

THE DYNAMICS OF PENALTY KICK SUCCESS: A LOGISTIC REGRESSION STUDY OF VELOCITY AND ANGLE IN LIGA 1 INDONESIA

Elang Aditya Putra^{1*}, Asril Pramutadi Andi Mustari², Galih Restu Fardian Suwandi¹

^{1, 2, 3} Department of Physics, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Jalan Ganesha No.10, Bandung 40116, Jawa Barat, Indonesia.
10222006@mahasiswa.itb.ac.id, pramutadi@itb.ac.id

Abstract

The successful execution of penalties takes an utmost significant position in any football match. It has both biomechanical and tactical complexities. Visualising from a physical lens, the velocity of the ball, the angle of the approach, and the placement of the shot directly impact the keeper's reaction time and anticipatory skill. This research examines 74 penalty kicks from Liga 1 Indonesia, during game week 30. This probabilistic model was developed using shot velocity and angle of approach towards the goal, and then visualised using a penalty kick scoring heat map and a velocity angle scatter diagram. The result indicated maximum penalty success rates mostly with shot velocities exceeding and shot angles of 5 to 10 degrees. The heat map demonstrated a distinct and overwhelming preference towards the goals' lower corners with the highest penalty shot success probability. Velocity and angle scatter concentration contours on the lower goal corners illustrated the shot's success. The final aim of this research was to prove the amount of scoring with the specific angles at which the shot was taken. The shot velocity and angle scatter plot indicated the keeper was unable to defend the shot with 25 degrees of elevation. This study suggests a highly nonlinear method for estimating shot placement success with respect to angle and velocity vectors. Thus, success from penalty kicks bears on both physical and strategic planning of how the shot will be taken.

Keywords: penalty kick, ball velocity, approach angle, shot placement, logistic regression.

DINAMIKA KEBERHASILAN TENDANGAN PENALTI: STUDI REGRESI LOGISTIK TERHADAP KECEPATAN DAN SUDUT DI LIGA 1 INDONESIA

Abstrak

Keberhasilan eksekusi penalti memegang peranan yang sangat penting dalam setiap pertandingan sepak bola. Hal ini melibatkan kompleksitas baik dari segi biomekanika maupun taktik. Ditinjau dari perspektif fisika, kecepatan bola, sudut awalan (pendekatan), dan penempatan arah tembakan berdampak langsung pada waktu reaksi serta kemampuanantisipasi penjaga gawang. Penelitian ini menganalisis 74 tendangan penalti dari Liga 1 Indonesia pada pekan ke-30. Model probabilistik dikembangkan menggunakan variabel kecepatan tembakan dan sudut awalan menuju gawang, kemudian divisualisasikan menggunakan *heat map* tingkat keberhasilan penalti dan *scatter plot* kecepatan-sudut. Hasil penelitian menunjukkan tingkat keberhasilan penalti tertinggi terutama terjadi pada tembakan dengan kecepatan tinggi dan sudut tembakan antara 5 hingga 10 derajat. Peta panas memperlihatkan preferensi yang jelas dan dominan terhadap sudut bawah gawang sebagai area dengan probabilitas keberhasilan tertinggi. Kontur konsentrasi sebaran kecepatan dan sudut pada sudut bawah gawang menggambarkan keberhasilan tembakan tersebut. Tujuan akhir penelitian ini adalah untuk membuktikan tingkat keberhasilan mencetak gol berdasarkan sudut spesifik saat tembakan dilakukan. Diagram sebar kecepatan dan sudut menunjukkan bahwa penjaga gawang tidak mampu menghalau tembakan dengan sudut elevasi 25 derajat. Studi ini mengusulkan metode yang sangat non-linear untuk

mengestimasi keberhasilan penempatan tembakan berdasarkan vektor sudut dan kecepatan. Dengan demikian, keberhasilan tendangan penalti bergantung pada perencanaan fisik maupun strategis mengenai bagaimana tembakan tersebut akan dieksekusi.

Kata kunci : tendangan penalti, kecepatan bola, sudut pendekatan, penempatan tembakan, regresi logistik

INTRODUCTION

One defining moment during a football match that can impact its outcome is a penalty kick. This singular action can, and often is, the defining moment of a match, and the event that shapes a team's success or failure. While the action of a penalty kick may appear trivial, there is a deep matrix of forces, motion dynamics, and even biomechanics woven into the process. Within that complexity, other factors play a role. For example, the attention, precision, and mental fortitude exercised by the kicker are only a part of the puzzle – equally vital is the split-second timing and strategic thinking the goalkeeper employs. In recent years, growing interest has emerged in applying physics-based models to better understand the mechanics of penalty kicks, particularly in relation to ball speed, kick angle, spin, and scoring probability.

The ball trajectory during a penalty kick can be modeled using Newton's second law, where acceleration is governed by the net force acting on the ball. Such a force is a result of the swing of the player's leg and their impact with the ball, whereby the leg swing and impact with the ball subsequently propel it linearly and at times even rotationally, moving it in the angular direction. This angular movement, in combination with airflow, triggers the Magnus effect, in which a ball curves in the air due to pressure differential, which allows the chances of outsmarting the goalkeeper to increase. As pointed out by Wesson (2002) and further elaborated in his book *The Science of Soccer* (2019), these fundamental principles can be used to quantify the conditions under which penalties are most likely to succeed (Wesson, 2002, 2019).

Speed is a critical parameter in penalty performance. Top-level football players can shoot the ball in less than 0.4 seconds when measured from the penalty area to the goal due to the 30m/s (108km/h) velocity achieved (Rachman & FARUK, 2020). This brief interval offers goalkeepers minimal time to react, forcing them to anticipate rather than respond. At such speeds, even a minor change in ball direction or spin—caused by the angle of football impact—can drastically alter the ball's final position.

Accuracy, on the other hand, is influenced by factors such as foot orientation, approach angle, body posture, and psychological pressure. Research conducted by Fariña et al. (2013) demonstrates how penalty kick takers expose spatial flaws in the movements of the goalkeeper by aiming the shot at the goal's bottom corners, which are more challenging to reach in a set reaction time (Fariña et al., 2013). Additionally, at spin or roll-induced yaw, a ball's movement may be subject to some attention forecasted by air drag, which, along with friction with a pitch surface at lower ball velocities, increases a motion's drag, though the influence is not significant. This particular study attempts to ascertain the relationship between the angle of approach and speed of the penalty kick and the scoring success of the kick using the logistic regression model. As opposed to other models available for this kind of binary analysis, given the threshold of a goal or a miss, goal scoring success or scoring a goal is a more elusive outcome, and the angle and speed approach does lend itself to a logistic regression analysis. The sigmoid nature of the logistic function makes it ideal for capturing nonlinear dependencies and threshold effects, which are common in sports scenarios involving rapid decision-making and execution (Hosmer Jr et al., 2013; LaValley, 2008).

Empirical data for this analysis were collected from Liga 1 Indonesia during gameweek 30, including shot locations, outcomes, estimated velocities, and angles. Visual instruments like heat maps and scatter plots allow you to discern objectives and performance distribution, along with certain patterns. With this in view, the research study intends to not only provide

scientific knowledge but also serve the players, coaches, and sports analysts with the practical value of enhanced techniques and strategies with respect to penalty kicks.

METHODS

The penalty kick in soccer can be explained using the principles of physics and probability. As stated in 'The Laws of the Game' by FIFA, a penalty is taken 11 metres from the goal, facing the goalkeeper only. The ball moves according to Newton's laws of motion, in which velocity depends on the force acting on the ball, its mass, and the impact angle. In most cases, additional spins through the Magnus effect impart curvatures to the ball because of differences in the quantity of pressure in the airflow on the body of the ball. All of these factors greatly affect the scoring percentage, which is why penalty kicks serve well to be the topics of such examinations.

This study employs Logistic Regression to quantify predicted probabilities of success given each physical amenity. These variables can take on probabilities between 0 and 1 due to the functionality of the Logistic model, which is well-suited for binary criteria such as scoring a goal or missing a goal. The logistic function takes an S-shaped curve that reflects the nonlinear way in which increases in velocity and optimal kicking angles improve the likelihood of scoring. The general model is expressed as:

$$P = \frac{1}{1 + e^{-z}}, \text{ with } z = \beta_0 + \beta_1 v + \beta_2 \theta \quad \dots(1)$$

where P represents the probability of scoring, v is the velocity of the shot, and θ is the approach angle, while β_0 , β_1 and β_2 are coefficients estimated through maximum likelihood.

The dataset for this study was obtained from Liga 1 Indonesia during gameweek 30, recorded from Live.lapangbola.com. In total, 74 penalty kicks were collected, of which 64 resulted in goals and 10 were missed. For each attempt, information was gathered on the outcome, the target area of the goal divided into a 3×3 grid, and the estimated values of shot velocity and angle.

Three steps were taken in the data analysis process. To determine which target zones were most commonly selected and most successful, a heat map was first created to show the objective distribution throughout the 3x3 grid. Second, in connection with shot speed, approach angle, and scoring opportunities, scatter plots were employed and found clusters of successful attempts under certain conditions, which countered other attempts under different conditions. To finally gauge the relationship between the three parameters and the outcome, a logistic regression model was used. The regression curve tells a story of its own; controlling the angles at which a shot is taken and the speed applied to the shot will significantly increase the chances of scoring. The scattered data and calculated data of mechanics and strategies of successful penalty kicks, combined with the physics of the world, which in turn is modelled mathematically, serve as the essence of the methodology used in the above example.

RESULTS AND DISCUSSION

Based on the data collected, there were 74 penalties just within the sampled duration, and 64 successful goals were recorded alongside 10 misses. This translates to an approximate 86.5% success rate, signifying that the players' prowess in scoring penalties was within the realm of adept. The relatively small number of missed attempts (13.5%) highlights the effectiveness of the penalty takers, though it also leaves room for analysis on the possible factors contributing to those missed opportunities, such as goalkeeper performance, shot

placement, or psychological pressure. Overall, this dataset provides a solid basis for evaluating penalty kick performance, identifying patterns in successful attempts, and exploring strategies to improve scoring efficiency in future scenarios.

Figure 1 depicts losses associated with successful penalty goals attained within the frame of the goal, in the breakdown of vertical and horizontal spatial fields. The goal is divided into 3x3 cells, each having 3x3 divisions that represent different ‘areas’. The lower part of the net is where the majority of the goals are located. The bottom left corner, which is the lowest left cell, has the highest recorded number of goals at 17, while the lower right corner, with 14 goals, is the second most. In contrast, central zones and upper corners, such as the top-center and top-right, show much fewer successful shots, with only 3 and 2 goals, respectively.

This pattern suggests that players tend to target lower corners, possibly due to reduced goalkeeper reach in those areas and a higher likelihood of accuracy at lower heights. The distribution also suggests a deliberate strategy among players to aim at locations that are more challenging for a goalkeeper to visualise and to save. This heat map provides data that offers insights into player targeting, including penalties and assists, as well as tactical training for both shooters and goalkeepers.

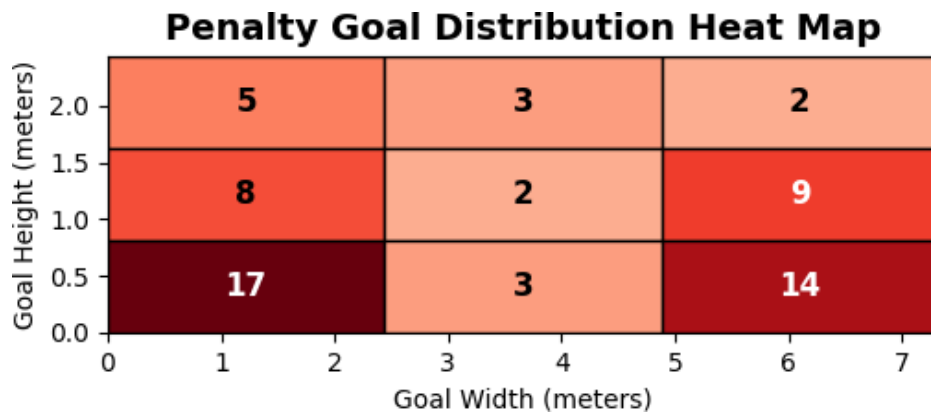


Figure 1. Penalty Goal Distribution Heat Map

Figure 2 scatter plot ‘coloured by success rate’ will analyse the relationship between success rates and shot velocity and approach angle towards a penalty shot. Each dot represents an individual shot, and its colour indicates success probability from low (purple) to high (yellow). An observable pattern indicates that the success rate for shots exceeding 25 m/s is significantly higher, provided the angle of approach is between 5 and 10 degrees. These shots are therefore classified as high velocity and low angle, and are predominantly yellow, indicating near-perfect success.

On the other hand, shots with lower velocity had lower success rates across the board, with the lowest success rates at higher angles (shots below 23 m/s). These areas with low chances of success (scoring) are indicated by lower colour ranges (green to purple) on the prediction models. This means that grace and angles with perpendicular thresholds tend to have low precision. The ease of anticipation and prediction of the directional flow of the ball by the goalkeepers is also a possibility. Overall, the graph reinforces the finding that optimal penalty performance is achieved with a balance of high velocity and a moderate, controlled approach angle.

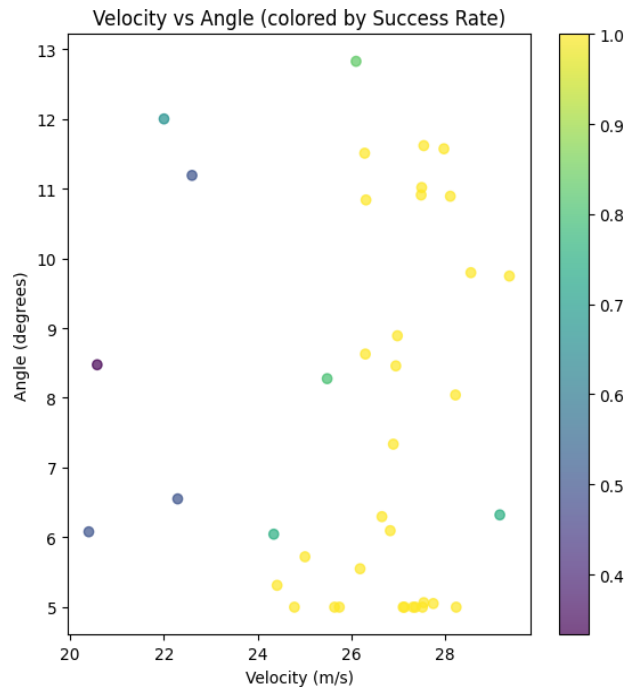


Figure 2. Velocity vs Angle Success Rate

From the graph (Figure 3), the predictor variable (Standardised Z-Score) and the predicted probability of success have an S-shaped relationship, which the Z-Score's Logistic Regression Curve illustrates. The logistic function, which shows how the blue line represents the likelihood of success, increases. The blue curve is closely fitted by the datapoints illustrated by red dots, which demonstrate a good model fit.

This plot demonstrates a core principle of logistic regression: probabilities transition smoothly from 0 to 1 as the input variable increases. At a Z-score of around 0, the model predicts a 50% chance of success, with probabilities increasing above 0.5 for positive Z-scores and decreasing below 0.5 for negative ones. The proximity of the data points and the curve demonstrates that the logistic regression is valid and not spurious. Its relationship with the predictor and the binary outcome sustains the argument for the logistic regression analysis in predicting the outcome of the success of penalties with respect to the performance factors.

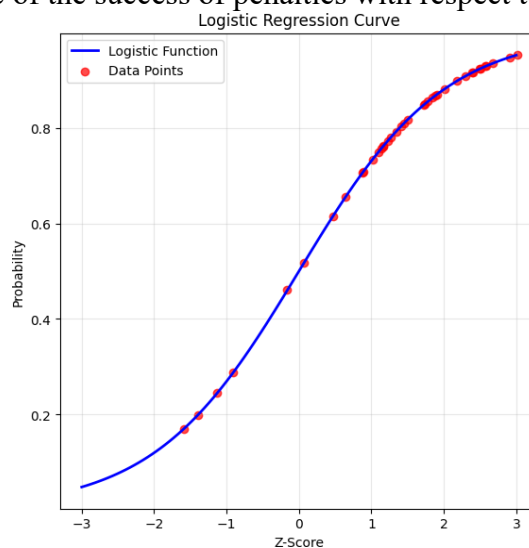


Figure 3. Logistic Regression Curve

Analysing 74 penalty kicks in Liga 1 also provides evidence that scoring chances stem from the spatial position and the velocity of the kicked ball. Figure 1 shows that most successful penalties taken were aimed at the lower corners of the goal. This suggests that players aim their shots at the corners, which would be more difficult for goalkeepers to reach, which confirms the findings of Evaluating the Effectiveness of Penalty Kicks in Soccer (Schaflechner et al., 2024), where it was demonstrated that shots that are low and fast tend to be the most successful.

There was also a shot velocity which appeared to be another important factor in successful penalties. Figure 2 shows that for kicks of over 25 m/s, accompanied by an approach angle of 5-10°, the success probabilities are significantly high. This supports the Optimum Strategy in Penalty Kicks (Zhou & Inomata, 2009), which illustrates a balance in power and placement of kicks. On the other hand, slower kicks at steeper angles showed more variation in success and are an illustration of the predictable nature and over-anticipation from the goalkeeper. The importance of psychological and perceptual considerations should not be overlooked. While goal frequency was most dominant in the lower-left and lower-right zones, some attempts in these zones also crossed the ‘missed’ threshold (Figure 1), suggesting that, under pressure, there is a more fundamental execution-evaluation process that can vaporise strategic options. The same contention was made in Einflussfaktoren auf den Erfolg von Strafstoßen im Fußball (Noël et al., 2015), where the relevance of the situation pressure on the outcome of the penalty was the main focus. Also, in Penalty Kicks in Soccer: An Empirical Analysis of Strategy and Success (Bar-Eli & Azar, 2009), the emphasis was placed on how the score and the importance of the match influence the decision and execution of the shot.

Figure 3, which displays a significant nonlinear relationship between the predictor variables and scoring probability, demonstrates the predictive capability of our logistic regression model. The logistic curve's strong fit to the observed data supports the applicability of logistic regression for simulating binary outcomes in sports. This is consistent with recent developments in sports analytics, where logistic regression is increasingly being used to assess performance indicators in dynamic and unpredictable circumstances.

While training innovations offer a more profound understanding that's complementary, it's Not All About Power: Improving Penalty Kick Performance Using Augmented Reality (Bloechle et al., 2024) proved that simulation-based training tends to enhance decision-making and execution under tension. This correlates with our finding in Figure 2 that accuracy at moderate angles is no less critical than sheer power. From the goalkeeper's vantage point, Mastering the Art of Saving Penalty Kicks (Annes et al., 2024) clarified the importance of anticipation, since purely reactive movements at those speeds are insufficient. This accounts for why, in our dataset, the fastest shots were the most untouchable and, thus, poorly saved.

The combination of physics-based modelling with contextual and psychological reasoning suggests that penalty kicks are, indeed, multilayered. Our figures illustrate how quantitative relationships complement previous work, while situational and perceptual factors highlight gaps for further interdisciplinary inquiry. There is practical value in these findings for coaches and players in designing training that goes beyond the fundamental elements of speed and placement to include psychological resilience and deception.

CONCLUSION

This study examines how performance metrics—approach speed, kick angle, and ball velocity—interact with and influence the probability of success in penalty kicks using logistic regression modeling. The reconfirmed logistic regression curve demonstrates a similar nonlinear relationship, showing that speed and optimum angle values lead to a greater probability of success. Players able to generate high velocity and moderate angle shots to the target, as shown in the velocity-angle scatter plot, consistently reach the best success rates.

Furthermore, the distribution of goals using the heat map shows a strong tendency to aim at the lower corners, where chances of scoring are maximised.

In conclusion, the biomechanical model and the shot placement strategy combined prove to be vital in determining the performance of penalties. Coaches can enhance training by focusing on the optimal physical and goal zone tactical approaches to be able to approach at high speed, maintain ball control and aim at the target. These insights together suggest that logistic regression offers a useful technique to analyse success factors in penalties and serves them in a granular way.

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