8
Frisbees

Over 300 million Frisbees have been sold worldwide. Once people get the hang of how to throw it, the ability to skim a lightweight object for a hundred meters and have it seemingly hover in midair becomes an addictive pleasure.

People have doubtless flung flat objects around since time immemorial, realizing that spin somehow allowed objects to fly that otherwise could not. The key point is that a flat plate tends to pitch up in flight, and this tendency must be suppressed in order to have sustained flight. The basics are outlined in Schuurman (1990) and Lorenz (2004). This suppression is achieved by some combination of aerodynamic tuning to reduce the pitch-up moment and the application of spin to give gyroscopic stiffness. These are, however, only palliative measures that

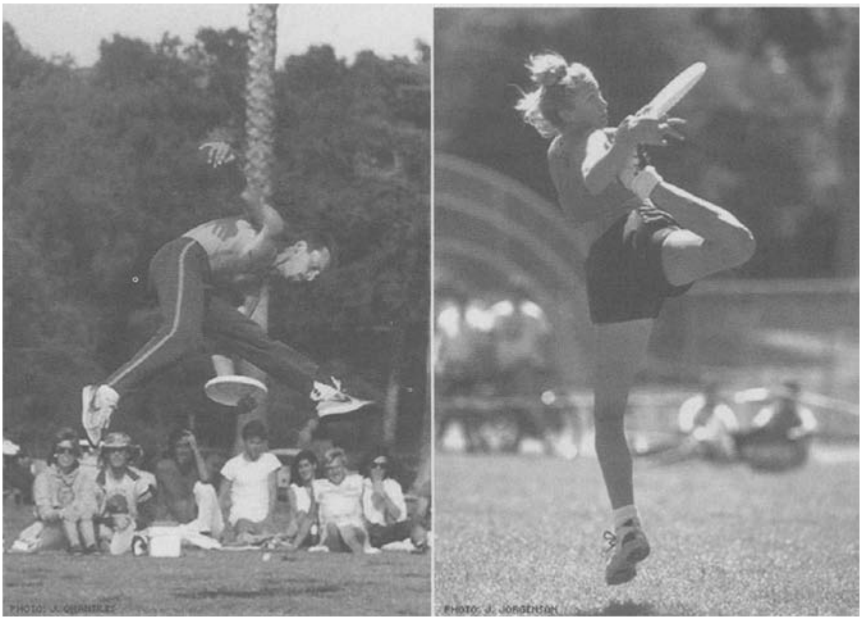

Figure 8.1. Stylish and athletic moves characterize the Frisbee sport of Freestyle. Photos courtesy of Larry Imperiale of the Freestyle Players Association: www.freestyle.org.

extend the duration of level flight—simple adjustment of shape and flight parameters cannot keep an object flying forever for the following reason: Spin stabilization only slows the destabilizing precession due to the pitch-up moment—the useful flight time is only a transient interval whose duration is proportional to the spin rate divided by the pitch moment. Of course, if the pitch moment could be made zero, then the spin axis precession would take an infinitely long time. However, it seems impossible to make a flying shape that has a zero pitch moment at all angles of attack, and since the angle of attack will change in flight due to the changing flight speed and flight path angle (due to the actions of gravity, lift, and drag), then sooner or later the pitch moment must be dealt with.

Frisbee History

But long before the problem was thought of in these terms, whatever objects were at hand have been flung with spin. It so happens that one of the more popularized and effective objects were the pie tins of the Connecticut baker William Frisbie. These pie tins were a good size and weight to throw, as students at nearby Yale University found. The deep lip of the tins tended, as we discuss later, to reduce the pitch-up moment, permitting the spin axis to remain stable enough for a flight of a few seconds.

The next major development was the availability of plastics after World War II. Two former Air Force pilots, Warren Francisconi and Walter (Fred) Morrison, saw that plastic would be an ideal material to make a throwing toy. Francisconi and Morrison named their toy a "flying saucer," capitalizing on the recent publicity from UFO sightings in Roswell, New Mexico.

By 1952 sales were not doing well, and Francisconi and Morrison drifted apart. Morrison, however, continued to market flying discs, naming one the Pluto Platter. (The book by Johnson (1975) does not mention Francisconi's role at all; Malafronte's 1998 book gives the two pioneers more or less equal billing.) Morrison patented the disc in his name and teamed up with the Wham-O Manufacturing Co. of California, and the company (with much better marketing abilities than Francisconi and Morrison had) began to sell the discs.

Fortunes improved substantially when a disc player, Ed Headrick, became vice-president at Wham-O, and saw the potential for improving the disc and its sales. He added grooves on the upper surface of the disc (which presumably tripped the boundary layer into turbulence and therefore reduced drag—even such small changes can make performance differences, though probably the key was to differentiate the product enough to patent the new version.) The

"Professional Model Frisbee Disc" received the U.S. Patent 3,359,678 in 1964.

The importance of good marketing cannot be overstated. Although many people were playing with discs, all he did "was offer them a 'Pro' model, white with a black flame painted ring, a gold foil label that said 108 grams, as if anyone cared, and the Olympic rings upside down." The product was promoted by Headrick's forming the International Frisbee Association, setting up the various championship competitions and appearing on TV.

In addition to the millions of Frisbees just tossed between friends to pass the time in a vaguely athletic sort of way, several specific sports have developed, notably Guts, Freestyle, Ultimate, and Disc Golf.

Guts is a game in which two opposing teams take turns throwing the disc at each other, the goal being to have the disc hit the ground in a designated zone without being caught. Freestyle is more of a demonstration sport like gymnastics, with exotic and contorted throws, catches, and juggles evaluated for difficulty, precision, and artistic impression.

The game of Ultimate, a team passing game with similarities to basketball and American football, has become a popular sport, and is featured in the World Games. The rules were developed by high school students in 1968, being refined somewhat in the following few years. In essence, a team must work the Frisbee forward across a 70-yard long field, 40 yards across, by passing from one team member to the other. If possession is lost, either by the disc going out of bounds, falling to the ground without being caught, or being caught by a member of the opposing team, the opposing team takes possession. A point is scored when the disc is caught in the endzone.

It is of course natural to do "target practice" with a disc, and a sequence of targets makes for a golf-like game, with the aim being to hit the targets in as few throws as possible. The practicalities of a target that gives unambiguous indication of a "hit" without damaging the disc led Headrick to patent a Disc Pole Hole, a device which could catch a Frisbee. The device consists of a frame supported by a pole: ten chains hang down from the frame, forming a paraboloid of revolution. This paraboloid sits above a wide basket. The chains absorb the momentum of a correctly thrown disc and allow it to fall into the basket (without the chains, a disc would typically bounce off the pole, making scoring near-impossible). The first Disc Golf course was set up in Pasadena, California (in fact rather close to NASA's Jet Propulsion Laboratory). A large range of different golf discs are available, with their weight and shape optimized for different throw ranges and wind conditions. According to the U.S. Professional Disc Golf Association, there are over 3 million regular players of disc golf, with several hundred tournaments per year.

Participation in Frisbee sports is not even confined to human beings. The TV sports network ESPN has begun to broadcast "Hot Zone," a competition sport where a player throws a Frisbee to be caught in a specified zone by a dog (often a sheepdog breed).

In terms of exploiting the widest range of aerodynamic properties of the disc, Ultimate is arguably the key sport. A thrower must toss to a teammate while avoiding interception, and therefore curved flights are essential. Sometimes the thrower may be blocked by an opposing player and thus must use an exotic throw, such as the overhead "hammer" where the disc is thrown over the shoulder in a vertical orientation, to roll onto its back and fly at near –90 degrees angle of attack. The catcher must anticipate how long the disc may hang in the air, and especially any turns it may make towards the end of its flight.

Innumerable variations on the Frisbee theme have been made—discs with flashing lights, discs with ropes attached so dogs can pick them up easily, inflatable discs, and so on. But in fundamental terms, the simple—albeit cleverly shaped—plastic disc seems here to stay.

Figure 8.2. In the sport of Ultimate Frisbee, players must throw discs to be caught by their teammates without being intercepted by the other team. This nominally noncontact sport requires careful throws that exploit the disc's unusual aerodynamic properties, as well as some athletic catches. Photo courtesy Andrew Davis www.freeheelimages.com.

Mechanics of Frisbee Flight: Wind Tunnel Measurements

As often seems to be the case, it was fairly late in the history of these objects that they began to be studied scientifically. In addition to studying the basic aerodynamic parameters, these investigations have tried to grapple with the possibility that the spin rate may affect not only the gyrodynamics, but also the aerodynamics. These aspects have assumed new importance with the prospect that a controllable drone or Unmanned Aerial Vehicle (UAV) might be patterned on a Frisbee: the behavior of control surfaces such as flaps would need a better understanding of the flow over the disc.

As far as just throwing a disc goes, the basic mechanical point is that a Frisbee is just a low-aspect ratio wing—in that sense its lift and drag can be considered conventionally. Admittedly, it is a wing that is sometimes deliberately operated even at –90 degrees angle of attack, but even then—in common with many low-aspect ratio shapes—its behavior is predictable.

The key is the pitch moment and how to mitigate its effects. The conventional Frisbee does this in two ways. First, the deep lip reduces the pitch moment to manageable values. Secondly, the thickness of the plastic in a Frisbee is adjusted across the disc, such that much of the disc's mass is concentrated at the edge, to make a thick lip. This has the effect of maximizing the moment of inertia, making the Frisbee like a flywheel. The precession rate is equal to the pitch moment divided by the moment of inertia and spin angular velocity. Keeping the precession down to a few degrees over the flight duration of a couple of seconds is all that is needed.

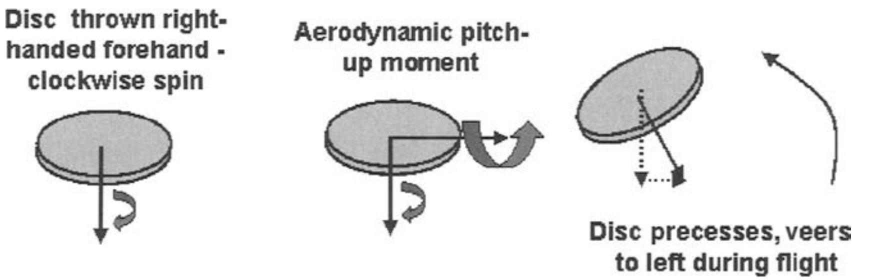

Figure 8.3. Schematic of the behavior of an object with pitch-up moment.

The earliest documented wind tunnel measurements of Frisbee-type vehicles appear to be those of Stilley and Carstens (1972), who reported force and pitch moment coefficients for a nonspinning disc, and asserted that the forces at least were unaffected by the spin rate. (Their interest was in the possible use of a spinning disc configuration to loft a flare.)

Nakamura and Fukamachi (1991) performed smoke flow-visualization experiments on a Frisbee at low flow velocity in a wind tunnel (~1 m/s). The disc (a conventional, although small, Frisbee) was spun with a motor at up to 3 times per second, yielding an advance ratio of up to 2.26. The smoke indicated the presence of a pair of downstream longitudinal vortices (just like those behind a conventional aircraft) which create a downwash and thus a lift force. These investigators also perceived an asymmetry in the vortex pattern due to the disc's spin, and also suggested that the disc spin increased the intensity of the downwash (implying that the lift force may be augmented by spin). While this work may be the first investigation of these phenomena, it is important to bear in mind the low flow velocity (~20 times smaller than typical flights); the effect of rotation in these experiments may have been disproportionate.

Yasuda (1999) measured lift and drag coefficients of a flying disc for various flow speeds and spin rates. He additionally performed a few free-flight measurements on the disc (with the disc flying a short distance indoors in the field of view of a camera) and wind tunnel measurements on a flat disc. His free-flight measurements on a conventional disc show that typical flight speeds are 8—13 m/s and rotation rates of 300—600 rpm (5—10 revolutions per second) and the angle of attack was typically 5—20 degrees. The most common values for these parameters were about 10.5 m/s, 400 rpm, and 10 degrees, respectively.

The flat disc had a zero lift coefficient at zero angle of attack, and a lift curve slope between 0 and 25 degrees of 0.8/25. The Frisbee had a slight lift ($C_L \sim 0.1$) at zero angle of attack, and a lift curve slope of ~1/25.

The Frisbee paid a price for its higher lift: its drag was commensurately higher. The flat plate had a drag coefficient at zero angle of attack of 0.03 and at 25 degrees of 0.4; the corresponding figures for the Frisbee were 0.1 and 0.55. (The drag curves are parabolic, as might be expected for a fixed skin friction drag to which an induced drag proportional to the square of the lift coefficient is added.) Yasuda notes that the lift:drag ratio of a flat plate is superior to that of the Frisbee. No significant dependence of these coefficients on rotation rate between 300 and 600 rpm was noted.

Higuchi et al. (2000) performed smoke wire flow visualization and PIV (particle image velocimetry) measurements, together with oil flow measurements of flow attachment on the disc surface. They used a cambered golf disc, with and without rotation and (for the most part) a representative flight speed of 8 m/s, and studied the downstream vortex structure and flow attachment in some detail.

To date, the most comprehensive series of experiments have been conducted by Jonathan Potts and William Crowther at Manchester University in the UK, as part of the Ph.D. research of the former. One aim of the research was to explore the possibilities of control surfaces on a disc wing.

In addition to measuring lift, drag, and pitch moment at zero spin for the classic Frisbee shape, a flat plate, and an intermediate shape, these workers measured these coefficients as well as side-force and roll moment coefficients for the Frisbee shape at a range of angles of attack and spin rates. These coefficients will be discussed in a later section.

Additionally, Potts and Crowther performed pressure distribution measurements on a nonspinning disc, smoke wire flow visualization, and oil flow surface stress visualizations. (They performed these on the regular Frisbee shape, and one with candidate control surfaces.)

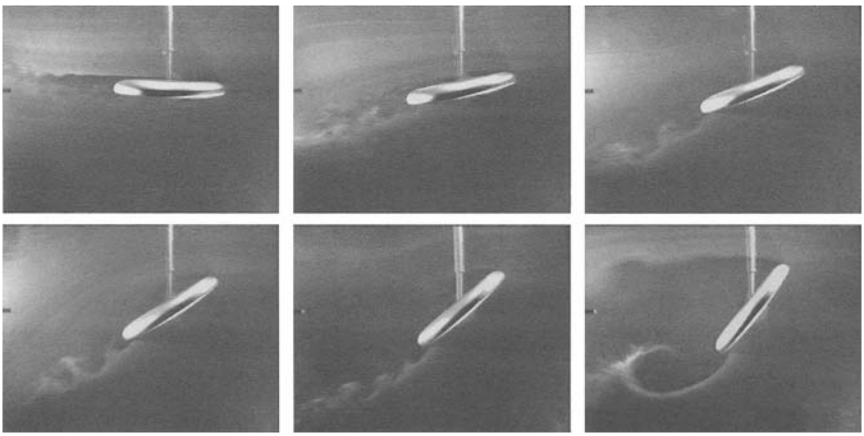

Figure 8.4. Smoke flow visualization of a nonspinning Frisbee model at increasing angle of attack (0–50° in 10° increments). Separated flow on the upper surface (stall) and strong vortex shedding into the wake is evident at high angles of attack.

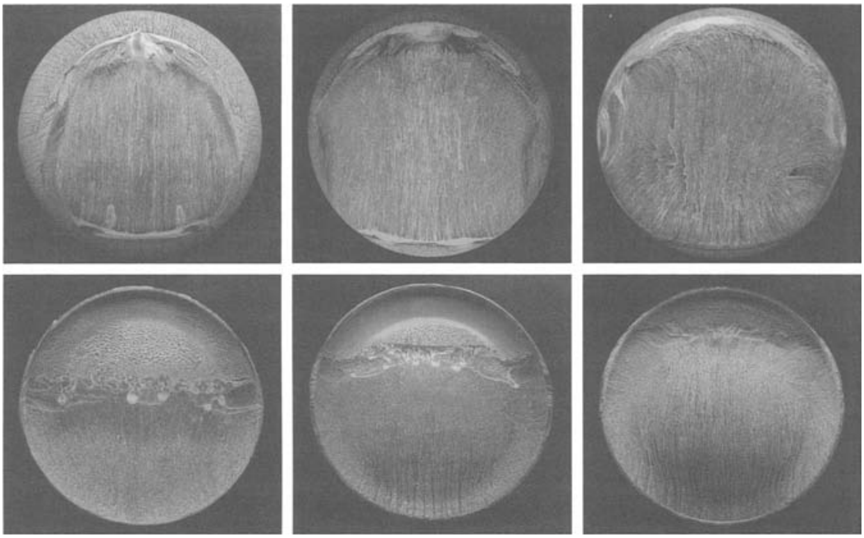

Figure 8.5. Upper (top) and lower (bottom) surface paint flow photographs illustrating the surface stress on a Frisbee at angles of attack of 5°, 15°, and 25°. Flow speed is 15 m/s. Photo courtesy of Richard Crowther and Jonny Potts.

In addition to these papers cited above, wind tunnel measurements on Frisbees appear to be a perennial research topic for undergraduate education. The quality of these measurements, and the rigor of their reporting, can be variable, and these reports are difficult to obtain. The determined investigator should consult the reference list of Potts and Crowther (2002) for at least a partial list of such reports.

Figure 8.6. Perspective view of fluorescent paint flow. Notice how the surface flow diverges behind the leading edge, where the separation bubble reattaches. Figure by Potts and Crowther, used with permission.

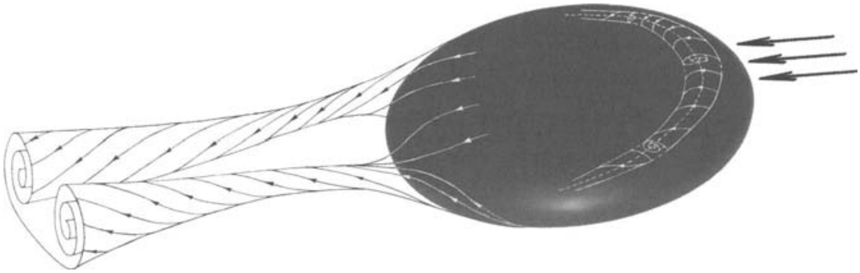

Figure 8.7. Sketch of the flow circulation on a Frisbee at a typical flight condition. Two trailing vortices like those on conventional aircraft are shown, together with a small circulation bubble associated with the suction peak just behind the leading edge. Figure by Potts and Crowther, used with permission.

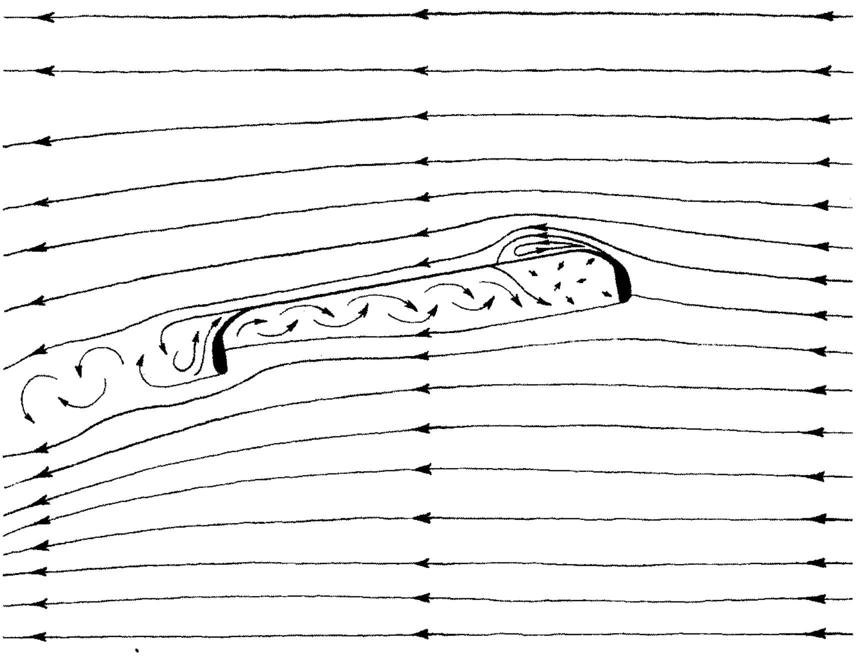

Figure 8.8. A sketch of the flow around a Frisbee at modest angle of attack, as deduced from flow visualizations. Notice how the trailing side of the lip "catches" the airflow to cause a pitch-down. Figure by Potts and Crowther, used with permission.

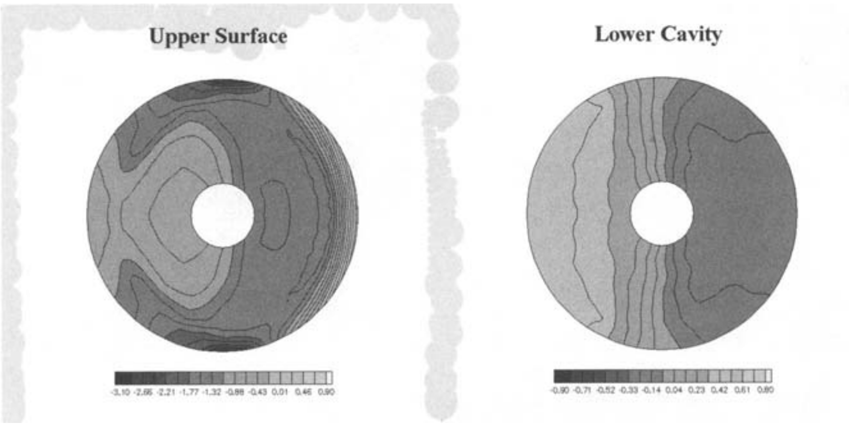

Figure 8.9. Pressure distribution on a Frisbee's upper and lower surface at 14 m/s and 15° angle of attack. Figure by Potts and Crowther, used with permission.

Computational Fluid Dynamic Studies

In the last decade or so it has become practicable to substitute calculations (numerical solutions of the Navier-Stokes equations) for wind tunnel measurements.

One undergraduate report (at the time of writing, an electronic file was available at Sarah Hummel's website) is that of Dankowsky and Cohanim at Iowa State University in 2002. These students performed some wind tunnel measurements (NB of a "golf disc" with a flat rim, rather than the classical Frisbee configuration) as well as simple "panel method" aerodynamic calculations.

A more elaborate CFD (computational fluid dynamics) study was undertaken by Axel Rohde in connection with his Ph.D. thesis. This study explored the flow around a disc (again a disc golf type, although a more conventional cross-section than that just above.) It should be noted that the thrust of the thesis was the development of a CFD solution method (a code for implementing this method is available on the web at www.microcfd.com, at which site the Ph.D. thesis can also be downloaded) rather than the study of Frisbee aerodynamics per se, and the flight parameters explored in this work are not those one might view in the park or on a beach—specifically the disc is a spinning oblate spheroid and more particularly the flight Mach number is 0.5!

CFD remains an area with considerable unrealized potential in Frisbee studies. However, as with wind tunnel experiments, spin introduces significant complications.

Free Flight Studies

Another method of determining the aerodynamic properties of an object is by observing its trajectory in free flight, and determining by simulation what coefficients are consistent with the observed flight path. (This is the principal technique applied in studying boomerang flight—see chapter 11.) To obtain a full set of coefficients with reasonable confidence, a number of different flights must be made, and it is possible—if not likely—that some regions in parameter space cannot easily be explored this way. Stilley and Carstens also matched the trajectories of flying discs, albeit rather stubbier ones than conventional Frisbees, by launching them off a cliff and observing with cine film!

Sarah Hummel and Mont Hubbard at UC Davis in California employed the video approach, using high-speed video cameras to track LED markers on a thrown Frisbee. (Yasuda et al. used video to determine the typical free-flight parameters of a disc, but used wind tunnel measurements to evaluate the coefficients at those parameters.) The sequence of position measurements was then used to evaluate the aerodynamic coefficients by progressively adjusting an assumed set of coefficients and forward-simulating the flight until the squared differences between the simulated and observed positions were minimized. The same technique has been applied in ballistic range tests of hypersonic re-entry vehicles at NASA Ames. Scale models of capsules and probes are shot down a partly evacuated tunnel along which a series of cameras are mounted: measuring the position and orientation of the vehicle at each spot allows the aerodynamic coefficients to be measured.

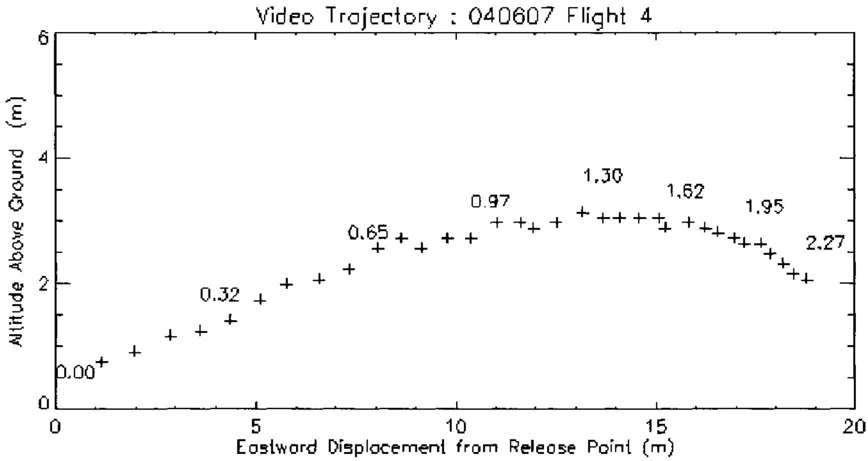

Figure 8.10. A Frisbee flight path obtained by digitizing the location of the disc in a video sequence obtained with a conventional camcorder from ~20m away. The numbers along the trajectory are the time in seconds since launch.

Aerodynamic Coefficients of Frisbees

A useful and instructive comparison can be made between a flat plate and a Frisbee. Indeed, Potts and Crowther make measurements of both. Let us first consider drag. The drag coefficient is the drag force normalized with respect to dynamic pressure ($0.5\rho V^2$) and the planform area of the disc. Since at low incidence angles the area of the disc projected into the direction of flow is very small (they used a plate with a thickness : chord ratio of 0.01), it follows that a flat plate will have a very low drag coefficient, ~0.02. On the other hand, the Frisbee, with its deep lip (thickness : chord ratio of 0.14) has a much larger area projected into the flow, and its drag coefficient at zero angle of attack is therefore considerably larger (~0.1). The Frisbee maintains a more or less constant offset of 0.1 above the value for a flat plate. This in turn has a parabolic form with respect to angle of attack, owing to the combination of a more or less constant skin friction drag term and the induced drag term, which is proportional to the square of lift coefficient.

While a flat plate has zero lift at zero angle of attack, and a lift coefficient that increases with a slope of ~0.05/degree, the Frisbee, having a cambered shape, develops appreciable lift at zero angle of attack (C_{L0} ~ 0.3)—its lift curve slope is similar.

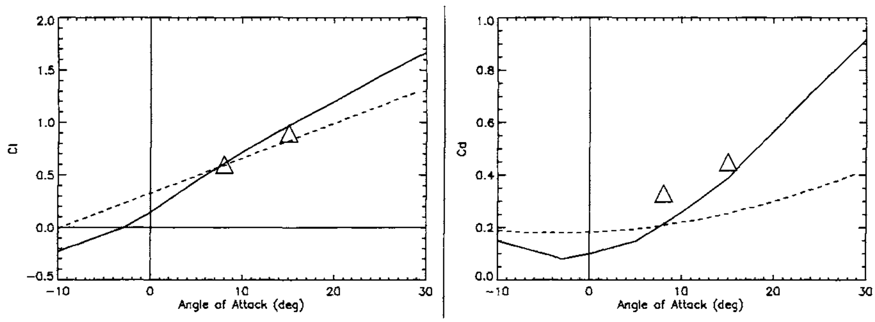

Figure 8.11. Lift and drag coefficients of a Frisbee. Solid line is wind tunnel results from Potts and Crowther; dashed line is from video measurements by Hummel; triangles are free-flight acceleration data from Lorenz (see later).

The major difference between the Frisbee and flat plate is in the pitch moment coefficient. While this is zero for a flat plate at zero angle of attack (which is not a useful flying condition, since a flat plat develops no lift at this angle!), it rises steeply to ~0.12 at 10 degrees. Because the Frisbee's trailing lip "catches" the underside airflow and tries to flip the disk forward, the pitch-up tendency of the lift-producing suction on the leading half of the upper surface is largely compensated. Its pitch moment coefficient is slightly negative at low incidence and is zero (i.e., the disc flies in a trimmed condition) at an angle of attack of about 8 degrees. Over the large range of angle of attack of −10 to +15 degrees, the coefficient varies only between −0.02 and +0.02.

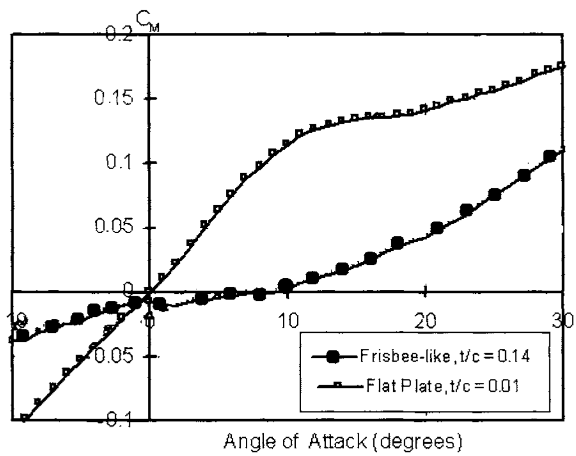

Figure 8.12. Pitch coefficient measurements by Potts and Crowther showing that a Frisbee-like shape has a much lower pitch moment than a flat plate. Indeed, the Frisbee pitch moment coefficient is zero at around 8 degrees.

The astute reader will realize that, while perhaps not useful in a game of Ultimate, the existence of a trimmed position (pitch moment coefficient CM = 0) permits the possibility of a stable glide. If the disc is flying downwards at a speed (dictated by the lift coefficient at the trimmed condition) such that drag is balanced by the forward component of weight, then the speed will remain constant. However, although the zero pitch moment means the disc will not roll, the roll moment is not zero, and so the spin axis will be slowly precessed forward or back, changing the angle of attack.

Hummel has pointed out the role of the sign change in pitch moment in causing the sometimes serpentine (S-shaped) flight of Frisbees. When thrown fast at low angle of attack, the pitch moment is slightly negative and causes the Frisbee to very slowly veer to the right. However, as the disc's speed falls off, its lift no longer balances weight and it falls faster downwards, increasing the angle of attack. When the angle of attack has increased beyond 9 degrees, the pitch moment becomes positive and increases rapidly. This leads to the often-observed left curve at the end of a flight.

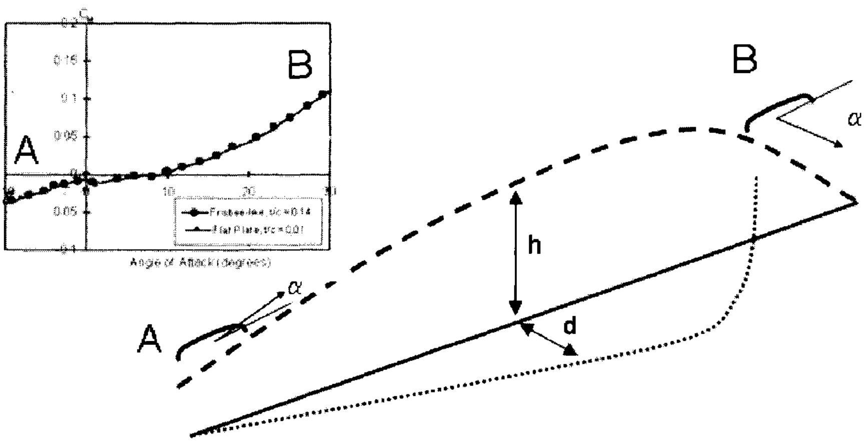

Figure 8.13. Why a Frisbee "hooks" to the left at the end of its flight. At the beginning (A) the flight path (dashed line) is shallowly upwards and the angle of attack α is small or negative, with a small and negative pitch moment causing a slight curve to the right as indicated by dotted line groundtrack. Later, however, at (B) the Frisbee is falling and has a large positive angle of attack and so a large positive pitch moment, causing the veer to the left.

Potts and Crowther also study the side-force coefficient (which might be thought of as due to the Robins—Magnus force, although in reality it is rather more complicated, since most of the boundary layer develops over the flat surface of the disk, rather than its somewhat cylindrical lip) and the roll moment.

The side-force coefficient is not strongly variable over the range of angles of attack studied (−5 to 15 degrees). It does vary, as one might expect, with spin rate. For low values of advance ratio AR (< 0.5, at an airspeed of 20 m/s) the coefficient is just slightly positive (0.02). However, for more rapid spin, the coefficient increases—at AR = 0.69, C_s = 0.04—0.05, and for AR = 1.04, C_s ~ 0.8. To first order, then, these data show that the side-force coefficient is proportional to advance ratio; a reasonable expectation is that the coefficient is in fact directly proportional to the tip speed, although this parameter was not varied independently in these tests.

Although the lift and drag coefficients were not appreciably affected by spin, the pitch moment did become more negative (by 0.01 —almost a doubling) at 0–10 degrees angle of attack as the spin rate was increased from AR = 0 to 1.

The roll moment coefficient was also determined. This was almost zero (within 0.002 of zero) for low spin rates and more or less constant with angle of attack over the range −5 to 15 degrees. However, the higher aspect ratio data showed a significant roll moment—C_M ~ −0.006 for advance ratio AR = 0.7 and C_M ~ −0.012 for AR = 1: in both cases the moment coefficient increased in value with a slope of about 0.0006/degree. Although measuring and understanding these coefficients is important in considering long-duration flight stability of powered or guided disc-UAVs, whether these more subtle effects can be exploited in a controlled and conscious fashion in a Frisbee throw is not yet clear.

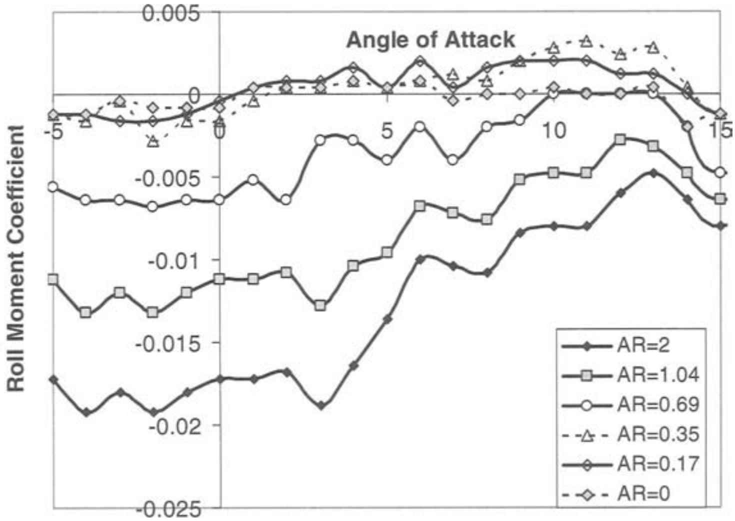

Figure 8.14. The effect of spin on a Frisbee's roll moment coefficient from the experiments of Potts and Crowther. Below advance ratios (AR) of about 0.5, the coefficient is small, while for AR of 1 and higher the moment becomes quite significant.

Instrumented Free-Flight Experiments

My own investigations into Frisbee dynamics (Lorenz, 2005) have centered on using instrumented discs to record accelerations and attitude motions during flight. Data is acquired using microcontrollers mounted on or in the disc from sensors which include sun sensors and magnetometers to measure attitude (calibrated by mounting the Frisbee on a "lazy susan" turntable, in turn set up on the precision angle mount of an 8-inch telescope), accelerometers, and other sensors like microphones and pressure sensors. The appendix to this book gives further details.

Note that to recover aerodynamic coefficients from in-flight accelerations, it is necessary to also measure the flight speed and flight path angle so that the angle of attack can be reconstructed from the attitude. Even a crude video record such as that in Figure 8.10 is adequate for meaningful results to be calculated (triangles in Figure 8.11.)

Among the interesting phenomena identified in these studies is the prominent existence of nutation in the early part of the throw. A good

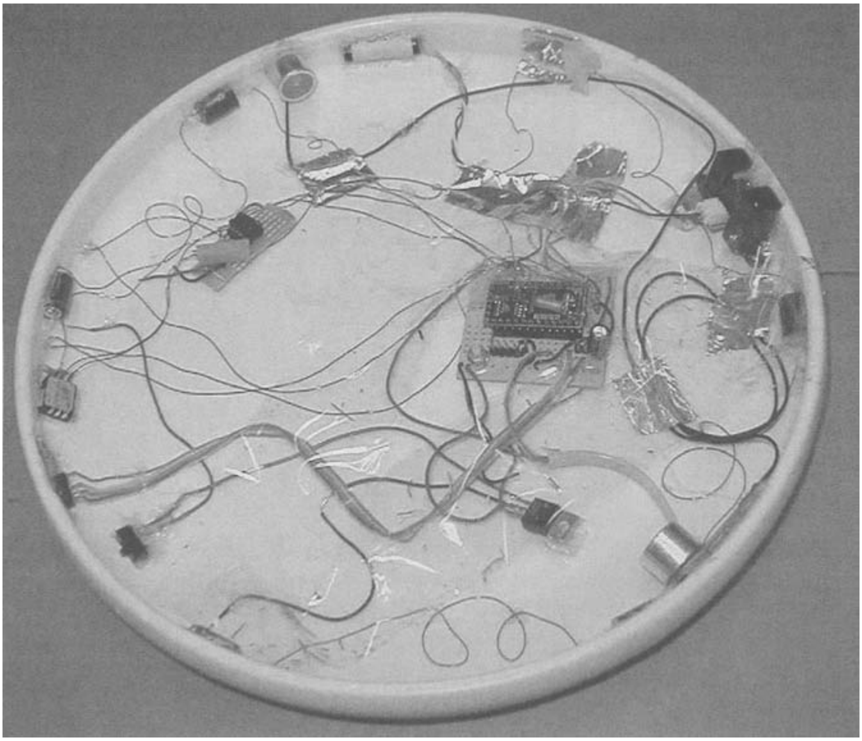

Figure 8.15. Frisbee underside with electronic components mounted. Most are glued onto the base or rim of the disc, and covered with clear adhesive tape to minimize abrasion damage and airflow disruption. The heaviest components, the batteries, are mounted in cavities milled into the rim to maximize the moment of inertia.

throw will avoid exciting nutation, which seems to substantially increase drag. Hummel's video work has also identified this, although whether it is damped by aerodynamic effects, or structural dissipation, remains to be determined. It can be seen in some photographs of hard Frisbee throws that the disc becomes visibly deformed by inertial loads—the disc is held only at one edge, and to reach flight speeds of ~20 m/s in a stroke of only a meter or so requires 20 g or so of acceleration. Consider half the disc (90 grams) being accelerated at this rate as needing a force of 20 N: since this is roughly equivalent to hanging a 2 kg weight at the edge of the disc, one can readily imagine a transient deformation that might excite nutation.

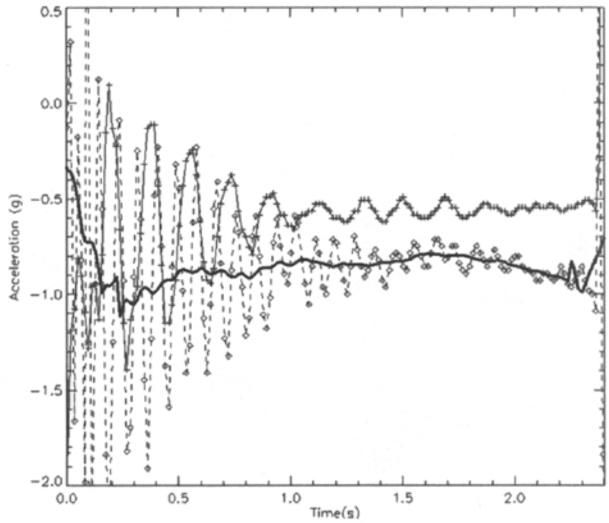

Figure 8.16. Accelerations measured during a conventional Frisbee flight. Solid line with crosses is the radial acceleration, with a centripetal component upon which a once per revolution drag is superimposed. The dashed-diamond curve is the axial acceleration. This shows a twice per revolution variation, characteristic of nutation. The thick line is a smoothed version of the axial data, showing how lift balances about 90% of the weight throughout the flight.

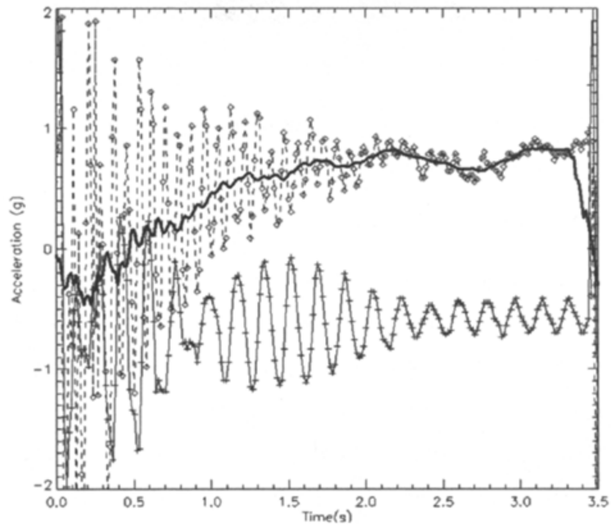

Figure 8.17. Same as Figure 8.16 but for a "hammer" throw. In this throw the Frisbee is thrown in a roughly vertical orientation at a slightly negative angle of attack. The pitch moment causes the disc to roll onto its back, giving the ~+1 g axial acceleration. As the disc turns over, the lift and drag components in the radial direction cancel out temporarily. The spin modulation on the radial component vanishes temporarily before growing to a maximum and then falling again.

In-flight measurements offer the prospect of measuring flow properties such as pressure on the rotating disc. Pressure distributions can be measured in the wind tunnel (Figure 8.9 shows data from Potts and Crowther), but because these measurements use little pipes to draw the pressure from the disc to an array of pressure sensors, it is impossible to spin the model. Free-fright experiments could explore how spin affects the flow separation near stall—trial measurements with just a small microphone show how as the angle of attack increases, the pressure fluctuations on the disc become larger even as the flight speed decreases towards the end of the flight.

A control surface, such as a flap, would have little useful effect on a Frisbee's flight were it to be simply fixed onto the disc. As the disc spins around, the control effect would vary or even reverse, and the spin-averaged effect would be small. However, if on-board sensors were used to trigger a fast-acting flap at a particular phase of rotation, the prospect of a maneuverable Frisbee can be envisaged. This might simply involve some stability augmentation—say to suppress the hook at the end of the flight. But much more appealing ideas become possible—a Frisbee with a heat sensor to detect a player, such that the disc tries to avoid being caught!

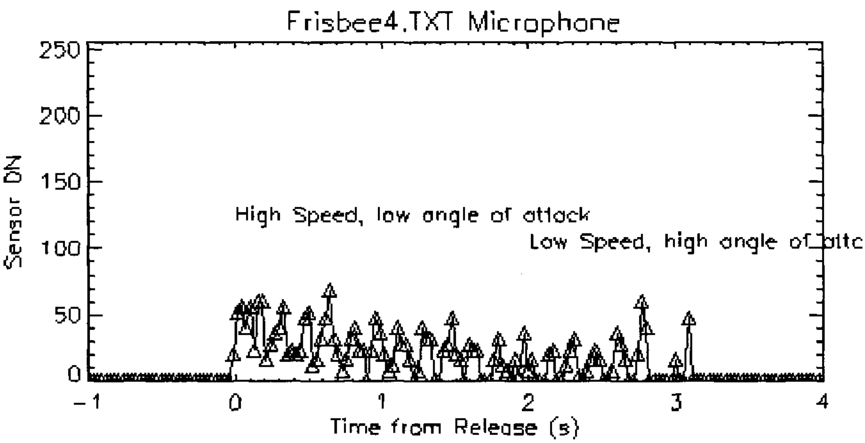

Figure 8.18. Signal from a small microphone on the upper surface of a Frisbee. The signal, which presumably corresponds to turbulent fluctuations in pressure on the upper surface, is spin-modulated at 6 Hz or so at the beginning of the flight. The mean signal falls as the disc slows down, but oscillations increase towards the end of the flight as the angle of attack increases.

Biomechanics of the Frisbee Throw

The challenge in the Frisbee throw is that the overall flight is very sensitive to the initial parameters—small variations in angle of attack can lead to very different flights. (Were this not the case, Frisbee might lose much of its appeal.) Consequently, it can be frustrating to learn.

As performance in sports becomes ever more important, scientific methods can be applied to understand how the throw is executed and how it could be improved. This is not to say that describing to a person what the velocity and angle history he or she should apply to the disc will actually allow them to execute the throw (neuromuscular control in humans is not, like the kinematics of a robot, specified as a set of deterministic commands), but it does give some insight into the technique.

This sort of biomechanical study formed another part of Sarah Hummel's work. It involved the construction of a mathematical musculoskeletal model of the Frisbee throw. The thrower is modeled as a kinetic chain of rigid elements—twist of the torso, and angular motion around the shoulder, elbow, and wrist cause the hand/disc to swing through space at high speed before the disc is released.

High-speed (180 frames per second) video was obtained with four cameras to track the motion of reflective markers mounted on a test subject who threw the disc. Torso twist defines three phases of the throw—wind-up, acceleration, and follow-through. Wind-up refers to the left twist before the throw.

In the acceleration phase, the arm becomes uncoiled, and the torso twists right and bends forward as the player shifts weight from the left to the right foot. A typical history of the various angles is shown in Figure 8.20.

By introducing the masses and moments of inertia of the various kinetic segments, the torques and energies exerted by each joint can be determined—the horizontal adduction of the humerus is the prime source of energy at release, with a power of some 100 W. The wrist flick only contributes around 8 W.

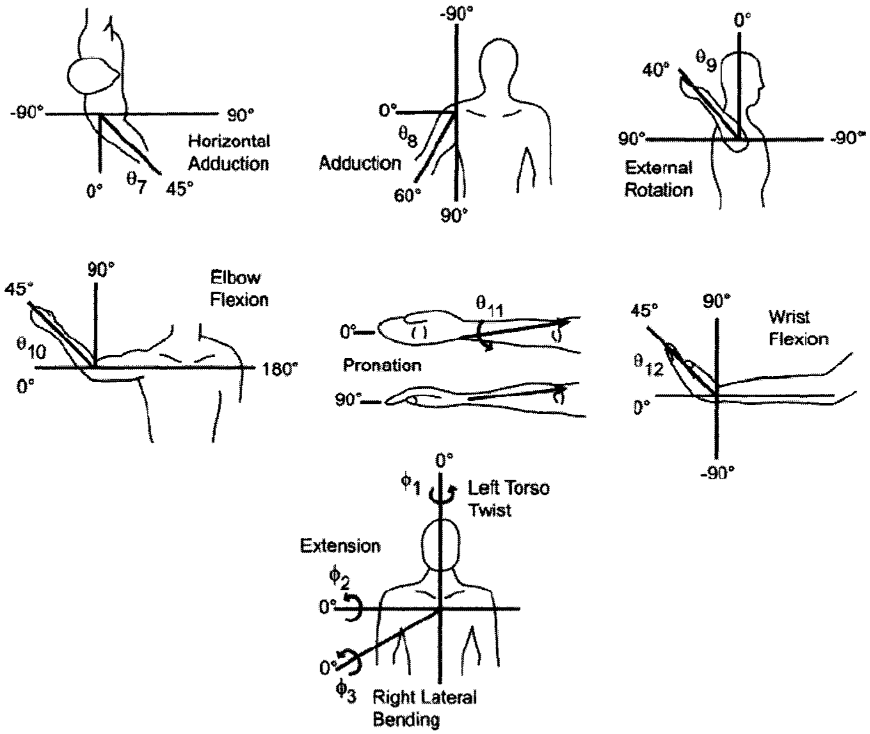

Figure 8.19. A biomechanical model breaks the movement down into a set of joint rotations. Since the bones between the joints are of fixed length, the set of joint angles defines the state of the system. The known masses of the various arm etc. segments allow the work performed in each angular acceleration to be calculated. Figure courtesy of Sarah Hummel.

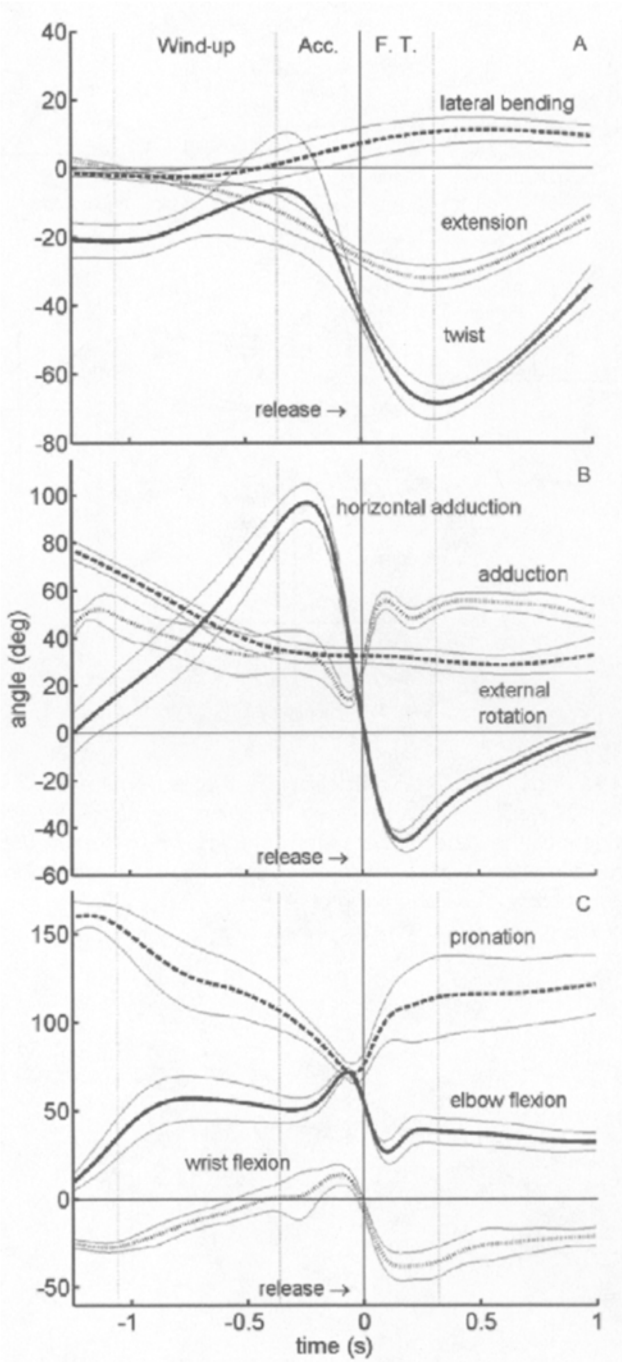

Figure 8.20. Rotations of the torso, humerus and ulna measured from high-speed video by Hummel (2003). Graphic courtesy of Sarah Hummel.

This investigation suggests that Frisbee players should devote attention to improving their shoulder movement, in contrast to the often-emphasized wrist.

Figure 8.21. A player in the 2005 Kiwani Ultimate championships puts her shoulder into a forehand throw. Photo courtesy of Andrew Davis, www.freeheelimages.com.

Instrumented discs can also give some insight into the throw by documenting the acceleration and spin history of the disc (Figure 8.22). It may be possible to measure the disc deformation during a throw with strain gauges or other sensors.

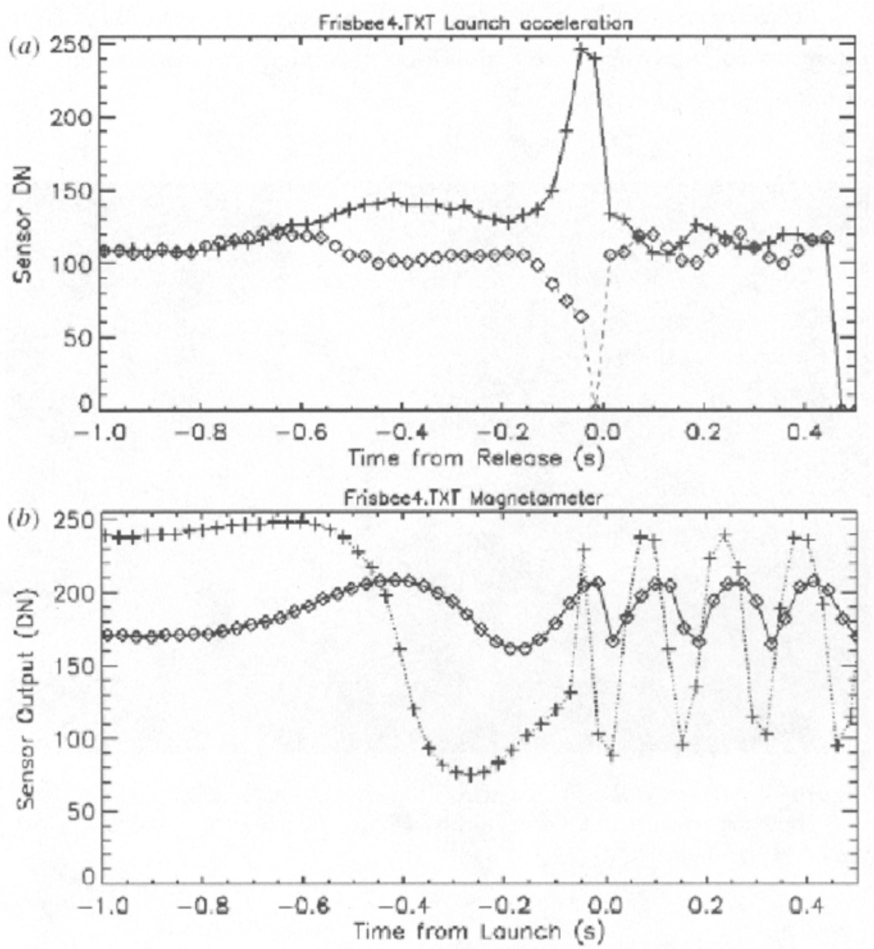

Figure 8.22. Accelerometers on a disc (a) show how about half of the total velocity acquired by the disc is picked up in a swing of about 0.4 s in duration, the rest being picked up in about 0.1 s by a snap of the wrist. The magnetometer record (b) shows how almost all of the spin is derived in this 0.1 second.

References

The 2003 paper by Potts and Crowther must be considered a benchmark work in the field. Hummel's Ph.D. thesis is also essential reading. Both items, and their websites, have lots of background and further references.

Higuchi, H., Goto, Y., Hiramoto, R., & Meisel, I., Rotating flying disks and formation of trailing vortices, *AIAA 2000–4001*, 18th AIAA Applied Aero. Conf., Denver, CO, Aug. 2000.

Hubbard, M., Hummel, S. A., 2000. Simulation of Frisbee flight. In *Proceedings of the 5th Conference on Mathematics and Computers in Sports*, University of Technology, Sydney, Australia. (at Hummel's website below)

Hummel, S., *Frisbee Flight Simulation and Throw Biomechanics*, M.Sc. thesis, UC Davis, 2003.

Johnson, S., Frisbee—*A Practitioner's Manual and Definitive Treatise*, Workman Publishing, 1975.

Lorenz, R. D., Flight and attitude dynamics of an instrumented Frisbee, *Measurement Science and Technology* 16, 738–748, 2005.

Lorenz, R. D., Flight of the Frisbee, *Engine*, April 2005b.

Lorenz, R. D., Flying saucers, *New Scientist*, 40–41, 19 June 2004.

Malafronte, V., *The Complete Book of Frisbee: The History of the Sport and the First Official Price Guide*, American Trends Publishing, 1998.

Nakamura Y. & Fukamachi N., Visualisation of flow past a Frisbee, *Fluid Dyn. Res.*, V7, pp. 31–35, 1991.

Potts, J. R., & Crowther, W. J., Visualisation of the flow over a disc-wing. *Proc. of the Ninth International Symposium on Flow Visualization*, Edinburgh, Scotland, UK, Aug. 2000.

Potts, J. R., Crowther, W. J., 2002. Frisbee aerodynamics AIAA paper 2002–3150. In *Proceedings of the 20th AIAA Applied Aerodynamics Conference*, St. Louis, Missouri.

Rohde, A. A., *Computational Study of Flow around a Rotating Disc in Flight*, Aerospace Engineering Ph.D. dissertation, Florida Institute of Technology, Melbourne, Florida, December 2000.

Schuurmans, M., Flight of the Frisbee, *New Scientist*, July 28, 127 (1727) (1990), 37–40.

Stilley, G. D., & Carstens, D. L., adaptation of Frisbee flight principle to delivery of special ordnance, *AIAA 72–982, AIAA 2nd Atmospheric Flight Mechanics Conference*, Palo Alto, California, USA, Sept. 1972.

Yasuda, K., Flight- and aerodynamic characteristics of a flying disk, *Japanese Soc. Aero. Space Sci.*, Vol. 47, No. 547, pp. 16–22, 1999 (in Japanese).

Frisbee Sports:
www.discgolfassoc.com/history.html
www.freestyle.org

www.whatisultimate.com/
www.ultimatehandbook.com/Webpages/History/histdisc.html

Frisbee Dynamics:
www.disc-wing.com
www.lpl.arizona.edu/~rlorenz
mae.engr.ucdavis.edu/~biosport/frisbee/frisbee.html