*Overview of aerodynamic influences in select thrown-ball athletics*

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**Introduction**

From the Ancient Olympics Games to modern day, sport has been an ever-advancing aspect of human culture and activity, documented for over 2200 years [1]. Over this time, sport has seen major technological advancements likely unimaginable to the Ancient Greeks, notably within the detail of equipment manufacture and physical technique. There are, however, certain aspects of sport that have remained as permanent fixtures – a static medium through which sport is played. While certain aspects of game performance may be improved with better technological capabilities and knowledge, there are still physical bounds by which sport is governed. These frames could mainly be considered as its entertained and physical nature – the interaction with cultural and material media. Simply put: sport has been, is, and will be entertainment of competitive class that is operated within a medium of its physical bounds. Cleats can allow for greater traction on the ground, but one is only as fast as their legs can move. With knowledge of the physical effects of their actions, players can implement particular techniques to optimize their play. Within this frame, aerodynamics of thrown-ball sport will be discussed here.

**The Thrown-ball Sport**

Thrown-ball sport will generally consist of throwing, passing, shooting, hitting, or otherwise aiming and ejecting a ball or projectile as a core component of the game. This is often incorporated in tandem with sprinting, jumping, and accelerating. Common games to be considered under this label include baseball/softball, football, soccer, and golf. The ascribed motion of both the player and the ball are conducted through air (with partial exception to only include water polo). Motion through an air medium is a core component of the thrown-ball sport; and as such, it is important to consider aerodynamic influences on the game.

In thrown-ball sport it is generally the goal to possess the ball in order to attempt to score – or to defend an opposing side from scoring. Players travel the playing area under their own power, and do not often encounter significant aerodynamic effects to their person. A player’s rate of motion under their own power is almost never fast enough to impose any considerable aerodynamic force, relative to the momentum garnered by their bodily mass at that (relatively) low rate of translation. Consequently, only ball effects will be considered here.

**General Aerodynamics in Thrown-ball Sport**

Relative to the player, the ball has a much lesser mass and generally travels at faster rates. In almost all thrown-ball sport, the ball will operate within a Reynolds number ranging 40,000 - 400,000 [2]. The ball often encounters aerodynamic forces that impose quite significant effects on its motion. Not only is it significant in magnitude, one would be amiss to forgo aerodynamic consideration in strategy of thrown-ball sport. Indeed, it is often the situational goal of the player to impose specific aerodynamic forces onto the ball in its travel. In typical flight, a thrown ball may experience an opposing force comparable to its respective weight [3]. Namely, this is the air drag. A ball in flight can also generate large forces perpendicular to its travel, with magnitude around 50% of that of its weight. This factor is largely influenced by any spin applied to the ball, and by its surface geometry relative to its motion [4].

In throwing, passing, shooting, or hitting the ball, players will often apply specific initial conditions to its travel in order to achieve advantageous aerodynamic effects. These conditions are typically applied by contact forces normal and tangent to the ball surface [5]. Examples include a spiral, backspin, topspin, lateral rotation, or 1ing. These effects can be situationally beneficial to the player as to achieve greater travel distance on the thrown ball, to cause an opposing player to miss the ball in flight by unexpected pathing, or to bypass an opposing player/obstacle. It is also worth noting that ball compression is sometimes utilized on these initial conditions – especially so on inflated balls, and in post-impact spin [5]. These effects are secondary, and are somewhat muted in comparison to the primary effects we will consider here.

**Detailed Aerodynamics in Thrown-ball Sport**

Two essential aerodynamic factors to be contextualized within thrown-ball sport are drag and lift. Aerodynamic drag and lift are given by the following expressions, respectively:

, [6].

where is the coefficient of drag, the coefficient of lift, the free stream density, the free stream velocity, and the reference area. A simple Second Law representation of these forces applied to a thrown ball in flight is then given by

[7].

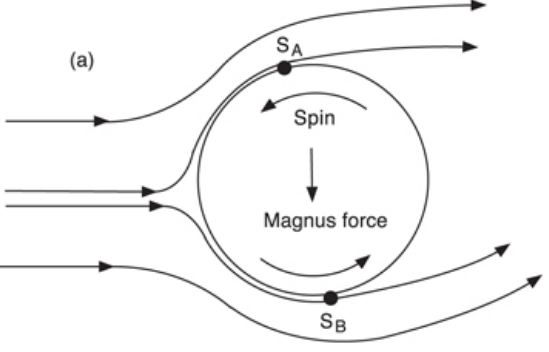
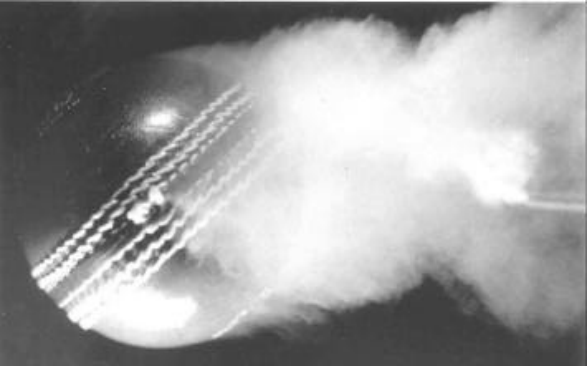
where m is the mass, g is gravitational acceleration, and a is resultant acceleration. Drag is seen to depend on drag coefficient, the fluid density, the relative speed, and the reference area. What isn’t explicitly shown in this equation is that drag in thrown-ball sport has a substantial dependence on both rotation and surface roughness. Achenbach *et al.* saw that as surface roughness increases, drag crisis is induced at lower Reynolds number and becomes less severe. Rotation has been found to increase of a ball by around 20% [8]. Surface interruptions such as stitching and lacing are also found to significantly influence the aerodynamic effects encountered by the ball, yielding higher drag and lift coefficients. [7].

It is important to consider the impact that spin has on the ball’s lift. Commonly known as the Magnus effect, spin has significant influence on the lifting and lateral aerodynamic forces encountered by all thrown balls being considered [9]. These forces produce effects perpendicular to the ball’s travel, and result in a lateral or lift coefficient around 0.3 [10]. The Magnus effect, although named after German chemist and physicist Gustav Magnus, was perhaps first described by Sir Isaac Newton:

*“For, a circular as well as a progressive motion…, its parts on that side, where the motions conspire, must press and beat the contiguous air more violently than on the other, and there excite a reluctancy*

*reaction of the air proportionably greater.”* (Newton, 1672) [11].

That is to say, as a ball travels through air with an applied spin, one side of the ball rotates forward and the opposing side rotates backward relative to oncoming airflow. The side that is rotates against the airflow consequently experiences a faster airflow relative to its surface, and the side rotating with the airflow sees a slower velocity. This results in

unequal opposing pressures and asymmetric boundary layer effects, creating a lateral and/or lifting force [11]. Rotation creates opposing sides of high and low pressures Boundary layer effects are a very core component in the aerodynamic effects experienced in thrown-ball sport. Asymmetric boundary layer separation can also be induced without means of rotation. Suitably angled stitching or seams on the surface of the ball can trip the boundary layer of one side into turbulence, whereas the opposing side may maintain a laminar state at separation [12]. This asymmetric separation can be seen to deflect the wake trailing upward in Fig. 2, to produce a downward force on the ball. Here, the bottom boundary layer is being tripped while the top layer remains laminar at separation. This turbulent boundary layer applies a greater shear stress compared to its laminar counterpart [13]. This effect is akin to the well-documented fluid mechanics of lift imparted by flow over a cylindrical shaft in rotation – only three-dimensional. The Kutta-Joukowski theorem for lift/span of a rotating cylinder, and the lift of a rotating sphere are represented below, respectively:

**Fig. 2**: Pallis *et al.* flow visualization over a cricket ball.

**Fig. 1:** Visualization of the Magnus effect. (IOP Publishing)

, [14] [15].

Where is the free stream density, the free stream velocity, the circulation, the coefficient of lift, the reference area, and the rotation. Ideal lift of a spinning ball can also be derived from the Kutta-Joukowski theorem as

[16].

with the same definitions and r as the radius. These equations of lift for a spinning sphere provide characterization of the Magnus effect to thrown-ball sport for both lifting and lateral effects.

There are other asymmetric wake effects that are likewise leveraged within thrown-ball sport, including knuckling. Knuckling will be defined here as the time-varying motion of a thrown ball perpendicular to the direction of throw. Knuckling is most commonly achieved by imposing no (or precisely little) rotation to the thrown ball. These seemingly unpredictable, erratic motions are associated with varying wake perturbations and influenced by vortex shedding and asymmetric shear destabilization [13] [17].

The spiral is yet another aerodynamic effect players implement to optimize their play in thrown-ball sport. Spiraling the ball upon release reduces drag and imparts gyroscopic stabilization to the ball during flight [18]. The spiral reduces wake size and aids in resisting ball reorientation as a result of conservation of momentum, imparting gyroscopic and aerodynamic torque [19] [20].

**Situational Implementation and Control of Aerodynamic Effects**

As elaborated, there are ­­­3 main categories encompassing most common aerodynamic effects within thrown-ball sport. These have been termed spiral, knuckling, and rotation. Spiral is perhaps most mainstage in (American) football. As the quarterback releases a forward pass to an intended receiver, he invariably applies a spiral to the ball. As presented, this acts to increase the accuracy of the throw by stabilizing its flight and minimizing the drag effects. It also can extend maximum throw distance and minimizing flight time [21]. Knuckling is utilized in various games as a means to impose erratic motion to the ball’s pathing. Its unpredictable pathing induced by vortex shedding is used in soccer to evade the goalie to score [22] [23]. In baseball, to cause and evade the swing of an offensive player [13]. And most widely utilized, rotation-driven aerodynamic effects have multiple implementations through all thrown-ball sport [11] [12] [24] [25].

One would be remiss to neglect surface geometry of the thrown ball, as it holds significant impact on its aerodynamic effects. Design of seams and stitching, and the roughness present on soccer balls, baseballs, footballs, and golf balls all play founding roles in the resultant pathing of a thrown ball [26] [27]. Golf has perhaps the most intriguing surface geometry specifically designed to create a thin turbulent layer to act in boundary to the ball, reducing the wake and drag [28]. There are also aerodynamic effects seen on the body of the player, but significance of these effects are almost exclusive to non-thrown-ball sport [29].

**Aerodynamics in non-thrown-ball sport**

There certainly exist other categories of sport that are influenced by aerodynamic effects – some even more centrally than thrown-ball. Sailing is a clear case for this. Sailing in vessels like America’s Cup class yachts places huge importance on control over aerodynamic drag and lift [30] [31]. Aerodynamics is likewise present in many facets of cycling [32]. Tennis balls experience many of the same aerodynamic effects present in thrown-ball sport [33]; as do badminton shuttlecocks [34]. Aerodynamic effects influence many instances of sport in significant manners, not all of which lie within the scope of this review.

**Summary**

In an ever-evolving field such as sport, new equipment and techniques are always pursued to gain a “leading edge” over an opponent. That is certainly the case regarding the aerodynamics of thrown-ball sport. Whether a pitcher is determined to perfect their fastball, curveball, or knuckleball, or a striker working on their bending or knuckling shots, a quarterback to improve the tightness of their spiral, or a golfer to finally bend that drive around a tall tree: players have been optimizing the applied aerodynamics of their craft for centuries. Whether it be in the form of the asymmetric impact of rotation on the boundary layer experienced during the ball’s flight, the intended vortex shedding and asymmetric shear destabilization of the ball to induce an erratic pathing, or introduction of gyroscopic and aerodynamic torques via spiraling, there are quite complex aerodynamic effects behind the commonplace thrown ball.

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