strategies

The outcome of a penalty shot is determined by how the shooter's and goalkeeper's strategies interact. For example, if a shooter aims down the middle of the goal, this will likely succeed if the goalkeeper moves early, but fail if the goalkeeper doesn't move until after the shooter kicks the ball. However, the strategy each player chooses is not independent. Both players can observe the other's behaviour up until the ball is kicked, and that behaviour can influence decision making (Van der Kamp, 2006; Weigelt et al., 2012), and ultimately the outcome of the penalty.

In Chapter 3 I identified a trade-off between shot speed and unpredictability, with the direction of fast side-foot shots easier to predict than slower side-foot shots. Distinguishing between shots to the left or right was likely easier for fast shots because shooters exhibit a large range of motion (Browder, 1991; Lees & Nolan, 2002a), exaggerating the intent of the movement (Smeeton & Williams, 2012). In Chapter 3 I also found the predictability of shots was dependent on when predictions were made (as discussed earlier) and the kicking technique used. Thus, the likelihood a goalkeeper dives in the correct direction is not just a product of when they choose to dive, but how this interacts with the shooter's strategy (shot speed, kick technique) to determine the predictive quality of the information presented by the shooter's body.

While goalkeepers are interpreting the shooter's approach to the ball to predict shot direction, they likely form judgements of shot speed as well. In Chapter 4 I found evidence of this, with goalkeepers tending to move earlier on faster shots (Chapter 4, Figure 4.4). If anticipating a fast shot to the extremities of the goal, goalkeepers would instinctively compensate and move earlier, allowing more time to move across the goal. In Chapter 4, I also found when goalkeepers could reach the ball, faster shots were more difficult to save than slower shots (Chapter 4, Figure 4.5). Due to a trade-off between speed and accuracy (Fitts, 1954), faster shots were more likely missed by the goalkeeper, or deflected off their body into the goal.

Deception is reliant on an interaction between competing agents. For a deceptive shooting strategy to be effective the goalkeeper must use cues presented by the shooters body to predict shot direction, and believe it is an honest signal. In Chapter 4 I found deception, quantified by the shooter's runup angle and non-kicking foot angle, had no effect on the likelihood goalkeepers correctly guessed shot direction. Anecdotally, the goalkeepers in Chapter 4 indicated they knew shooters sometimes use a deceptive strategy. They believed it equally likely the cues presented by the shooter's body were a dishonest signal as an honest signal. Therefore, if a shooter sends a dishonest signal of shooting to the left, the goalkeeper may predict the shot will go left, and 1) move left or 2) also predict the shooter is trying to be deceptive, so move right. If the perceived likelihood of these two events is the same, then deception has no advantage over a non-deceptive strategy. While a more detailed kinematic analysis is required to determine its efficacy in game situations, my results suggest deceptive strategies may not be as effective as previous research suggests (Dicks, Button, et al., 2010a; Smeeton & Williams, 2012).

Optimal Scoring Strategies

The optimal scoring strategy is that which best manages the inherent error when kicking (Hunter, Angilletta Jr, et al., 2018) and directs the ball toward regions of the goal least likely to be defended by the goalkeeper. In Chapter 5 I presented a model, parameterised with results from Chapters 2-4, that predicts the likelihood of success for any strategy available to shooters.

Generally, faster shots aimed close to the ground had the greatest chance of scoring. Aiming close to the ground minimises the likelihood shots will miss above the goal (Chapter 2, Figure 2.2), and faster shots are more difficult for the goalkeeper to block with their body (Chapter 4, Figure 4.5).

However, the optimal target in the horizontal dimension is dependent on when the goalkeeper is likely to initiate movement (Chapter 5, Figure 5.4). According to the model's predictions, shooters should aim toward the centre of the goal if the goalkeeper tends to move early. In this instance the goalkeeper vacates the middle of the goal, leaving it undefended when the ball enters the goal. If the goalkeeper moves closer to when the ball is kicked however, shooters should aim toward the extremities of the goal, at an appropriate distance inside the goal-post to minimise the chance of missing the goal to the side. The model predicts this distance will be dependent on shot speed and kicking technique. As faster shots are less precise, shooters should aim further inside the goal-post compared to slower shots. Furthermore, individual skill level should influence the optimal target, with more accurate kickers able to choose targets closer to the extremities of the goal.

Previous models of penalty success suggest shooting toward the centre of the goal because goalkeepers have a strong tendency to dive to either side of the goal (Bar-Eli et al., 2007; Chiappori et al., 2002). This tendency has a psychological component. Norm theory (Kahneman & Miller, 1986) proposed that individuals perceive negative outcomes as worse when they can easily imagine a better outcome. In other words, negative feelings are worse if they acted abnormally and failed, compared to if they acted normally and failed. In the context of a penalty shot, diving to either side is considered the norm among goalkeepers (Bar-Eli et al., 2007). Thus, if a goal is scored, goalkeepers feel worse if they acted abnormally and did not move, compared to if they acted normally and did move (Bar-Eli et al., 2007). Because the feeling of failure after a goal is stronger if goalkeepers don't move, they prefer to dive to a side – "It was a goal, but at least I tried by diving to one side." In Chapter 3 (Figure 3.2) and Chapter 4 (Figure A4.1) professional and semi-professional/amateur goalkeepers tended to initiate movement, on average, approximately 0.2 s before ball contact, diving to either side of the goal. Aiming down the centre of goal should be very effective against these goalkeepers. As expected, the model predicted aiming centrally to be the optimal strategy against these goalkeepers, if shooting at slow to medium speeds.

As deceptive strategies had no influence on goalkeeper behaviour (Chapter 4) this was not included in the predictive model. However, not all forms of deception were investigated. In the penalty shoot-out of the 1976 UEFA European Championship Final, Antonin Panenka gave the impression he would kick the ball hard, but deftly kicked the underside of the ball. This resulted in a very slow shot that went in the air down the centre of the goal. As the goalkeeper had dived to a side of the goal, the ball entered the goal undefended. Subsequently, the "Panenka" is a strategy used by penalty takers across the world. Using this strategy and aiming centrally can be a very effective strategy because 1) giving the impression of kicking near maximal speed likely causes the goalkeeper to move relatively early (Chapter 4, Figure 4.4), and 2) with a very slow shot speed, the ball takes a relatively long time to reach the goal. Together, this ensures the goalkeeper has enough time to completely vacate the centre of the goal. With a faster shot aimed centrally that gets to the goal in less time, there is still a chance the goalkeeper could block the shot with their legs.

For the model I constructed, the "Panenka" highlights where improvements could enhance the model's predictions. Firstly, while the model accounts for goalkeepers moving earlier for faster shots, it does not predict when they move if a shooter only gives the impression of a fast shot, a form of deception. Currently, it only considers the eventual slow speed of the shot and delays goalkeeper movement, thereby increasing the likelihood they defend the middle of the goal. If goalkeepers are susceptible to this form of deception, the model could be improved by estimating goalkeeper leave-time based on the expected shot speed (deception), not the actual shot speed. Secondly, the predictive model heavily rewards fast shots by reducing the likelihood they are saved, even when reached by the goalkeeper. Professional goalkeepers likely save a much higher proportion of fast shots compared to the goalkeepers used to parameterise the model. If so, the model currently overestimates the efficacy of strategies with high shot speeds when matched against professional goalkeepers. Against better goalkeepers, shooters need to select strategies, like the "Panenka," that place the ball beyond the goalkeepers reach, rather than strategies that rely on goalkeeper error. To improve the predictive model, a "goalkeeper ability" parameter could be included that changes the linear function describing the relationship between shot speed and likelihood of blocking the shot. Lastly, the way the goalkeeper is currently modelled, the likelihood a shot is successfully saved is constant, regardless of where it hits the goalkeeper. However, saving a shot with the lower body is likely harder than saving a shot with the upper body. Against a slow shot aimed centrally, a goalkeeper who tends to leave early will only be blocking the middle of the goal with their lower body (or not at all) by the time the ball reaches the goal. As the predictive model currently predicts this slow shot will almost definitely be saved if it is within reach of the goalkeeper's "legs," it overestimates the likelihood they block the shot, reducing the efficacy of this strategy. The model could be improved by including a function that estimates the likelihood of a blocked shot dependent on where it strikes the goalkeeper's body.

Future Directions

While this thesis advances our understanding of the trade-off between speed and accuracy when kicking a ball, in the context of a penalty shot this is limited to a keeper-independent strategy where the shooter simply chooses a target in the goal to kick toward. Little data is available on how shooting accuracy across a range of speeds is affected by either a keeper-dependent strategy (Van der Kamp, 2006; Wood & Wilson, 2010b) or deception. To estimate the efficacy of these different shooting strategies we must first determine their effect on both the speed and accuracy of shots. With this, one could estimate the error structure for both deceptive and keeper-dependent shots across a range of speeds and determine if these strategies have a greater chance of success than a keeper-independent strategy. The susceptibility of goalkeepers to deception is also unclear (Smeeton & Williams, 2012) (Chapter 4). A detailed kinematic analysis of deception using multiple shooters could identify what strategies send an effective dishonest signal, while a detailed analysis of goalkeeper strategies could reveal if such signals are received and/or ignored. With this, one could quantify how deception affects the likelihood goalkeepers predict shot direction, a crucial element of the predictive model presented.

The predictive model is most applicable in a professional context where data on individual goalkeepers (leave-time) is easily obtained (Chapter 3). With this, one could determine the optimal shooting strategy against that individual. Therefore, to improve the model's predictions, data on shooting accuracy for professional players needs to be collected. Also crucial is to determine how shot speed affects a professional goalkeeper's ability to block shots. Lastly, one must determine the likelihood goalkeeper's successfully block shots if forced to use their lower body to intercept the ball.

While I have built a model that predicts shooting success, the data collected could also be used to identify the optimal goalkeeping strategy. From Chapter 4 there is a collection of 1278 penalty shots with a known speed and shot location (Chapter 4, Figure 4.2). Considering the likelihood goalkeepers move in the correct direction dependent on leave-time, one could model the optimal leave-time distribution that maximises the proportion of shot locations blocked by the goalkeeper.

At its most basic level, the soccer penalty is a contest between two agents whose performance is constrained by biomechanical trade-offs. Furthermore, during the contest imperfect information is transferred between them allowing anticipation of each other's intent. Thus, the principles developed here could be applied to a range of similar situations. Sports such as tennis, basketball, handball, and American football all involve an interaction between opposing players and require skills subject to biomechanical trade-offs. By identifying such trade-offs and quantifying their influence on success, one can identify strategies that achieve favourable outcomes and design training programs appropriately. Biologists could also benefit from this approach. For example, animal survival can be dependent on such traits as sprint speed, acceleration, and agility (Clemente & Wilson, 2015; Elliott, Cowan, & Holling, 1977; Huey & Hertz, 1984; Husak, 2006; Webb, 1976; A. M. Wilson et al., 2013; J. W. Wilson et al., 2013). A greater understanding of how such traits interact to influence success during a predation event could allow biologists to build more comprehensive models of predator / prey interactions. This would increase our understanding of animals' movement choices in nature.

Conclusions

Biomechanical trade-offs constrain physical performance, and how individuals manage these determines whether they succeed or fail. The aim of this thesis was to quantify the trade-offs faced by two competing agents, the strategies they use to overcome them, and how these strategies interact to determine the outcome of the contest. In the context of a soccer penalty shot, I found shooters face a clear trade-off between speed and accuracy. Goalkeepers must choose a movement time that balances the trade-off between predicting shot direction and allowing enough time to intercept the ball. Goalkeepers also face a trade-off between speed and accuracy, with faster shots more difficult to save. Finally, I built a model to predict how the strategies of each player interact to determine the outcome. The optimal shooting strategy is determined by an interaction between shot speed, target location, kick technique, and footedness, and when the goalkeeper tends to initiate movement.

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APPENDIX

From Chapter 3

A3.1: Survey instructions

Hi,

Thanks for taking part in this experiment. It should only take 10-15 minutes of your time.

You are about to find out how good a soccer goalkeeper you are. You will watch 60 different videos of soccer players shooting a penalty at you and your task is to guess if their shot went to **your** left or right. Each video will stop before the ball is actually kicked so you have to make your prediction based on their body cues. Some videos will stop right at ball contact while others stop at various points during the players run-up/kicking action so the amount of information you have to make your decision will vary.

You will only be able to watch each video once before making your prediction. Try not to think too much about it, just go with your gut instinct. You should be making your prediction within a couple of seconds of each video finishing.

You will have 10 practice trials to get familiar with how it all works and you will find out if your predictions were correct during the practice trials. When you move onto the 60 test trials, you will not get any feedback on whether your predictions were correct. No kicks you watch throughout this survey will be repeated.

To make your prediction click on either the “left” or “right” button. You will see these to either side below the video

In the example below, this shot has gone to the right.

Please note:

Participation in this study is voluntary. You do not have to take part in this project and you are free to withdraw at any time. Your withdrawal would not be held against you in any way. You may not directly benefit from participation in this study. For analysis, electronic information will be de-identified with ID numbers so no individual will be personally identifiable. All information will be stored on a password protected computer at the University of Queensland. All reports generated from this research will present data either in aggregated form or in a de-identified manner.

This study has been reviewed and approved by one of the Human Research Ethics Committees at The University of Queensland. If you have any questions about this research study or your participation please contact: Andrew Hunter at a.hunter@uq.edu.au

Should you wish to discuss the study with somebody who is someone not directly involved, you can contact the Ethics Officer on (07) 3365 3924 or humanethics@research.uq.edu.au.

If you're happy to participate, hit the '>>' arrow at the bottom right to continue.

A3.2: Demographic questions from Chapter 3

What best describes your soccer playing experience **under** the age of 18?

- Never played
- I occasionally kicked a ball around with friends and/or played in social competitions
- I regularly played in organised leagues - small-sided or 11-a-side

Was your experience **under** 18 primarily as an out-field player or goalkeeper?

- Out-field
- Goalkeeper

What best describes your soccer playing experience **over** the age of 18?

- Never played
- I have occasionally kicked a ball around with friends and/or played in social competitions
- I have regularly played in organised leagues - small-sided or 11-a-side
- I have regularly played in semi-professional leagues - some players are payed to play
- I have regularly played in fully professional leagues - all players are paid and this is their main source of income

Was your experience **over** 18 primarily as an out-field player or goalkeeper?

- Out-field

- Goalkeeper

What is your age in years?

What is your gender?

- Male
- Female
- Other

Table A3.1: Tukey-HSD comparisons identifying differences in correctly guessing shot direction based on soccer playing experience over the age of 18. 1) never played, 2) played socially, 3) amateur player, 4) semi-professional.

Comparison	Δ Mean	Lower 95% CI	Upper 95% CI	*p*
2-1	0.064	0.040	0.089	<.001
3-1	0.074	0.049	0.099	<.001
4-1	0.079	0.049	0.109	<.001
3-2	0.010	-0.013	0.033	0.678
4-2	0.015	-0.014	0.043	0.555
4-3	0.005	-0.024	0.033	0.975

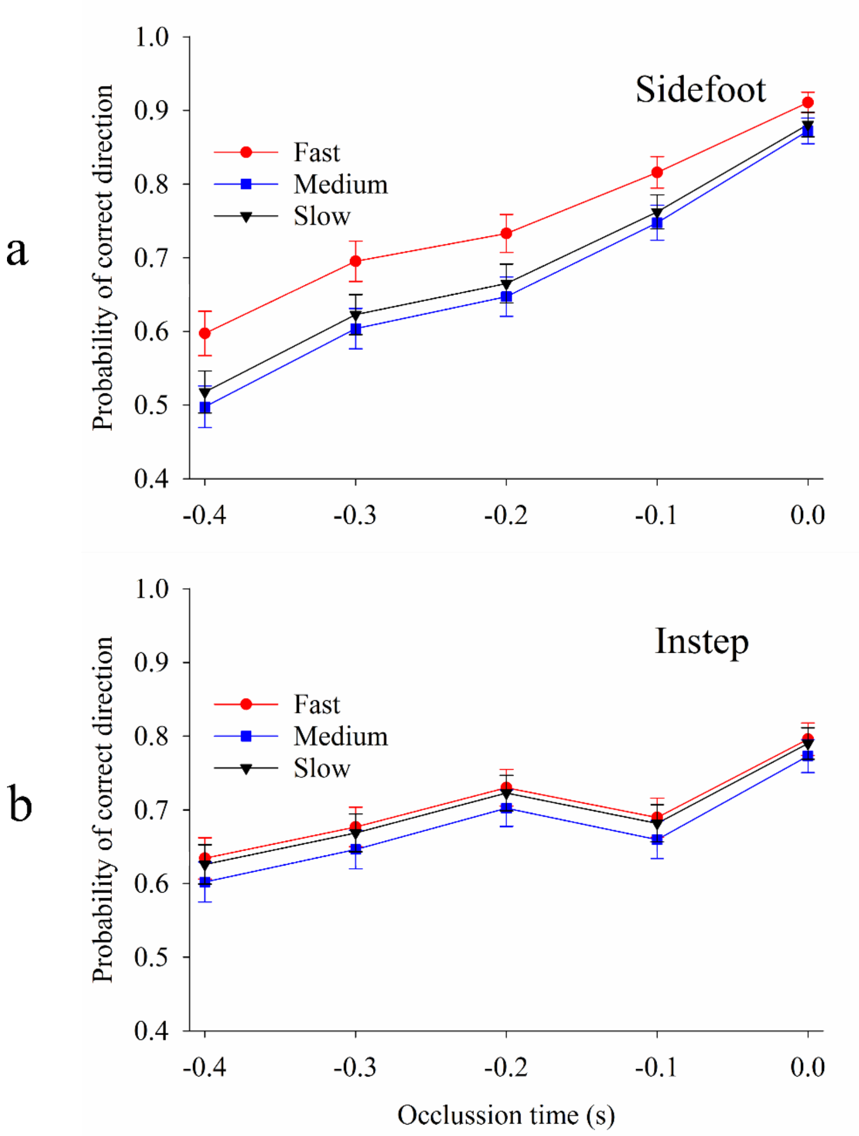

Figure A3.1: For participants over the age of 18 with goalkeeping experience, probability of correctly guessing shot direction dependent on occlusion time and shot speed. Probabilities and Standard Error bars calculated using averaged parameter estimates from statistical model. **a)** Side-foot shots. **b)** Instep shots.

From Chapter 4

A4.1 Further Explanation of Measures, Intra-Rater and Inter-Rater Reliability

Description of Raters

Rater 1 refers to the person who extracted all data used in analyses. This person has 30 years of experience playing and coaching soccer. Rater 2 also has 30 years of experience playing while Rater 3 has no soccer playing experience.

Ball speed, non-kicking foot angle and run-up angle

To test intra-rater and inter-rater reliability of our measures of ball speed, foot angle, and run-up angle, data from a random subset of 100 penalty shots was re-extracted by Rater 1 and Rater 3. Soccer playing experience was deemed nonessential for testing the inter-rater reliability of these measures. Mostly, individual frames captured by the high speed cameras produced accurate representations of the soccer ball after it was kicked, easily allowing its centre to be estimated in Matlab. Occasionally, due to the cameras automatically adjusting their shutter speed to account for low light, the image of the ball was blurred. For these trials we assigned the centre of the blur as the ball's position. This could be consistently located because the size and shape of the blurred image remained constant across all frames. Further, as we were only interested in measuring the ball's speed, not its position in space, it was necessary only to click on the same location on the ball in each frame, not accurately locate its centre. When measuring the position of the non-kicking foot at ball contact, one or both anatomical markers were sometimes blocked from view by the ball or the shooter's kicking foot. In almost all cases the non-kicking foot remained in a stable position from before ball contact until after contact. This allowed accurate position data to be extracted when the markers became visible after ball contact. In the rare instances the non-kicking foot moved before the markers became visible, these trials were removed from analysis.

Note: The measure of shot location was not included when Chapter 4 was submitted for publication. As such, intra-rater and inter-rater analysis was not done on this measure. Due to the orientation of the cameras used to measure shot location, an accurate representation of the ball was almost always produced.

Goalkeeper leave-time and goalkeeper deception

To test intra-rater and inter-rater reliability of our measure of goalkeeper leave-time, data from a random subset of 100 penalties was re-extracted by Rater 1 and Rater 2. Extracting leave-time data for some goalkeepers was straightforward as they remained stationary until initiating a dive to a side. Generally, their first movement was lifting a foot, or straightening out of a squat position toward one side of the goal. Other goalkeepers required more subjective judgement. For example, one goalkeeper generally jumped forward off the goal-line before then diving to one side. When making the initial jump forward and still in the air, his upper body would sometimes dip to the side of the goal he dived toward while his legs and feet shifted in the opposite direction. This suggests he decided the direction of his dive before the initial jump and prepared his body for the change in direction while still in the air. On other occasions, he would jump forward with his upper body in a balanced, neutral position, and his feet spread apart wider than shoulder width. Then, in mid-air he would extend toward the ground the foot opposite his eventual dive direction. This suggests he decided which direction to dive while in the air, after the initial jump forward. We were interested in identifying when goalkeepers choose to commit their movement to a side of the goal. Thus, in the first example the identifying movement was the start of the jump forward, while in the second example the identifying movement was the extension of the foot toward the ground.

To test intra-rater and inter-rater reliability for our measure of goalkeeper deception, data from a subset of 100 penalties was re-extracted by Rater 1 and Rater 2. This sample included all penalties Rater 1 judged deceptive when first extracting the data (N=15), and a further 80 that were randomly selected. Generally, when a goalkeeper is being deceptive they initially move toward a side of the goal then quickly dive toward the opposite side. They hope the shooter sees the initial movement and kicks toward the other side of the goal, the side the goalkeeper dives to. For this strategy to be effective the goalkeeper's initial movement must be obvious enough to send a signal to the shooter and occur early enough to allow the shooter to alter their shot direction (Van der Kamp, 2006). We used these criteria to assess if goalkeepers were being deceptive. For example, many of our goalkeepers made movements during the shooters run-up. In some, their movements were small and appeared to reflect decision changes by the goalkeeper on their dive direction, not an attempt at deception. In others their movements were large but repetitive and consistent, jumping from side to side. This was not considered deception as it didn't suggest the goalkeeper would dive in a particular direction. It simply created doubt in the shooter's mind on what direction the goalkeeper might dive, which can similarly occur if the goalkeeper is motionless. To be considered deceptive, a goalkeeper had to make an aggressive movement to one side of the goal that was obviously of a larger amplitude than other movements they were making. This movement also had to occur early enough in the shooter's run-up to influence their choice of shot direction (~ -0.4 s or more before ball contact) (Van der Kamp, 2006). It was also rated deceptive if a goalkeeper positioned themselves toward one side of the goal before the shooter commenced their run-up. As goalkeepers rarely position themselves perfectly in the centre of the goal (Masters, Kamp, & Jackson, 2007), the bias toward one side needed to be obvious (> 1 m) to be considered intentional and deceptive.

Penalty Outcome

To test intra-rater and inter-rater reliability for our rating of the goalkeeper touching the ball (touched, not touched, not touched but within reach), data from a subset of 100 penalties that were goals was re-extracted by Rater 1 and Rater 2. This sample included all shots Rater 1 initially judged not touched but within reach (N=9), a random sample of 41 shots initially judged as touched, and a random sample of 50 shots initially judged as not touched. Goalkeepers often dive before the ball is kicked propelling their body in the air, parallel to the ground, with arms outstretched anticipating a shot toward the corner of the goal. However, the shot may go toward the centre of the goal and pass either just above or below the region of their hips. In this case, they could reach the ball with either their hands or legs, but often do not have time to adjust their body position to effect a save. In cases such as this, the shot was judged to be not touched but within the goalkeepers reach.

Table A4.1: Intraclass correlation coefficient (ICC) estimates for measures of ball speed, non-kicking foot angle, run-up angle, and goalkeeper leave-time. All estimates based on a single rating, agreement, two-way model.

Measure	ICC	Lower 95% CI	Upper 95% CI	*F*	df1	df2	*P*
Ball Speed							
R 1.1 v R 1.2	0.98	0.97	0.99	109	99	100	<.0001
R 1.1 v R 3	0.95	0.86	0.98	51.9	99	11.2	<.0001
R 1.2 v R 3	0.95	0.88	0.97	47.6	99	17	<.0001
Foot Angle							
R 1.1 v R 1.2	0.98	0.97	0.99	93.9	99	88.6	<.0001
R 1.1 v R 3	0.97	0.96	0.98	74	99	72.3	<.0001
R 1.2 v R 3	0.99	0.99	0.99	211	99	99.2	<.0001
Run-up Angle							
R 1.1 v R 1.2	1	1	1	12674	99	23.3	<.0001
R 1.1 v R 3	0.99	0.98	0.99	137	99	99.8	<.0001
R 1.2 v R 3	0.99	0.98	0.99	140	99	99.6	<.0001
Goalkeeper Leave-time							
R 1.1 v R 1.2	0.81	0.73	0.87	9.94	99	86.4	<.0001
R 1.1 v R 2	0.77	0.68	0.84	7.79	99	99.3	<.0001
R 1.2 v R 2	0.83	0.7	0.90	13	99	27.5	<.0001

R 1.1 = Rater 1 full extraction

R 1.2 = Rater 1 sub-sample extraction

R 2 = Rater 2 sub-sample extraction

R 3 = Rater 3 sub-sample extraction

Table A4.2: Cohen's Kappa estimates for rating goalkeeper deception (yes, no) and penalty outcome (touched, not touched, within reach).

Measure	k	Lower 95% CI	Upper 95% CI	z	*P*
Goalkeeper Deception					
R 1.1 v R 1.2	0.96	0.89	1	5.73	<.0001
R 1.1 v R 2	0.88	0.74	1	5.05	<.0001
R 1.2 v R 2	0.83	0.67	0.99	4.70	<.0001
Penalty Outcome					
R 1.1 v R 1.2	0.95	0.89	1	10.77	<.0001
R 1.1 v R 2	0.91	0.84	0.99	10.38	<.0001
R 1.2 v R 2	0.95	0.89	1	10.50	<.0001

R 1.1 = Rater 1 full extraction
R 1.2 = Rater 1 sub-sample extraction
R 2 = Rater 2 sub-sample extraction

Table A4.3: Count data of penalty outcome for side-foot and instep shots.

	Goal	Miss	Save	Total
Side-foot	775	128	161	1064
Instep	144	42	28	214
Total	281	816	181	1278

Table A4.4: Descriptive statistics for side-foot shot speed and instep shot speed for each shooter.

	Side-foot Shot Speed (ms^{-1})					Instep Shot Speed (ms^{-1})				
Shooter #	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max
1	39	27.75	1.47	24.81	30.06	2	30.49	0.16	30.37	30.61
2	54	24.17	1.01	20.7	26.13	12	24.58	5.5	14.05	28.18
3	72	24.16	1.2	20.68	26.43	0	NA	NA	NA	NA
4	26	23.78	1.24	20.54	26.08	1	26.05	NA	26.05	26.05
5	49	22.89	1.45	19.35	25.17	13	26.47	1.57	22.56	28.69
6	25	25.86	1.67	22.79	29.51	18	27.41	1.12	25.02	28.9
7	73	23.3	1.13	20.1	26.57	18	24.96	1.29	22.8	27.18
8	20	25.25	0.81	24.06	26.75	5	26.3	1.48	24.16	27.73
9	42	24.86	1.74	20.84	29.71	24	27.29	1.61	23.81	29.33
10	70	21.54	1.58	16.97	23.81	30	25.21	2.11	19.38	28.85
11	141	23.89	1.42	18.84	26.13	29	27.73	1.37	24.71	29.97
12	36	22.01	1	18.92	23.86	0	NA	NA	NA	NA
13	167	22.25	1.27	18.75	25.24	3	24.52	1.89	22.36	25.88
14	14	23.57	1.04	21.04	25.36	12	24.69	0.95	23.33	26.65
15	15	20.9	2.36	15.8	26.45	23	25.17	2.8	13.79	28.3
16	182	23.15	1.16	19.22	26.02	0	NA	NA	NA	NA
17	38	25.12	1.89	20.71	28.5	23	29.18	1.34	27.14	31.51

Table A4.5: Count data of all shooter's self-reported run-up angle (True, Neutral, Deceptive) for shots across the body and to the open side of the goal. Across/Open refers to which side of the goal the shot finished, so includes shots aimed down the centre of the goal that finished slightly to one side.

	True	Neutral	Deceptive	Total
Across	93	454	120	667
Open	188	362	61	611
Total	281	816	181	1278

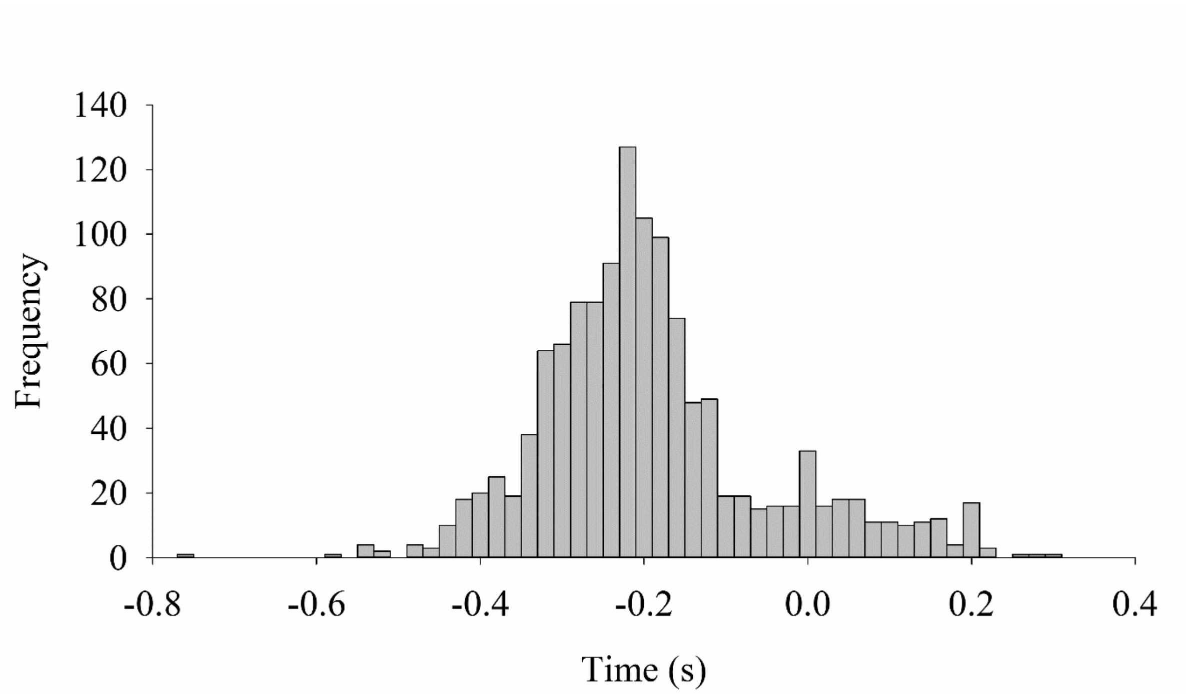

Figure A4.1: Frequency distribution of when goal-keepers moved relative to the shooter contacting the ball. Data is all Goal-keepers combined. Positive time values are after ball contact.

From Chapter 5

Further Explanation of Bivariate Distributions of Shooting Error

To develop bivariate distributions of error for each shooting situation (Air-Air, Air-Ground, Ground-Ground, Ground-Air), we wanted to accurately represent the data, but also promote simplicity in the predictive model. We plotted frequency distributions of horizontal and vertical error for each shooting situations using the data from Chapter 2 (Figures A5.1 to A5.4). From these plots, using a Normal Distribution was deemed appropriate for most situations. As Air-Ground shots had very data points, a Normal Distribution was assumed for vertical error. Regarding vertical error for Ground-Air shots (Figure A5.3), this is non-normally distributed and a different distribution (eg. Poisson) may have been more appropriate. However, for a high target (Air-Air), the distribution of vertical error became more normal (Figure A5.1). We needed to model this change in shape and generate distributions of vertical error for targets of any height. Thus, a Truncated Normal truncated at the ground was deemed most appropriate.

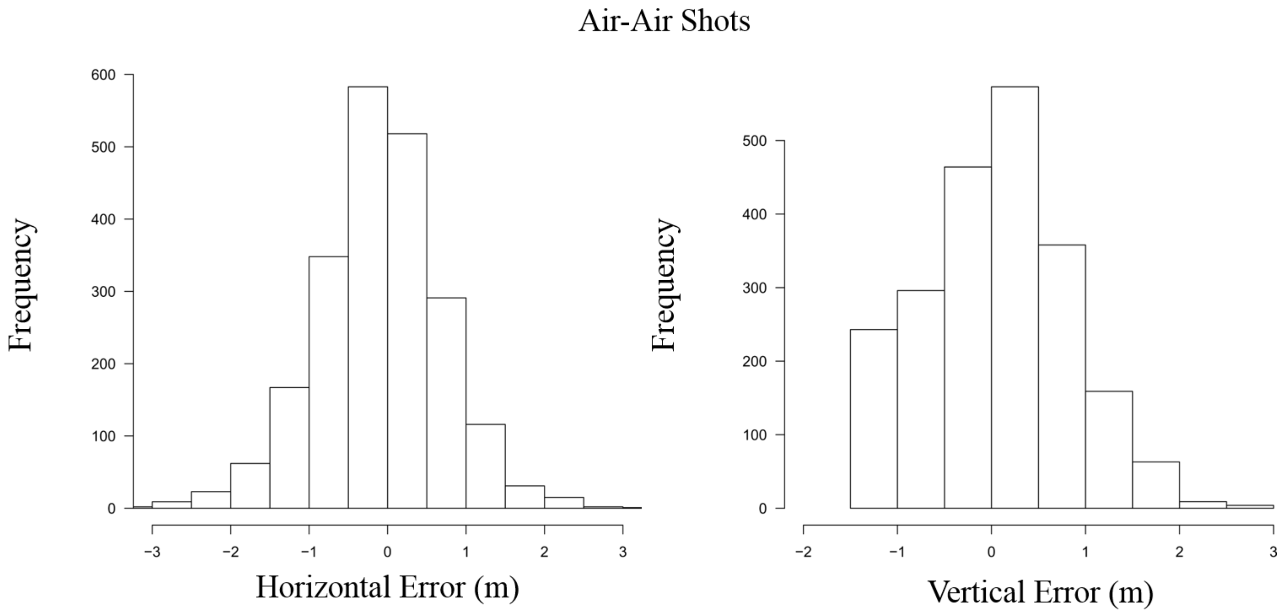

Figure A5.1: Frequency distributions of horizontal and vertical error for shots aimed at a target in the air (y = 1.6 m) and the shot goes in the air. Data was corrected for shooter footedness (all shooters are right-footed)

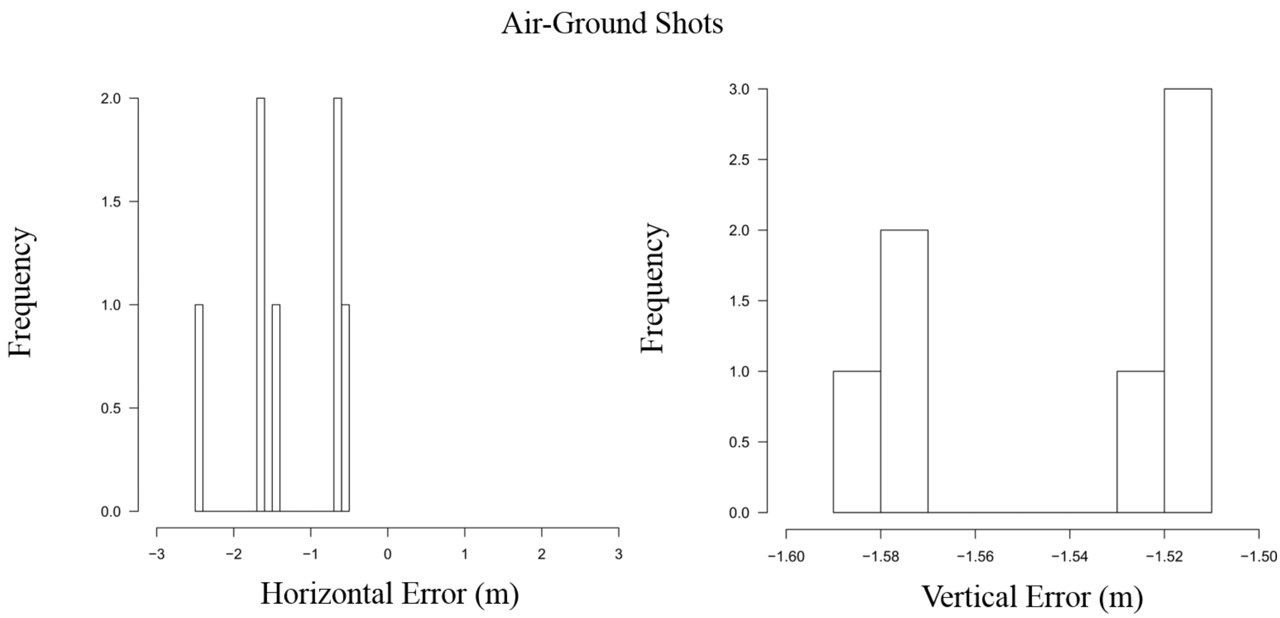

Figure A5.2: Frequency distributions of horizontal and vertical error for shots aimed at a target in the air (y = 1.6 m) and the shot goes along the ground. Data was corrected for shooter footedness (all shooters are right-footed).

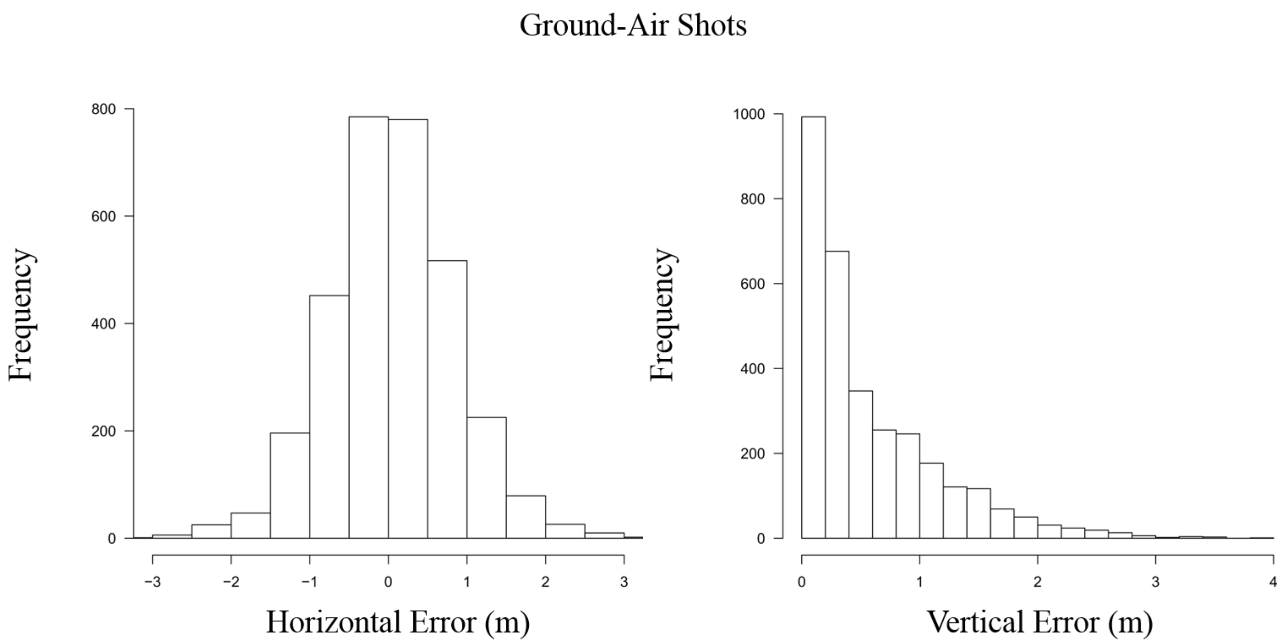

Figure A5.3: Frequency distributions of horizontal and vertical error for shots aimed at a target on the ground, and the shot goes in the air. Data was corrected for shooter footedness (all shooters are right-footed)

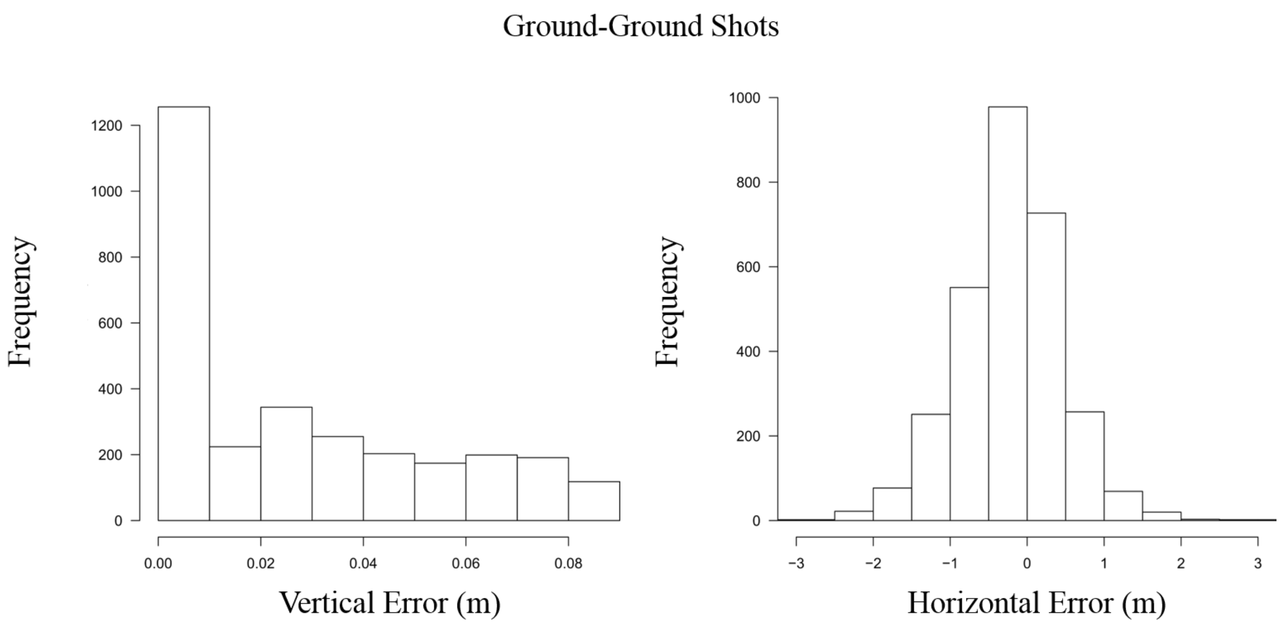

Figure A5.4: Frequency distributions of horizontal and vertical error for shots aimed at a target on the ground, and the shot goes along the ground. Data was corrected for shooter footedness (all shooters are right-footed)

We chose a generalised extreme value distribution to model horizontal error for Air-Ground shots (shots aimed in the air that go along the ground). When right-footed players miss below a high target, they tend to also miss to the left, with the opposite true for left-footed players (Chapter 2). However, with very little Air-Ground data we needed to make some assumptions about the likely distribution of horizontal error, and how this might change with target height. We assumed that for target heights close to the ground, horizontal error for shots that go on the ground are likely to be normally distributed, while for higher targets the distribution would be skewed (right-footed players missing to the left). To test this assumption, we grouped the Air-Air data by vertical error, then plotted the horizontal error of these groups (Figure A5.5). For shots that go close to the target in the vertical dimension (Figure A5.5A and A5.5B), horizontal error is normally distributed. However, when shots miss far below the target, the data is skewed (Figure A5.5E). This supported our assumption that for shots aimed in the air that go along the ground (Air-Ground), the shape of the horizontal error distribution likely changed across different target height. For targets close to the ground horizontal error is likely normally distributed, while a skewed distribution (dependent on shooter footedness) is likely for high targets. The generalised extreme value distribution allowed us to model this shift.

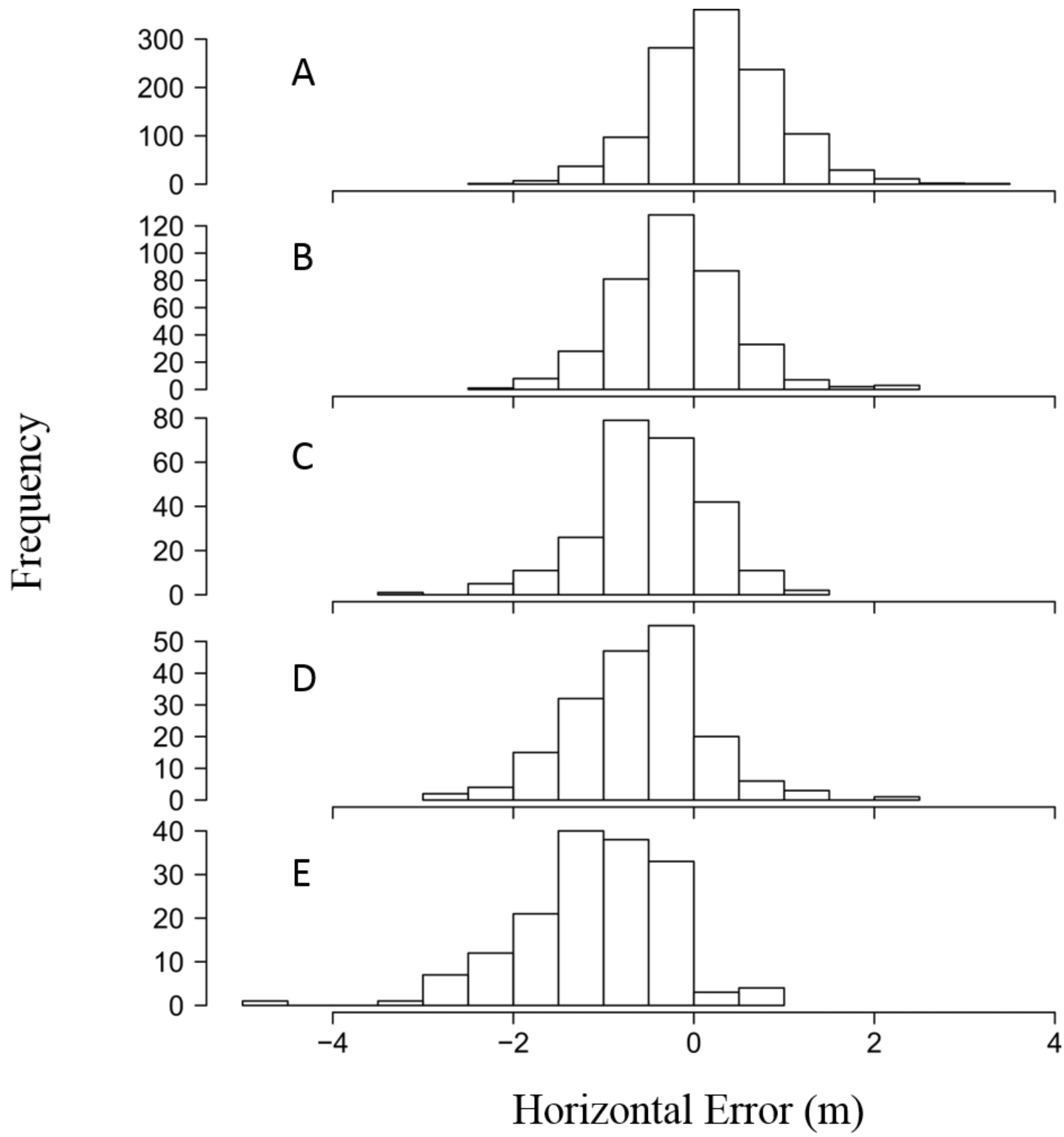

Figure A5.5: Frequency distributions of horizontal error for shots aimed in the air (y = 1.6 m) and the shot goes in the air. Data was first grouped by vertical error: **A)** shots above the target. **B)** shots between 0 m and 0.4 m below the target. **C)** shots between 0.4 m and 0.8 m below the target**. D)** shots between 0.8 m and 1.2 m below the target. **E)** shots between 1.2 m and 1.5 m below the target. Data was corrected for shooter footedness (all shooters are right-footed).

THE UNIVERSITY OF QUEENSLAND

Institutional Approval Form For Experiments On Humans Including Behavioural Research

Chief Investigator:	Mr Andrew Hunter
Project Title:	Can We Improve A Footballer's Kicking Performance Using Optimisation Theory?
Supervisor:	Dr Robbie Wilson
Co-Investigator(s)	None
Department(s):	School of Biological Sciences
Project Number:	2012001078
Granting Agency/Degree:	PhD
Duration:	30th June 2016

Comments:

Expedited Review - low risk.

Name of responsible Committee:-
Behavioural & Social Sciences Ethical Review Committee
This project complies with the provisions contained in the *National Statement on Ethical Conduct in Human Research* and complies with the regulations governing experimentation on humans.

Name of Ethics Committee representative:-
Associate Professor John McLean
Chairperson
Behavioural & Social Sciences Ethical Review Committee

Date 27/9/2012 Signature JMcL