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REVIEW PAPER

The Aerodynamic Characteristics and Flow of Soccer Balls

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ABSTRACT

In recent years, it has become well known that performance in sports involving balls or projectiles is significantly influenced not only by body movements but also by the aerodynamic and flight characteristics of these objects. This review paper examines recent developments in the drag coefficients of soccer balls. It demonstrates that the critical Reynolds number of the Al Rihla (used in the 2020 FIFA Qatar World Cup) is smaller than that of the Jabulani (used in the 2010 South Africa World Cup). Additionally, considering the unsteady nature of free flight in actual ball kicks, the relationship between the side force coefficient and the spin parameter is explored. Findings suggest that as flow velocity decreases, the spin parameter increases while the side force coefficient decreases. Furthermore, in scenarios where the ball is in a non-spin (low-spin) state during flight, such as in a knuckle kick, changes in the vortex structures in the ball's wake are observed. These changes in vortex structures are believed to cause fluctuations in aerodynamic forces, resulting in the ball wobbling or dropping. Moreover, using an optical 3D motion capture system, the inclination angles of the foot relative to the frontal plane during ball impact in instep kicks, curve kicks, and knuckle kicks are analyzed. The results show that the inclination angle is smallest for instep kicks, followed by knuckle kicks, and largest for curve kicks.

Keywords:
ball, curve, drag, spin, soccer

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Introduction

In ball games, not only the structure, function, and movement techniques of the body but also the flight trajectory and the airflow around the ball significantly influence performance[1-3]. To date, the flight trajectory and airflow around balls have been studied from the perspectives of fluid science and engineering[4-16], yielding various outcomes. However, many unresolved issues remain. This mini-review addresses recent findings and challenges related to the drag characteristics of soccer balls[17-21], the interaction between spinning soccer balls and airflow[22-33], the behavior of non-spinning soccer balls and their airflow interactions[34-39], and the control of spin in ball kicking[40-45].

Method

Drag Characteristics of Soccer Balls

The fundamental aerodynamic properties of soccer balls have often been studied through wind tunnel experiments, examining relationships such as wind speed (*U*) and drag (*D*), or Reynolds number (Re) and drag coefficient (*Cd*)[17-20]. Wind tunnel experiments have compared the drag coefficients of six different World Cup soccer balls, each with

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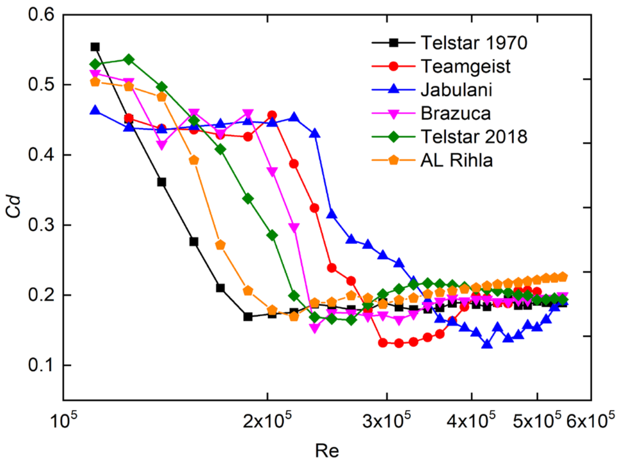

Figure 1. Drag characteristics of official World Cup soccer balls, including the AL Rihla (official ball of the 2022 FIFA World Cup in Qatar). Reproduced with permission from Asai T. Journal of Society of Automotive Engineers of Japan, 2023;77(5):94-99, Copyright 2023, Society of Automotive Engineers of Japan.

varying panel counts: 32-panel (Telstar 1970, 1970 Mexico World Cup), 14-panel (Teamgeist, 2006 Germany World Cup), 8-panel (Jabulani, 2010 South Africa World Cup), 6-panel (Brazuca, 2014 Brazil World Cup), 6-panel (Telstar18, 2018 Russia World Cup), and 20-panel (Al Rihla, 2022 Qatar World Cup)[21] <Figure 1>.

Analyzing the relationship between Reynolds number and drag coefficient, it was found that all balls exhibited a drag coefficient of approximately 0.5 in the low Reynolds number region. As the Reynolds number increased, the drag coefficient sharply decreased to around 0.1-0.2. This sudden drop in drag coefficient, known as the drag crisis, is characteristic of the aerodynamic properties of spheres and balls. The primary cause of the drag crisis is the transition of the boundary layer on the ball's surface (a shear layer where flow velocity changes rapidly near the surface) from laminar to turbulent flow. The Reynolds number at which this transition occurs, leading to the lowest drag coefficient, is known as the critical Reynolds number, a crucial indicator of the drag characteristics of spheres and balls.

For instance, comparing the 20-panel ball Al Rihla used in the 2022 Qatar World Cup with the 8-panel ball Jabulani, the critical Reynolds number for Al Rihla is approximately 2.2×10^5 (~14 m/s), while for Jabulani, it is about 4.2×10^5 (~27 m/s). In terms of drag coefficient, Jabulani shows a higher drag coefficient than Al Rihla in the medium-speed range (~15 < U < ~22 m/s). However, in the high-speed range (~22 < U < ~35 m/s), such as during a shot, Al Rihla has a higher drag coefficient than Jabulani. This indicates that Al Rihla experiences less air resistance than Jabulani in the medium-speed range but more resistance in the high-speed range. Consequently, Al Rihla is considered more suitable for achieving higher ball speeds in the medium-speed range. The difference in air resistance between Al Rihla and Jabulani is smaller in the high-speed range compared to the medium-speed range, indicating that Al Rihla generally has better flight characteristics.

As demonstrated, the critical Reynolds number is a key factor in the drag characteristics of soccer balls. However, even among FIFA official balls, there are various materials and panel designs, resulting in slight differences in their critical Reynolds numbers. Recent World Cup soccer balls show a trend of increasing critical Reynolds numbers as the number of panels decreases from 32 (Telstar 1970) to 14 (Teamgeist) to 8 (Jabulani). This is partly because fewer panels result in a smoother ball surface, closer to a smooth sphere. However, in later World Cup balls with even fewer panels, such as the 6-panel balls (Brazuca and Telstar18), design features such as increased seam length have led to a decrease in the critical Reynolds number, reverting to drag characteristics similar to the 32-panel balls.

Rotating Soccer Balls and Airflow

In soccer, it is common to apply spin to the ball during free kicks to intentionally alter its trajectory. When a soccer ball with lateral spin flies freely, the separation points of the airflow around the ball become asymmetrical relative to the direction of motion, resulting in a side force (S) due to deflected wake flow[27-28]. This side force, known as the Magnus force, is a fundamental mechanism behind curve kicks.

When examining the relationship between side force, flow velocity (ball speed), and ball spin rate, the side force coefficient (Cs) (Equation 1) and the spin parameter (Sp) (Equation 2) are commonly used.

$$S = Cs\,\rho\,U^2 A \qquad (1)$$

where S is the side force (Magnus force), Cs is

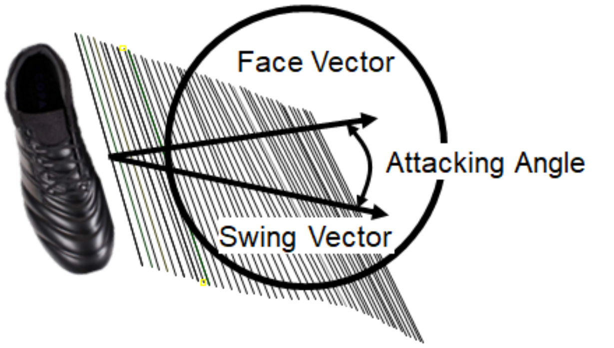

Figure 2. Schematic illustration of the angle of attack at ball impact. In this study, the angle of attack was defined as the angle between the face vector (the normal vector of the impact surface) and the swing vector (the velocity vector of the impact surface).

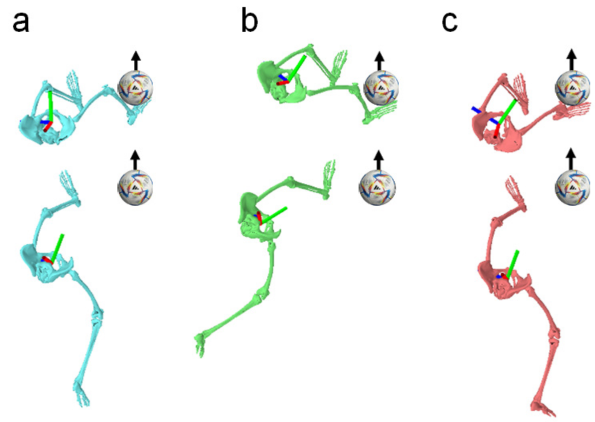

Figure 3. Lower limb skeletal posture and motion examples (top view) during ball impact (top panel) and backswing (bottom panel) in instep kick (a), curve kick (b), and knuckle kick (c), using an optical 3D motion capture system. Reproduced with permission from Asai T. Journal of Society of Automotive Engineers of Japan, 2023;77(5):94-99, Copyright 2023, Society of Automotive Engineers of Japan.

the side force coefficient, ρ is the air density, *U* is the flow velocity (ball speed), and *A* is the ball's projected area.

$$Sp = r\omega/U \qquad (2)$$

where *Sp* is the spin parameter, *r* is the ball radius, and ω is the ball's angular velocity.

In wind tunnel experiments, the side force coefficient (*Cs*) tended to increase with an increase in the spin parameter (*Sp*)[29, 31]. This relationship between the side force coefficient and the spin parameter is often used to simulate the flight trajectory of curve kicks[30, 33].

Non-Spinning Soccer Balls and Airflow

In soccer free kicks, techniques such as knuckle kicks, also known as non-spinning (or low-spin) kicks, are used to induce unpredictable trajectory changes by deliberately minimizing ball spin. In instep kicks (slight backspin), the large-scale vortex structures in the wake (streaklines) show continuous vortex shedding, with the flight trajectory being approximately parabolic. In contrast, knuckle kicks often exhibit wavy vortex structures in the wake, along with continuous vortex shedding[34]. Although the ball does not fly directly along these streaklines, the reaction forces from large-scale vortex fluctuations can cause variations in lift and side forces, contributing to the unstable flight path of knuckle kicks.

Spin Control in Ball Kicking

The generation of various types of spin such as curve balls and knuckle balls is a fascinating aspect of ball kicking. Equally intriguing is the technique for achieving these kicks. The angle between the normal vector of the foot impact surface (face vector) and the swing direction vector (swing vector) at the impact point <Figure 2>, known as the angle of attack (horizontal plane), has been shown to correlate with the ball's spin rate (lateral spin)[45] <Figure 3>. This principle is similar to the mechanism by which the loft angle of a golf club controls the ball's spin rate. By adjusting the angle of attack at impact, it is possible to control the ball's spin rate, enabling players to execute curve kicks and knuckle kicks with precision.

Discussion

As shown by wind tunnel experiment results, the critical Reynolds number is a key indicator of the drag characteristics of soccer balls. However, even among FIFA official balls, there are various materials and panel designs, resulting in slight differences in their critical Reynolds numbers. Recent official soccer balls have shown a trend of increasing critical Reynolds numbers as the number of panels decreases from 32 (Telstar 1970), to 14 (Teamgeist), to 8 (Jabulani). This trend is partially due to the reduction in surface roughness as the number of panels decreases, making the ball closer to a smooth sphere. However, in subsequent World Cup balls with even fewer panels, such as the 6-panel balls (Brazuca and Telstar18), the design of the surface panels and the increased seam length have resulted in a decrease in the critical Reynolds number, reverting to drag characteristics similar to the 32-panel balls.

The relationship between the side force coefficient (*Cs*) and the spin parameter (*Sp*), where the side force coefficient increases with an increase in the spin parameter, is based on the average values at a constant mainstream velocity in wind tunnel experiments. However, considering the unsteady nature of actual ball kicks during free flight, there is a possibility that with the decrease in flow velocity *(U)*, the spin parameter increases while the side force coefficient decreases, deviating from the relationship observed in average values obtained from wind tunnel experiments. Additionally, the slight decrease in ball spin rate during free flight may also impact the side force coefficient, which should be taken into account.

Observing the vortex structures in the wake of rotating and non-rotating (low-spin) freely flying soccer balls, distorted large-scale vortex pair structures are frequently observed[34-36]. For rotating balls like those in curve kicks, these distorted vortex pair structures tend to remain biased towards the direction of rotation when viewed from the rear. These vortex pairs, similar to wingtip vortices, generate side forces, causing the ball's flight path to deflect laterally. In contrast, for non-rotating (low-spin) balls like those in knuckle kicks, vortex pair structures exhibit rotation around the mainstream axis, with formation, breakdown, and reformation (reversal) of vortex pairs being observed. The resulting variations in aerodynamic forces due to these changes in vortex structures are thought to cause the ball to flutter or dip. Therefore, understanding and mastering the control of the strength and dynamics of these vortex pairs could lead to more effective kicking techniques suited to specific purposes.

Using an optical 3D motion capture system, it has been observed that the inward tilt angle of the foot relative to the frontal plane at ball impact is smallest in instep kicks, followed by knuckle kicks, and then curve kicks, showing an increasing trend[45]. Additionally, this inward tilt of the foot is accompanied by external rotation of the hip joint, which tends to shift the impact point of the foot to the inside. The hip joint posture in instep kicks is likely to create an angle of attack in the sagittal plane at impact, making it easier to generate backspin on the ball. In curve kicks, the hip joint posture facilitates the creation of an angle of attack in the horizontal plane, making it relatively easy to generate sidespin (external hip rotation posture). Furthermore, the hip joint posture in knuckle kicks is intermediate between instep and curve kicks (comparatively external hip rotation posture), allowing for a flat ball impact that minimizes both backspin and sidespin.

Future research should focus on the integration of biomechanical motion analysis with aerodynamic measurements to better understand how player technique influences ball flight characteristics. Such interdisciplinary approaches could provide valuable insights into optimizing soccer ball design for enhanced performance and consistency. Furthermore, innovations in ball panel structure and surface geometry, informed by both biomechanical and aerodynamic data, may lead to the development of soccer balls that maximize controllability and accuracy under various playing conditions.

Conflicts of Interest

The authors declare no conflicts of interest.

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