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A Comparison of Jabulani and Brazuca Non-Spin Aerodynamics

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Abstract
We present wind-tunnel experimental measurements of drag coefficients for non-spinning Jabulani and Brazuca balls. We find that the Brazuca ball's critical speed is smaller than that of the Jabulani ball, and the Brazuca ball's super-critical drag coefficient is larger than that of the Jabulani ball. We also find that compared to the Jabulani ball, the Brazuca ball suffers less instability due to knuckle-ball effects. Using our drag data, we create numerically-determined ball trajectories and postulate that though power shots are too similar to notice flight differences, goal keepers are likely to notice differences between Jabulani and Brazuca ball trajectories for intermediate-speed ranges. This latter result may appear in the 2014 World Cup for goal keepers used to the flight of the ball used in the 2010 World Cup.

Keywords
Jabulani, Brazuca, football, soccer, aerodynamics, drag coefficient, wind tunnel, computational modeling, knuckle-ball

1. Introduction

Much of the world is riveted by FIFA World Cup action, which takes place every four years. Since 1970, Adidas has provided the ball used at the World Cup. The 2002 World Cup in Japan and South Korean used the Fevernova ball, the last World Cup ball with the more traditional 32-panel design consisting of 20 hexagonal panels and 12 pentagonal panels (similar to a truncated icosahedron). The 2006 World Cup in Germany used a thermally-bonded 14-panel ball called the Teamgeist. Adidas created the Jabulani ball for the 2010 World Cup in South Africa, a ball that experienced some controversy.[1] Having just eight thermally-bonded panels, Adidas had to texture the surface to make up for a reduced number of seams. As balls get smoother, they experience more air drag at certain speeds.[2] By continually reducing panel number, Adidas had to add panel roughness if balls were to follow similar trajectories that previous balls followed. For the 2014 World Cup in Brazil, Adidas created the Brazuca ball, which has just six thermally-bonded panels. Because of so few panels, the ball, like the

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Jabulani ball, has been textured to increase surface roughness. Despite fewer panels, the Brazuca ball has nearly 68% longer total seam length

We report in this paper results of wind-tunnel experiments on balls used at the two most recent World Cup events. We use our wind-tunnel results to create model trajectories that will show how differences in aerodynamic properties lead to differences in flight trajectories. Soccer, perhaps more than any other sport due to its global popularity, has been studied extensively by scientists and engineers for a few decades now. Our work here adds to that large body of work. To keep this introductory section concise, we refer readers to a recent review article[3] on sport aerodynamics. That article contains a section on soccer with copious references to aerodynamics research performed mostly in the current century. Since that review article was accepted, more research has been published[4,5,6,7] that has furthered our understanding of soccer aerodynamics.

This paper is organized as follows. We describe our wind-tunnel experiment in Section 2, and then discuss the results of that experiment in Section 3. The numerical trajectories we created based on our wind-tunnel results are presented in Section 4, followed by some concluding remarks in Section 5.

2. Wind-Tunnel Experiment

We measured the aerodynamic forces acting on different types of balls in a low-speed wind tunnel at the University of Tsukuba that has a $1.5\,\mathrm{m} \times 1.5\,\mathrm{m}$ rectangular cross section with a turbulence level less than 0.1%. Two full-sized official FIFA soccer balls were tested: the Adidas Jabulani (0.22-m diameter and 0.438-kg mass), used in South Africa for the 2010 FIFA World Cup, and the Adidas Brazuca (0.22-m diameter and 0.433-kg mass), used in Brazil for the 2014 FIFA World Cup.

Each soccer ball was attached to a stainless steel rod. Figure 1 shows the Brazuca ball on the rod just before testing began. The position of the support rod relative to the bluff body is important in a wind-tunnel experiment, which means that we had to select an appropriate support orientation. For our experiments we chose to support from the rear,[8] a location we considered to have a comparatively smaller effect on the peeling off of the boundary layer from the ball's surface. Data were acquired over a period of 8.192 s using a six-component sting-type balance (LMC-6522; Nissho Electric Works Co., Ltd.), and they were recorded on a personal computer using an A/D converter board with a sampling rate of 1000 Hz. Each ball was set to be geometrically symmetrical; the ball panels were therefore asymmetrical in the vertical direction.

The aerodynamic forces were measured at wind speeds in the range $7\,\mathrm{m/s} \leq v \leq 35\,\mathrm{m/s}$ ($15.7\,\mathrm{mph} \leq v \leq 78.3\,\mathrm{mph}$). That speed range corresponds to a range in Reynolds number of roughly $100,000 < \mathrm{Re} < 500,000$. The force acting in the direction opposite to that of the wind was is the measured force we connect to the drag force. Because the ball feels no net force, the force from the rod on the ball matches the drag force, F_D, the ball feels from the oncoming air. The drag coefficient, C_D, is then extracted from the following equation:

$$F_D = \frac{1}{2}\,\rho\,A\,C_D\,v^2\,, \tag{1}$$

where $A = 0.038\,\mathrm{m}^2$ is the cross-sectional area of the ball and $\rho = 1.2\,\mathrm{kg/m}^3$ is the air's mass density.

We also studied effects that lead to knuckle-ball[9] phenomenon whereby a ball with little to no spin experiences forces perpendicular to its velocity that are due to an asymmetric shedding of the boundary layer from the back of the ball. Asymmetries arise because air on one part of the ball may move over a rougher part compared to air moving over a part of the ball directly opposite. The knuckle-ball effect is named after baseballs thrown with little to no spin for which air moving over a rougher part of the ball (stitches) separates farther to back of the ball compared to air moving over a smoother part of the ball.[10] Figure 2 shows the two orientations, labeled A and B, that we studied for the knuckle-ball effect. For each orientation, we measured the air's force on the ball at two speeds, 20 m/s (44.7 mph) and 30 m/s (67.1 mph). We split the component of the air's force that is perpendicular to the air's velocity into two components: a horizontal component that we call the side force, and a vertical component that we call the lift force.

3. Wind-Tunnel Results and Discussion

Figure 3 shows wind-tunnel experimental drag coefficient results for the Jabulani and Brazuca balls. The most striking feature of the wind-tunnel results is that the Brazuca ball's critical speed, i.e. the speed where there is a precipitous drop in C_D, is smaller than that of the Jabulani ball. This result may seem counterintuitive given that the Brazuca ball has two fewer panels compared to the Jabulani ball, but recall that the overall seam length on the Brazuca ball is nearly 68% longer than on the Jabulani ball. The Brazuca ball's drag coefficient curve is more similar to that of the 32-panel Adidas Tango 12 ball,[11] used in the 2012 UEFA European Championship, than it is to the Jabulani ball's C_D curve.

We also see in Figure 3 that the Brazuca ball's drag coefficient for large speeds, i.e. in the super-critical region, is larger than the Jabulani ball's drag coefficient. At the largest speed we tested, i.e. $v = 35\,\mathrm{m/s}$, $C_D = 0.16$ for the Brazuca ball and $C_D = 0.20$ for the Jabulani ball.

The drag coefficient data suggest possibly noticeable differences between ball aerodynamics in the 2010 World Cup compared to the 2014 World Cup. Compared to the Jabulani ball, the Brazuca ball will have less drag on it for intermediate speeds, i.e. $10\,\mathrm{m/s} \le v \le 20\,\mathrm{m/s}$ ($22.4\,\mathrm{mph} \le v \le 44.7\,\mathrm{mph}$). We postulate that intermediate-speed-range shots in the 2014 World Cup will appear to goal keepers to be faster than what they saw in the 2010 World Cup. For hard-kicked balls at speeds in excess of, say, 25 m/s (55.9 mph), the Brazuca ball's larger drag coefficient means that goal keepers in Brazil may perceive hard-kicked balls slowing more rapidly compared to what they saw four years previously.

Brazuca ball's smaller critical speed has implications for knuckle-ball effects. Figure 4 shows lift and side forces at an air speed 20 m/s on the two balls of interest oriented in the two ways shown in Figure 2. Figure 5 is just like Figure 4, except the air speed is 30 m/s. Each of the two aforementioned figures was created by recording force for 9 s.

At an intermediate-kick speed like 20 m/s, compared to the Brazuca ball, the Jabulani ball shows significantly greater force transverse to air velocity. That result suggests that a non-spinning Jabulani ball will be more erratic in its flight compared to a non-spinning Brazuca ball. The aforementioned result is explained by the fact that the Jabulani ball's critical speed is greater than the Brazuca ball's critical speed. For intermediate-speed kicks, the air's boundary layer experiences both laminar and turbulent separation from the Jabulani ball. A Brazuca ball moving at 20 m/s, however, has only turbulent separation of the boundary layer because the ball is super-critical at 20 m/s.

Moving to a power-shot speed like 30 m/s, Figure 5 shows an expected increase in the air's forces on the balls. Although position A for the Jabulani ball is perhaps slightly more stable than position A for the Brazuca ball, the Jabulani ball in position B is clearly the most unstable of all combinations of ball type and orientation we tried. We attribute this result to the more asymmetric distribution of panel boundaries on the Jabulani ball compared to the Brazuca ball. The nearly 68% greater total seam length on the Brazuca ball means surface roughness is more evenly distributed than it is on the Jabulani ball.

4. No-Spin Model Trajectories

We now consider possible no-spin soccer trajectories. Though our model ball will not be spinning, we ignore "knuckle" effects. Our goal is to use the drag coefficient data acquired from our wind tunnel to make comparisons between Brazuca ball and Jabulani ball trajectories.

There are two forces we consider on a soccer ball moving through the air. The first acts down on the ball, the ball's weight, $m\,g$, where m is the ball's mass and $g = 9.80\,\mathrm{m/s^2}$ is the constant magnitude of gravitational acceleration near Earth's surface. The second force is the drag force, which points opposite the ball's velocity and has magnitude given by equation (1). We ignore the buoyant force on the ball from the air because that force is small ($\sim 1.5\%$ of the ball's weight), and it is essentially accounted for when we measure the weight of a ball on a scale.

Taking the x axis to point along the horizontal and the y axis to point vertically upward, Newton's second law reduces to

$$\ddot{x} = -\beta\, v\, C_D\, \dot{x} \tag{2}$$

and

$$\ddot{y} = -\beta\, v\, C_D\, \dot{y} - g\,, \tag{3}$$

where $\beta = \rho A/2m$, $v = \sqrt{\dot{x}^2 + \dot{y}^2}$, and a dot signifies one total time derivative. For the Brazuca ball, $\beta = 0.0527\,\mathrm{m}^{-1}$; for the Jabulani ball, $\beta = 0.0521\,\mathrm{m}^{-1}$. The difference in β values is due to the Jabulani ball's mass being 1.15% larger than the Brazuca ball's mass.

We numerically solve equations (2) and (3) with appropriate initial conditions using a fourth-order Runge-Kutta algorithm.[12] For the speed-dependent C_D in equations (2) and (3), we stay as true to the experimental data as possible and use linear interpolation between data points. For those readers who wish to create their own trajectories, but desire an analytic equation for C_D, we offer[13,14]

$$C_D = a + \frac{b}{1 + e^{[(v - v_c)/v_s]}}\,, \tag{4}$$

where a, b, v_c, and v_s are fitting parameters. For the Brazuca ball: $a = 0.187118$, $b = 0.260996$, $v_C = 12.9084\,\mathrm{m/s}$, and $v_s = 0.717838\,\mathrm{m/s}$. For the Jabulani ball: $a = 0.163643$, $b = 0.306765$, $v_C = 17.3015\,\mathrm{m/s}$, and $v_s = 1.61952\,\mathrm{m/s}$. Data-fitting curves using equation (4) are shown in Figure 3. We note that differences between trajectories using a linear interpolation scheme and equation (4) are small enough to have no influence on the conclusions we reach in this paper.

We first analyze a power shot taken 20 m from the goal, perhaps from a free kick. The ball is kicked with an initial speed of 30 m/s (67.1 mph) at an angle of 10° above the horizontal. Figure 6 shows model trajectories for the power-shot case. Because ball speeds throughout the trajectories are all super-critical in this power-shot case, the Brazuca ball's C_D is about 20% larger than the Jabulani ball's C_D. Compared to the Brazuca ball, the Jabulani ball gets to the goal in about 14 ms less time (0.737 s vs 0.751 s), and passes through the goal plane about 6.8 cm higher (1.006 m vs 0.938 m) and 3.6% faster (25.09 m/s vs 24.21 m/s). We do not see large enough differences between the two trajectories, especially given what we see in Figure 6, to postulate that goal keepers will notice much difference between power shots taken in 2014 and those taken in 2010.

Goal keepers may, however, notice differences in the next shot we consider. Suppose the ball is kicked 20 m from the goal at an intermediate speed of 20 m/s (44.7 mph). To pass through the goal plane at a reasonable height, we need to increase the launch angle from the 10° power-shot case to 20°. Figure 7 shows model trajectories for the intermediate-speed case. Considering all speeds throughout the trajectories, the Brazuca ball never quite gets into the critical region shown in Figure 3, meaning its C_D does not change much. The Jabulani ball, however, spends its entire flight in the critical region, meaning its C_D increases as its speed decreases. Consequently, compared to the Jabulani ball, the Brazuca ball gets to the goal plane in 93 ms less time (1.168 s vs 1.261 s), and passes through the goal plane about 57 cm higher (0.965 m vs 0.393 m) and 17.7% faster (16.46 m/s vs 13.98 m/s). Given more than half a meter height difference and nearly 18% speed difference, we postulate that goal keepers will notice a difference between intermediate-speed shots in 2014 compared to what they saw in 2010.

Including knuckle-ball effects serves only to increase the differences discussed above. At 20 m/s, the Brazuca ball feels a drag force of about 1.7 N, whereas the Jabulani balls feels a 2.2-N drag force. Figure 4 shows that the lift and drag forces on the Jabulani ball are comparable, or even larger, than the drag force it experiences. At 30 m/s, the Brazuca ball has a 4.0-N drag force on it; the Jabulani balls feels 3.3 N of drag force. Although Figure 5 shows that those drag forces are comparable to the lift and side forces each ball experiences, the Jabulani ball has the greater chance for more erratic flight.

5. Conclusions

Our wind-tunnel experiments show that the Brazuca ball has a smaller critical speed than that of the Jabulani ball. The difference is large enough that intermediate-speed kicks should exhibit noticeable changes in flight patterns for players who participated in the World Cup in both 2010 and 2014. Our computer trajectories for launch speeds at 20 m/s at a distance of 20 m from the goal suggest that goal keepers will see the ball crossing the goal plane more than a half meter higher in 2014 compared to balls hit in 2010. Power shots at high speeds, however, should not have noticeable differences in 2014 compared to what players saw in 2010. There is not enough difference in the super-critical drag coefficients between Brazuca and Jabulani balls to lead to significantly different power-shot trajectories.

Because of the ball's reduced critical speed, goal keepers are likely to notice a significant reduction in erratic flight in the 2014 World Cup compared to the 2010 World Cup. The Brazuca ball's lower critical speed should give it more stable flight compared to the Jabulani ball.

We have tested and modeled only balls without spin. Our next set of wind-tunnel experiments will determine lift coefficients for spinning balls. Adding lift, also known as the Magnus force, to the trajectory model is trivial. A future publication will report lift coefficients and compare three-dimensional trajectories between balls used in the World Cup in 2010 and 2014.

Acknowledgement

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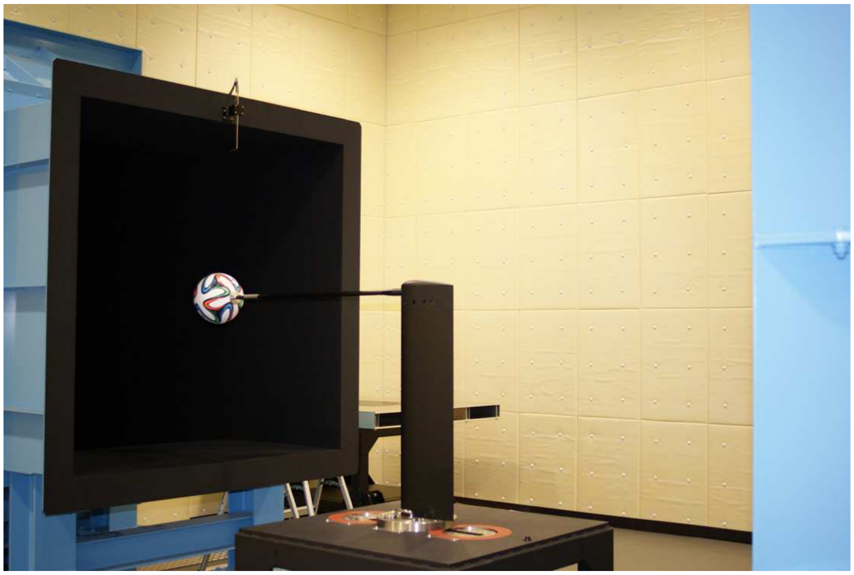

Fig. 1. Adidas Brazuca soccer ball mounted on stainless steel rod in preparation for wind-tunnel experiment.

Fig. 2. The two orientations we used to study knuckle-ball effects.

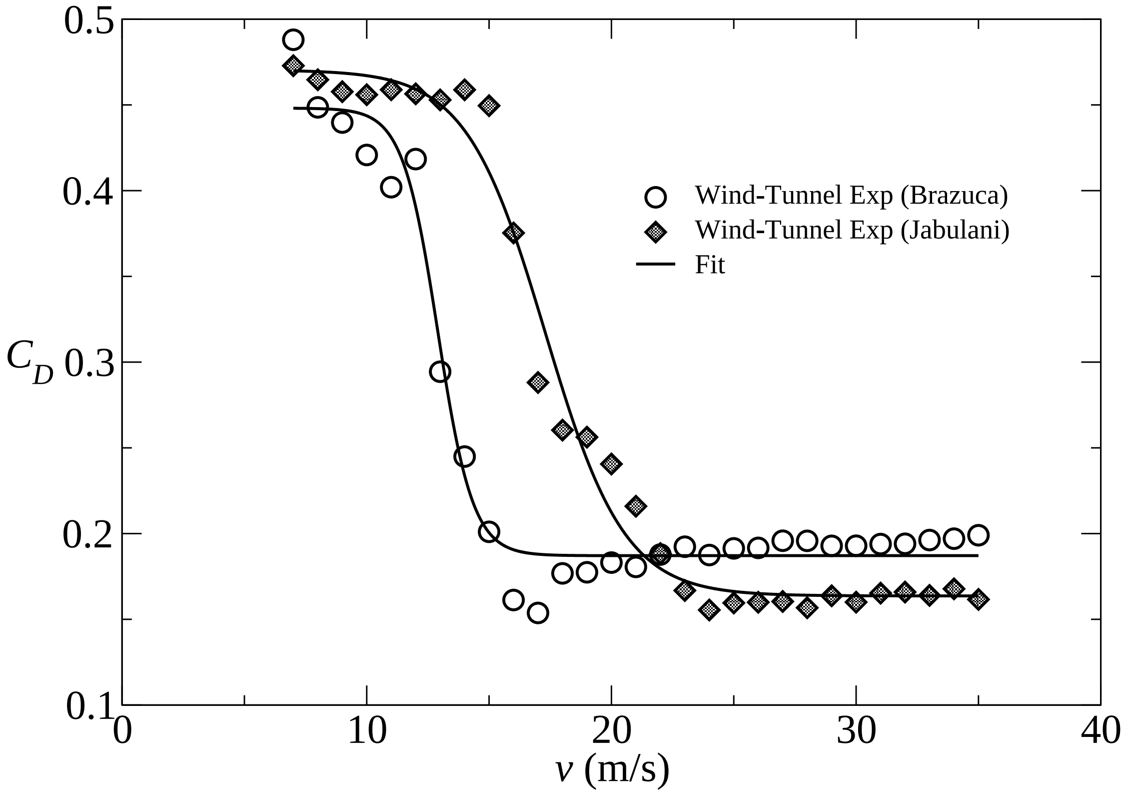

Fig. 3. Wind-tunnel experimental drag coefficient results for the Brazuca and Jabulani balls. The fitted curves come from equation (4).

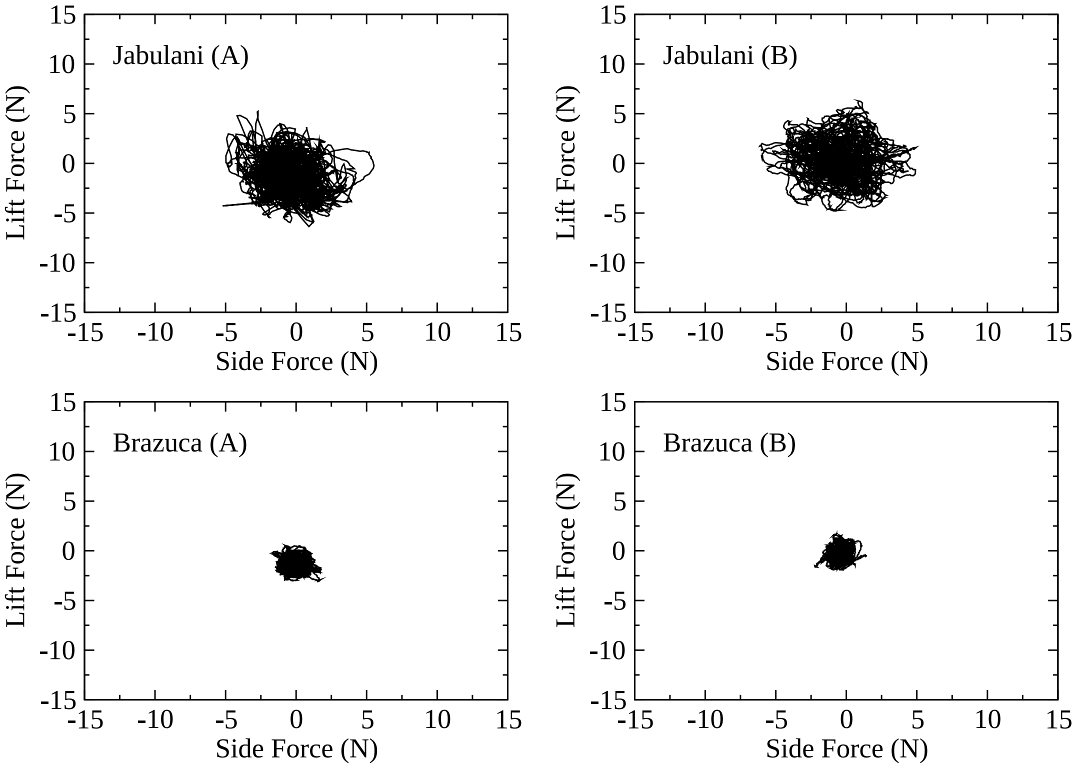

Fig. 4. Lift and side forces at an air speed of 20 m/s (44.7 mph) for the orientations shown in Figure 2.

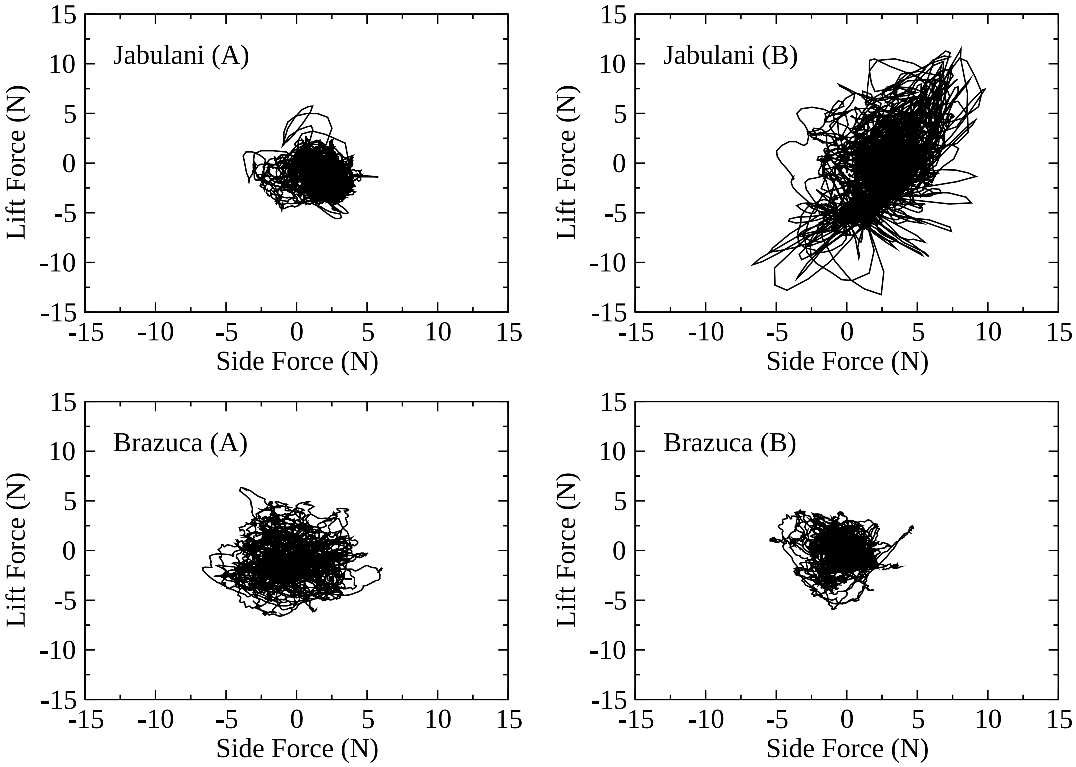

Fig. 5. Lift and side forces at an air speed of 30 m/s (67.1 mph) for the orientations shown in Figure 2.

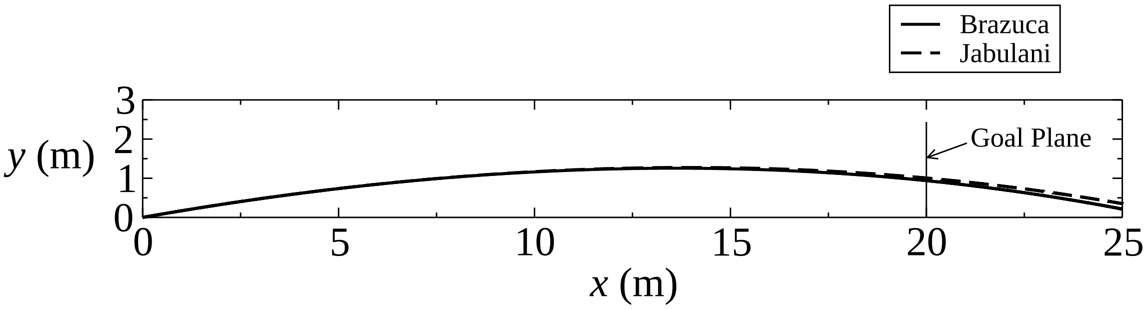

Fig. 6. Computational trajectories for Brazuca and Jabulani balls kicked 30 m/s (67.1 mph) at an angle of 10° above the horizontal. The goal plane is 2.44 m (8 ft) high.

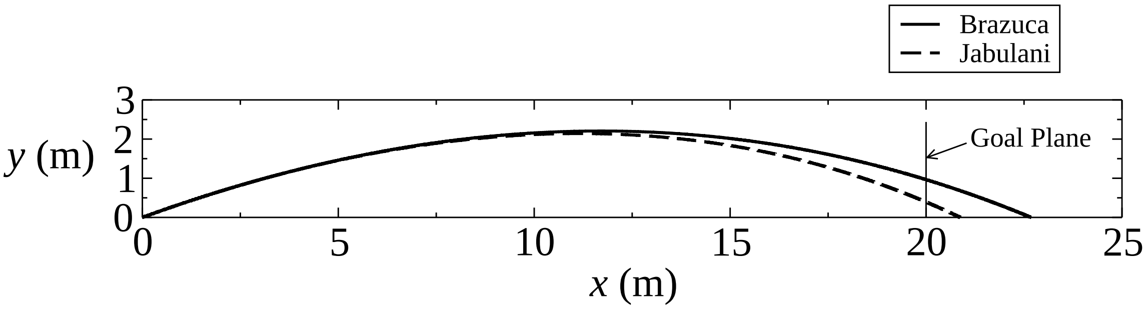

Fig. 7. Computational trajectories for Brazuca and Jabulani balls kicked 20 m/s (44.7 mph) at an angle of 20° above the horizontal. The goal plane is 2.44 m (8 ft) high.