Making the Unpredictable Shot More Predictable: Testing the Effect Panelling and Construction Has on the Predictability of Soccer Ball Flight

Dani Halbing
Department of Physics, The College of Wooster, Wooster, Ohio 44691, USA
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The predictability of flight of the Adidas Conext15, Adidas Jabulani, Nike Incyte, and Nike Ordem match balls were analyzed. Three trials of each of the four balls in the knuckleball state were video recorded for the investigation. Each of the videos were uploaded to Tracker in order to collect data on the spin, velocity, initial position, and final position of each of the trials. The data from the initial five frames of each trial was then used to create a theoretical final position of the ball using a radius of curvature equation. This theoretical final position was then compared it to the measured final position of the ball in order to see how much the ball had deviated from the theoretical flight path. This deviation was then used as the metric for unpredictability in the scope of this investigation. The balls were only analyzed in the x-direction, as the goalkeepers that had criticized the Jabulani at the 2010 World Cup mostly complained about the erratic lateral movement of the ball. It was ultimately found that the Nike Ordem had the most predictable flight with an average deviation of 0.20 ± 0.05 m, the Adidas Conext15 was the second most predictable with an average deviation of 0.26 ± 0.03 m, the Nike Incyte was the third most predictable with an average deviation of 0.40 ± 0.18 m, and the far outlier was the Adidas Jabulani with an average deviation of 1.23 ± 0.10 m. It was expected that the Jabulani would deviate the most; however the magnitude of the average deviation for the Jabulani was fairly shocking as it equated to approximately 17% of the length of the whole goal line.

I. INTRODUCTION

The construction of soccer balls and their panelling has come to the forefront of discussion in sports science ever since the 2006 FIFA World Cup. Adidas has been the official match ball supplier of the World Cup since 1970, and in 2006 the German company made a bold step by creating the first ever completely stitch-less match ball for the 2006 World Cup. The 2006 World Cup ball, known as the "+Teamgeist", was constructed of 14 thermally bonded panels instead of the traditional 32 stitched panel soccer ball, and garnered great attention for having what many called the "truest and most predictable flight" that any soccer ball had ever had [1]. Adidas planned to capitalize on this momentum when they created their second stitch-less match ball for the 2010 World Cup, called the Jabulani. The Jabulani consisted of just 8 panels that were once again thermally bonded; however as opposed to the +Teamgeist which had a completely smooth surface, the Jabulani had a series of grooves covering the entire surface of the ball. The Jabulani seemed to experience the unpredictable knuckleball effect more than any other match ball before it, and many believed it was due to its lack of seams and the added grooves on the surface of the ball. The knuckleball effect is when a ball is shot with very little spin, which would in theory produce a completely straight shot, yet the ball will move side-to-side in seemingly random ways due to changes in airflow around the ball [9]. Many goalies complained that the ball gave strikers an unfair advantage, and some even claimed that the ball was ruining the game of soccer due to the unpredictable lateral movement of the ball [2]. Ever since the Jabulani made its debut, considerable research and money has gone into developing a better and more predictable soccer ball to combat this issue of unfairness between the goalies and strikers. The investment in research has been especially true for the two major soccer equipment suppliers; Adidas and Nike.

The aim of this project is to analyze the flight of four different match balls in order to find which ball has the most predictable and stable flight. Two of the four balls analyzed in this project are Adidas balls, namely the aforementioned Adidas Jabulani (2010) and the Adidas Conext15 (2015). The Jabulani is one of the most controversial soccer balls ever and the Conext15 was its direct successor in terms of Adidas soccer ball construction. By choosing the direct successor of the most controversial ball ever, the goal is to see how the Conext15 performs and to evaluate whether or not the changes Adidas made following the Jabulani were effective. The other two balls that will be analyzed are the thermally bonded Nike Ordem (2013) and the stitched Nike Incyte (2014). These two balls were chosen because Nike made the somewhat odd decision to go back to stitching match balls with the Incyte in 2014 when they had already been thermally bonding match balls with the Ordem in 2013. Nike and Adidas now only thermally bond their match balls, but this decision by Nike to revert back to the old methods in 2014 was intriguing. Therefore, the purpose behind choosing these two Nike balls is to see whether or not thermal bonding the seams provides a more stable and predictable flight than stitching the seams.

Generally smooth and spherical objects tend to experience two types of airflow when in flight; turbulent and laminar airflow. Turbulent airflow occurs when there are changes in pressure and flow velocity around the ball, which generally is the most predominant airflow on curved shots in soccer [3]. Laminar airflow, on the

other hand, occurs when air flows past the ball in smooth parallel lines with no mixing [4]. The knuckleball effect occurs when turbulent flow transitions to laminar flow, and the deviation in motion at this transition is largely based on the roughness of the object or sphere in flight [5]. Therefore, it is expected that the Jabulani will be the least predictable in the knuckleball phase since it has the roughest surface, the Ordem will be the most predictable because it has a fairly smooth surface, the Conext15 will be the second most predictable since it has a relatively smooth surface, and the Incyte will be somewhere in the middle in terms of deviation but no where near the Jabulani since its surface is rough compared to the other two balls but compared to the Jabulani is still relatively smooth.

In order to analyze predictability in flight, initial data from a kick of a given ball will be used to create a theoretical flight path using radius of curvature and displacement equations. The theoretical displacement of the ball will then be compared to the actual displacement of the ball for each kick and the difference will then be averaged for each ball. The ball with the least amount of deviation from the theoretical flight path/landing place of the ball will be deemed as the most predictable ball in the scope of this study.

II. THEORY

In order to determine which ball has the most predictable flight, an equation which allows a theoretical or expected flight path to be produced has to be derived. If the forces on the ball throughout the entire flight of the ball were to be analyzed, then a differential equation which models the motion of the ball during the entire flight period would have to be created. However, such an equation is actually unnecessary since the only thing that truly matters in the scope of a soccer game is whether or not a ball lands where it is expected to based on a initial information provided by the kick of the ball. If the ball goes lands it is expected to, then both goalies and strikers can agree that the ball is predictable and in turn also fair. Therefore, only an equation that calculates where the ball will finally land has to be derived. Since the main complaint of the goalies was the unpredictable lateral movement of the Jabulani when in flight, each of the balls will be analyzed solely in the x-direction.

In order to predict the final landing spot of the ball in the x-direction, the initial forces on the ball have to be broken down. The flight of a ball with initial velocity v_i is shown in Fig. **??**. Using the setup shown in Fig. **??** and Newton's second law, the acceleration a of the side force on the ball is

$$a = \frac{F}{m}, \tag{1}$$

where F is the magnitude of the force of a spinning ball and m is the mass of the ball. If vertical drag on the ball

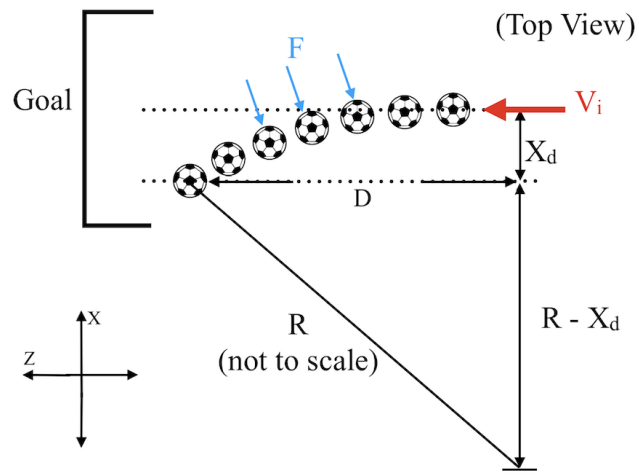

FIG. 1: Diagram depicting on overhead view of the flight of a ball with initial velocity v_i and force F of a spinning ball acting upon it. The diagram also shows the radius of curvature of the ball's flight R, the distance between the initial plane and final plane in the z-direction D, and the displacement in the x-direction X_d. Figure adapted from reference [8].

is neglected, then the radius of curvature of the ball's flight is

$$R = \frac{{v_i}^2}{a}, \tag{2}$$

where v_i is the initial velocity of the ball following the kick. The radius of curvature R can then be rewritten using Eqn. 1, becoming

$$R = \frac{m{v_i}^2}{F}. \tag{3}$$

The force on a spinning ball is dependent on the aerodynamic forces acting on the ball, and the magnitude of the force is

$$F = \frac{4}{3} C_l (4\pi^2 r s v_i b^3), \tag{4}$$

where r is the density of the air, s is the spin of the ball, and b is the radius of the ball [8]. The coefficient of lift C_l of a ball is

$$C_l = \frac{L}{2r{v_i}^2 \pi b^2}, \tag{5}$$

where L is the lift on the ball defined as

$$L = \frac{4}{3} v_i r (4b^3 \pi^2 s). \tag{6}$$

The formula for the lift L from Eqn. 6 can then be inserted into Eqn. 5 yielding

$$C_l = \frac{8\pi b s}{3 v_i}, \tag{7}$$

which represents the complete formula for the lift coefficient [6, 7]. Inserting F from Eqn. 4 into Eqn. 3, R then becomes

$$R = \frac{3mv_i}{16C_l\pi^2 rsb^3}. \tag{8}$$

Now that R can be calculated and the distance D between the initial and final planes of the ball in the z-direction can be directly measured, the displacement of the ball in the x-direction X_d can be derived using Pythagorean's Theorem. As depicted in Fig. 1, a right triangle is formed between R, D, and $R - X_d$. Therefore, applying Pythagorean's Theorem to the triangle, the relation becomes:

$$R^2 = D^2 + (R - X_d)^2. \tag{9}$$

In order to derive an equation for the displacement of the ball in the x-direction, algebra has to be done to isolate the expression for X_d to one side of the equation:

$$R^2 - D^2 = (R - X_d)^2. \tag{10}$$

Algebra can then be done to the relation until the final equation for the displacement of the ball in the x-direction becomes

$$X_d = R - \sqrt{R^2 - D^2}. \tag{11}$$

Therefore, by calculating the theoretical radius of curvature of the ball using initial points of data immediately following the kick of the ball as well as measuring the distance of the kick in the z-direction, the theoretical displacement of the ball in the x-direction can be calculated [8]. The difference between the measured displacement X_m and the theoretical displacement in the x-direction X_d can then be calculated to find the deviation of the ball from the expected landing spot:

$$X_s = |X_d - X_m|. \tag{12}$$

The deviations from the expected landing spot X_s will then be calculated for each recorded kick and then averaged for each ball to find which ball is the most predictable.

III. PROCEDURE

A. Experimental Setup

The experimental setup was designed in a way that would allow for the dimensions of the goal and field lines to act as markers when using a tracking software to analyze data after recording videos. The configurations regarding the goal, camera, and ball can be seen in Fig. 2. The ball was consistently shot from the top of the semi-circle which sits on top of the goalie box, as it was known that the distance from this spot to the goal line would always be 20.15 m. In initial test trials, the ball was shot from the center of the top of the goalie box which is 16.5 m away from the goal. This initial test spot, however, did not allow the ball enough space to exhibit the knuckleball effect in the knuckleball trials. Therefore, the shot spot was moved back to the top of the semi-circle in order to allow the balls to exhibit the desired knuckleball effect but still also have an easy-to-locate marker of where the shot would be taken with a consistent distance. The camera was setup one meter behind the initial position of the ball so that the separation of the camera to the ball was not too large, as this could have effected the tracking software when analyzing data. The camera was also elevated to 0.5 m above the ground in order to avoid having the ball be covered by the kicking foot in the initial frames of the video.

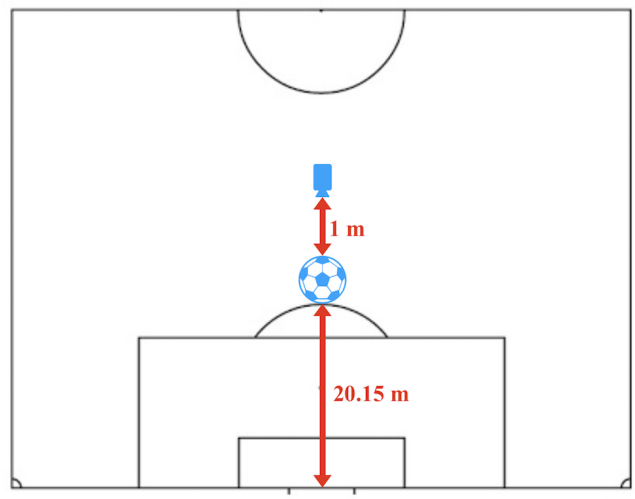

FIG. 2: Diagram of the experimental setup for each shot. The blue soccer ball represents the point at which each shot was taken from and the blue video camera represents where the camera was stationed. The camera was also elevated at a height of 0.5 m off of the ground. The diagram is not to scale.

B. Knuckleball Procedure

The knuckleball was the desired shot in this experiment because the knuckleball is the most unpredictable shot in soccer. No matter which ball is used, if it is shot using the knuckleball technique, its flight will be unpredictable compared to that of a curled shot. Therefore, by testing exactly how much each ball deviated from the predicted final location during a knuckleball, the magnitude of each of the ball's unpredictability could be compared.

In order to draw an accurate comparison, each of the trials had to be the same in terms of control variables. Therefore, each of the balls was pumped up to an air pressure of approximately 12 PSI, as this is the middle value of the allowed air pressure range that FIFA lists on

its quality standards for match balls. The balls were also always shot in the same experimental setup, as mentioned in the previous subsection. There was inherent variation amongst the balls, however, as the two Nike balls weighed around 0.430 kg whereas the two Adidas balls weighed approximately 0.440 kg. Although 0.010 kg is not a great difference, it is worth noting that the two companies seem to have different weight standards for their match balls.

For each of the four balls, three knuckleball shots were recorded using the video camera. Ideally, five to six shots would have been taken for each ball. However the knuckleball is a fairly difficult technique to hit consistently so the number of knuckleball shots per ball was set at three in order to allow for enough data to be collected to make an average while still collecting data for all four balls. After all the desired knuckleball shots were collected, the videos were uploaded to the Tracker Software in order to analyze the data.

C. Data Analysis Using Tracker

In order to analyze the data from each shot, the Tracker software was downloaded from the internet. Tracker allows for objects in a video to be tracked as each of the frames of the video progresses. The software then calculates a number of outputs, such as the distance the object travels or the velocity the object was traveling at. For the purposes of this experiment, the center of the ball was treated as a point mass and was used to track the ball's flight.

In order to get accurate data out of tracker, the video must first be calibrated. As shown in Fig. 3, the posts of the goal were used as reference points for the calibration. This is because the goal posts were measured to be exactly 7.32 m apart, and therefore they provided a consistent point of reference in the x-direction. The right post was set at a distance of 3.66 m where as the left post was set at a distance of -3.66 m so that the center of the goal would represent the origin in the x-direction. Furthermore in Fig. 3, the axes were purposefully aligned with the initial direction of the shot. This is because, as shown in Fig. 1, in order for the equations in the theory section to apply to the data, the initial velocity vector has to be aligned perpendicular to the x-axis.

After calibrating tracker appropriately, the center of the ball has to be selected in each frame in order to produce a flight path. Tracker has an autotracker feature which can select the object that is being analyzed and automatically track it through each frame of the video. While this is a useful feature in concept, it is not very useful in this situation as tracker had issues locating the center of the ball when autotracking. Therefore, the center of the ball was manually selected in each of the frames of each of the videos in order to provide the most accurate results. In Fig. 3, the final tracked flight path of a shot can be seen represented by a thin yellow line.

After the ball was sufficiently tracked throughout the entire length of the video, it was important to only select the relevant data to be calculated by Tracker. The relevant data for the purposes of this experiment were the displacement in the x-direction, the velocity in the x-direction, and the angular velocity which was used for the spin. After these two sets of data were collected, the data for the first five frames of each video was used to calculate the theoretical displacement in the x-direction using the relevant equations from the theory section. The initial position of the ball on the x-axis was then subtracted from the final position of the ball in the x-axis to calculate the total measured displacement of the ball in the x-direction. The theoretical and measured x-direction displacements were then put into Eqn. 12 to calculate the deviation from the expected final location of each shot. The deviations from the expected location were then averaged to find the average deviation for each ball.

FIG. 3: Snapshot of the calibration and setup for a shot analyzed on the Tracker Software. The red crosshairs at the top of each of the posts represent the calibration points, the purple lines are the axes, and the thin yellow line is the flight path that the ball takes after it is kicked.

IV. RESULTS

For each of the three shots of each of four balls, the radius of curvature was calculated as well as the theoretical and measured final displacement of the ball in the x-direction. As shown in Table I, these values were then used to calculate the deviation for each ball from the theoretical final position in the x-direction. The radius of curvature was calculated by using the angular velocity and velocity data from Tracker in Eqn. 8. After the radius of curvature was calculated, it could then be used in Eqn. 11 along with the measured distance between the initial and final planes in the z-axis D to

TABLE I: Theoretical and measured final displacement in the X-Direction for each shot for each of the four balls. R is the theoretical radius of curvature, X_d is the theoretical x-axis displacement, X_m is the measured x-axis displacement, and X_s is the deviation of the measured final position from theoretical final position.

Ball	R (m)	X_d (m)	X_m (m)	X_s (m)
Conext15	645	0.50	0.73	0.23
Conext15	240	0.85	1.12	0.28
Conext15	127	1.60	1.33	0.28
Jabulani	124	1.65	2.93	1.28
Jabulani	1070	0.19	1.30	1.11
Jabulani	61.7	3.38	2.09	1.29
Incyte	307	0.66	1.23	0.57
Incyte	203	1.00	1.22	0.22
Incyte	251	0.81	1.22	0.41
Ordem	336	0.60	0.85	0.24
Ordem	202	1.01	1.15	0.14
Ordem	118	1.74	1.96	0.22

calculate X_d. The data x-position data from tracker was then used to calculate the measured displacement of the ball X_m. Once these two values were calculated, the deviation of the measured displacement from the theoretical displacement could then finally be calculated using Eqn. 12, which yielded the desired deviation value X_s. The three values of X_s for each ball were then averaged and are shown in Table II.

The average deviation of the measured final position from the theoretical final position of the ball for all four balls is shown in Table II. This average deviation value represents the "unpredictability metric" of each ball in the scope of this investigation. While the Adidas Conext15, the Nike Incyte, and the Nike Ordem were all within 0.2 m average deviation of each other, the Adidas Jabulani was a clear outlier. This was expected, since the Jabulani has the roughest surface area of all of the balls used in this investigation. While it was expected that the Jabulani would have the greatest average deviation, the magnitude of average deviation is fairly shocking. The Jabulani deviated from the theoretical flight path on average by 1.23 ± 0.10 m, which is a significant distance. For a goalkeeper, 1.23 m is the difference between a ball flying straight into their hands and them having to make a diving save.

The rest of the balls also followed the expected trend, as the Nike Ordem had the smoothest surface area and deviated the least from the theoretical final position with an average of 0.20 ± 0.05 m. The Adidas Conext15 also did not deviate much from the expected final position. The Conext15 was expected to deviate the second least, however it was not expected to be so close of a second to the Ordem as it only deviated by 0.26 ± 0.03 m. Lastly, the Nike Incyte was fairly middle-of-the-pack in terms of average deviation with a value of 0.40 ± 0.18 m which also followed the expected trend.

TABLE II: Average deviation of the measured final position from the theoretical final position for each of the four balls. The error corresponds to the standard deviation of the data values for each ball.

Ball	Average X_s (m)
Conext15	0.26 ± 0.03
Jabulani	1.23 ± 0.10
Incyte	0.40 ± 0.18
Ordem	0.20 ± 0.05

V. CONCLUSION

In this investigation, the flight of the Adidas Conext15, Adidas Jabulani, Nike Incyte, and Nike Ordem match balls were analyzed. Three shots of each of the four balls in the knuckleball state were analyzed. The balls were only analyzed in the x-direction, as the goalkeepers that had criticized the Jabulani's erratic movement at the 2010 World Cup mostly only complained about the lateral movement of the ball. A theoretical final x-axis position was calculated for each of the shots and a measured final x-axis was also produced using the Tracker software. It was ultimately found that the Nike Ordem had the most predictable flight with an average deviation of 0.20 ± 0.05 m, the Adidas Conext15 was the second most predictable with an average deviation of 0.26 ± 0.03 m, the Nike Incyte was the third most predictable with an average deviation of 0.40 ± 0.18 m, and the far outlier was the Adidas Jabulani with an average deviation of 1.23 ± 0.10 m.

While it was no surprise that the Adidas Jabulani would deviate the most, the average magnitude of the Jabulani's deviation was fairly shocking. The Jabulani's average deviation equates to approximately 17% of the length of the goal line. That is an incredibly significant amount as it is the difference between the goalie making a comfortable catching save and the goalie having to make a diving save to claw a ball out of the corner. This distance is not necessarily the amount the Jabulani deviates at the last moment before reaching the goal, it is the distance it deviates from the initial expected flight path to the end of the flight path. The goalie can take this flight time to track the ball and react to the unpredictability and therefore the effect of the deviation of the ball on the game is not as great as the number makes it seem. However, it is telling how much the Jabulani deviates on average compared to the other balls.

It was expected that the smoother the surface of the balls were, the more predictable they would be because they were less inclined to have large changes in airflow while in the knuckleball state. The surface of each of the balls is pictured in Fig. 4. As shown in Fig. 4.A, the

FIG. 4: Pictures of the surface of each of the four balls that were investigated. The balls are denoted by the letter in the top left corner of the picture and go as follows: A) Adidas Jabulani, B) Adidas Conext15, C) Nike Ordem, D) Nike Incyte.

Jabulani has small embossed lines on the surface of the ball which leads to a very rough surface. This is contrasted directly with the surface of the Ordem, pictured in Fig. 4.C, as the Ordem has an incredibly smooth surface. It therefore makes sense that the Jabulani deviated the most from the expected flight path and that the Ordem deviated the least.

It is also interesting to note the effect of stitching on the unpredictability of the ball when in the knuckleball state. For instance, the Adidas Conext15 and the Nike Incyte have very similar surface roughnesses on the panels of the ball, as shown in Fig. 4.B and Fig. 4.D. However, the two acted differently in terms of predictability as the Conext15 had an average deviation of 0.26 ± 0.03 m compared to 0.40 ± 0.18 m of the Nike Incyte. A possible explanation for this difference is that the Nike Incyte is a stitched ball, which means that the seams are deeper and more pronounced compared to the Adidas Conext15+, which is a thermally bonded ball. Based off of this comparison, it seems that thermally bonded balls due tend to have a more predictable flight. This makes sense with the direction that the industry has gone in since these four balls were produced, as now all match balls are thermally bonded and there are no more stitched match balls.

A comparison of the deviation of all four balls is shown graphically in Fig. 5. The comparison in Fig. 5 shows

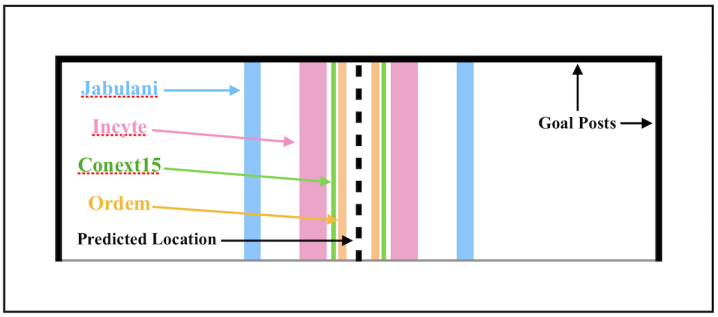

FIG. 5: Diagram of the average deviation in the x-direction of the four balls tested in the context of a soccer goal. The colored spaces represent where a given ball would deviate to if it were shot with a straight trajectory with a theoretical landing place along the black dotted line. The blue spaces represent the Adidas Jabulani, the pink spaces represent the Nike Incyte, the green spaces represent the Adidas Conext15, and the orange spaces represent the Nike Ordem.

just how much of an outlier the Jabulani is, as the other three balls would land fairly close to each other in the goal. The Nike Incyte had the greatest error associated with it, as shown by the widest possible landing space in Fig. 5. It is interesting to note that the two balls with the least amount of deviation, the Nike Ordem and the Adidas Conext15, also had the smallest uncertainty of all the balls. This meant that these two balls not only deviated by the smallest amount, but were also the most consistent in their deviation.

Based on the findings, it would seem that the smoother the ball, the more predictable the flight becomes. This raises the question, why do companies not try to make soccer balls completely smooth? Making a ball a perfect sphere and perfectly smooth makes sense when only looking at flight mechanics. However part of the game of soccer is also how the ball responds to the foot. Without any embossed features on the ball, there is very little friction between the cleat and the ball, especially when it rains, and this can make dribbling problematic. Therefore, the challenge is to find a perfect mixture of surface roughness and smoothness so that the ball is predictable in flight, but also does not slip off of the foot easily.

There were several potential sources of error in this experiment as it was generally very difficult to control the environment around the ball. For instance, the wind would often change intensities as recording occurred. This potential source of error was minimized by waiting for gusts of wind to pass, but it brings up the issue that the air conditions can never truly be controlled in an open field. Therefore, to get more truly characteristic results, one solution could be to perform the tests in an indoor facility where the air pressure, wind, and other air parameters can be controlled.

Another potential source of error is that most match balls are constructed in a way so that they only reliably hold air for up to two hours. The data recording session

lasted about three and a half hours, and the balls were pumped up again at the two hour mark, but it is difficult to say exactly what the air pressure of the balls were at all times since they were continuously deflating. This certainly affected the coefficient of lift calculation. One way to reduce this error would be to check the air pressure of every ball after every shot, but due to time constraints this was not a feasible option for this investigation.

For further research, it would be interesting to see how the weather conditions, such as rain or snow, affect the predictability of these four balls. It would also be interesting to see how a completely smooth soccer ball would behave in the low-spin knuckleball state, and if it would even knuckle at all.

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