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Abstract: The explanation of beveled edges on pointed bifaces has been the subject of archaeological debate in North America since the first systematic description of lithic assemblages in the 19th century. Debate has centered around two opposing camps. One view sees beveled edges as a feature of projectiles that cause them to spin during flight. The other position is that bevels are the product of edge resharpening which is done unifacially to conserve scarce resources. Typical of most archaeological reasoning, the treatment of biface beveling has taken place in a theoretical vacuum. Here, we take an evolutionary approach to examine the basis of each of these positions. First, we use an aerodynamic model to simulate the effect beveling has on projectiles. Second, we conduct wind tunnel experiments to test our simulation results. Our findings indicate that beveling produces in-flight rotation and that such rotation is an integral part of the ballistics of early projectile technology in North America. This does not mean that all biface beveling can be explained this way, but that clearly in-flight rotation must be considered the 'null' against which other interpretations must be tested.

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**Cover Letter**

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DEPARTMENT OF ANTHROPOLOGY

February 11, 2010

Alison E. Rautman, Ph.D. RPA
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Dear Dr. Rautman,

Please find enclosed a manuscript "Beveled Projectile Points and Ballistic Technology" written by myself, R.C. Dunnell, V. Harper and J. Dudgeon. We would like to have this manuscript considered for publication as a report for American Antiquity. The paper is reviews a long-standing debate about the functional aspects of so-called "beveled" projectile points that are found commonly during the Archaic of Eastern North America. Arguments about beveling go back to the roots of archaeology in the mid 19th century. Here, using models of aerodynamics and ballistics we evaluate the claim that beveling feature was added to points in order to make them spin. Our evidence suggests this is indeed the case and the effect of spinning produces more accurate ballistic trajectories for thrown projectiles.

The paper text is about 22 pages (7,800 words) with 12 figures. Let me know if you need any additional information.

Sincerely,

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# BEVELED BIFACES AND BALLISTICS TECHNOLOGY

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February 11, 2010

*NOT TO BE CITED WITHOUT PERMISSION FROM THE AUTHORS*

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# ABSTRACT

The explanation of beveled edges on pointed bifaces has been the subject of archaeological debate in North America since the first systematic description of lithic assemblages in the 19th century. Debate has centered around two opposing camps. One view sees beveled edges as a feature of projectiles that cause them to spin during flight. The other position is that bevels are the product of edge resharpening which is done unifacially to conserve scarce resources. Typical of most archaeological reasoning, the treatment of biface beveling has taken place in a theoretical vacuum. Here, we take an evolutionary approach to examine the basis of each of these positions. First, we use an aerodynamic model to simulate the effect beveling has on projectiles. Second, we conduct wind tunnel experiments to test our simulation results. Our findings indicate that beveling produces in-flight rotation and that such rotation is an integral part of the ballistics of early projectile technology in North America. This does not mean that all biface beveling can be explained this way, but that clearly in-flight rotation must be considered the 'null' against which other interpretations must be tested.

Beginning in the early Holocene and in various areas across North America, lithic assemblages began to include axially-symmetric pointed bifaces (“projectile points”) that exhibit a curious cross section. Rather than having edges that are formed by flaking from both faces resulting in lenticular cross sections, these bifaces have edges that are shaped by flakes removed at steep (> 40 degree) angles from a single face. What makes this method of edge formation intriguing is that it occurs on each face and on opposite edges. As a result, this beveling results in a characteristic parallelogram-shape in cross section perpendicular to the long axis of the biface (Figure 1). When so viewed, the beveled edges give bifaces a characteristic “twist” in the direction of the beveling.

Pointed bifaces that bear beveled edges begin to occur and then rapidly reach their peak frequency and distribution in the early Archaic. For example, beveling is a characteristic for the Dalton group that includes Hardaway and Greenbrier types, and common on later Early Archaic forms such as Hardin Barbed, Thebes, Lost Lake, St. Charles, Decatur, and Rice Lobed. Subsequently, occurrence is sporadic until the appearance of the bow and arrow as, for example, its appearance on some Early Woodland bifaces such as Dickson (Justice 1987).

Since the late 19th century, North American archaeologists have speculated about the role of ‘beveling’ (e.g., Black 1890; Mason 1894; Patterson and Sollberger 1990; Sellers 1886; Smith 1953; Solberger 1971;Wilson 1897, 1898, 1902). Debate has centered around two interpretations. The earliest conjecture in the Americanist literature on lithic “arrow-heads” posits that bevels impart rotation to projectiles in flight (Black 1890; Foster 1873; Fowke 1902; Mason 1894; Morgan 1851:358; Tait 1874; Wallace

1887; Wilson 1897, 1898, 1902). For this reason, many authors called these bifaces “twist, or “rotary” points.

The rotary explanation has been strongly criticized. For example, Holmes (1896:178) noted that beveling often occurs on bifaces too large to be used as the tips of arrows. Instead, he speculates that bevels were probably integral to their use as knives and tasks such as skinning and cutting. Others have argued that bevels are simply the by-product of steep unifacial flaking that is “necessary” to resharpen a blade (e.g., Patterson and Sollberger 1990; Sellers 1886; Smith 1953; Sollberger 1971). Sollberger (1971) supposes that unifacial resharpening conserves the amount of material removed from a biface and thus occurs when materials are scarce. Others simply assert that rotation makes no sense for projectiles or that bevels were simply unable to rotate a projectile in flight (e.g., Sellers 1886; Smith 1951). Dincauze (1971:360), for example, argues against bevels-as-rotation features since “one would have to demonstrate that there is some utility in the rotation of such weapons and, moreover, that such weapons would in fact rotate when used in their normal mode.” With a couple of notable exceptions, these “interpretations” of the “meaning” of beveling are *ad hoc* speculations rationalized in common sense and then repeated by subsequent authors (e.g., Ballenger 2001; Ryan 1988) presumably because they “make sense.”

Here, in taking an evolutionary perspective on pointed-biface beveling, we assume that pointed bifaces are hafted points from compound tools. In this context, we assume the pointed end is the functional element (Dunnell 1978), i.e., a portion of the artifact that interacts with the environment, as suggested by both construction and breakage. Consequently, all features of projectile point blades potentially affect function and thereby and necessarily come under selection. The task becomes one of determining what the selective pressures are and whether their magnitude is sufficiently great to impact fitness. If the effect on function is sufficiently small, then other forces such as technological (i.e., physiological or ‘internal’) or stylistic (stochastic or neutral) ones may have played a role in fixing the occurrence of beveling when and where it occurs in the archaeological record. It is also critical to remember that not all beveling may have the same cause as is seemingly assumed in the literature. If pointed bifaces have more than one function, either contemporaneously or over time, then the selective context will differ and thus the ‘cause’ of beveling will vary. Indeed, multiple causes are suggested by the known distribution of beveling, particularly the spotty distribution after the Early Archaic.

To reconnect this perspective with traditional archaeological interpretation, we examine the premise that beveling on axial-symmetric pointed-bifaces has an effect on flight aerodynamics leading to projectile rotation. We show that this rotation contributes to the accuracy of flight paths under particular circumstances consistent with the chronology of beveling. In order to do this, we demonstrate that rotation occurs in simulated modeling using computational fluid dynamics as well as through controlled wind tunnel experiments. In addition, we examine the mechanics of flight and rotation and examine the potential aerodynamic benefits of the spin of a projectile while in flight. Finally, we discuss the implications of these experiments for documenting and explaining variability of pointed bifaces with respect to their environment of use.

## A LITTLE HISTORY

Speculation on the purpose of beveling on pointed bifaces extends back to the earliest systematic observations of North American archaeology. For example, Squier and Davis (1848:212) remarked that "arrowheads" they found were "so chipped that the lines of their edges forms a large angle with their planes, as if to give them revolving or tearing motion." Lewis Henry Morgan (1851), writing about the material culture of the Iroquois, noted that "arrow-heads of chert, or flint, were so common, that it is scarcely necessary to refer to them. Occasionally, they are found with a twist to make the arrow revolve in flight." Later researchers repeated this account (Abbott 1877:275, 296; Beckwith 1879:202; Brunner 1897:156; Carr and Shaler 1876:14; Fairbank 1864:lvx; Foster 1887:206; Hill-Tout 1902:181; Moore 1894:22; Tait 1874) and speculated that the rotation resulted in greater damage on impact (Abbott 1881:265; Jones 1873:255), resulted in straighter flight and accuracy by averaging curvatures in shafts (Wallace 1887:43) or were simply idiosyncratic to manufacturing (Abbott 1881:266).

Archaeologists studying prehistoric lithics quickly challenged these assertions. Researchers argued that bevels could not have provided rotation for projectiles as they were too large and heavy to be hafted to arrow shafts (Fowke 1902:673-674, 1913:24; Holmes 1896; Read 1892). Holmes (1896:178), then the leading scholar in the study of lithic technology, argued that contemporary archers did not use beveling of their points to achieve rotation and he reasoned that rotation is not necessary or even a desirable feature for projectiles that must pass through the ribs of game and enemies. Others (e.g., Fowke 1902:674) challenged whether any rotation caused by a bevel would be sufficient to provide a benefit to the flight path.

Some suggested that the blade shape was functional. Fowke (1913) reasoned that the size of the blades and the thickness of the stems suggest their use as knives. He argued (1913:18) that the bevel creates a blade shape that "will stand rough usage and can be forced between pelt and the flesh or into the joints, with but small risk of breaking … so these implements may properly be called skinning knives." Holmes (1897:178) also claimed that beveled bifaces were likely used for skinning and stated that the bevel would "be necessary if the implement were held in the right hand and pulled toward the user."

One consistent argument that emerged in the last part of the 19th century is that bevels are the result of the process of manufacturing sharp edges and not related to flight performance. George Sellers (1886: 884-885) argued that "a ship is not steered at its stem but by the rudder at its stern and an arrow is not directed or held to its course by its point but by the feathers at the butt end of its shaft and if a rotary motion was required it would naturally be given by placing the feathers spirally round the shaft. The broad flat sides of these beveled points would neutralize any effect from the short bevels in passing through the air." Instead, Sellers claimed that beveling is the product of flaking one edge of a biface in order to sharpen it. Packard (1887:438), for examples, quotes Frank Cushing of the National Museum: "…I cannot help it. When I hold the butt end of the arrowhead against the ball of my thumb, I have good bearing, and can take off long flakes; but when I reverse the object to chip the other side, I have a poor bearing, and can take off only small chips. The same is true of the opposite edge, only the long chips will come from alternate sides, giving the appearance of a twist." Thus, the bevel is derived by unifacial flaking on opposite sides of a biface, the orientation of which is determined by the handedness of the worker. This explanation has the added benefit of explaining why most beveling appears consistent with right-handedness (Sellers 1896:884). Similarly, Read (1892:17) suggests that beveling is determined by the position in which the object was held when chipped and resulted in a stronger cutting or scraping edge. Why all bifacial points were not made this way initially is not addressed.

Thomas Wilson (1898:142) responded to claims that beveling on edges was simply a result of resharpening or “freaks of the workmen … without signification or intentional for particular purpose.” In order to challenge this assumption, Wilson (1898) conducted a series of experiments to demonstrate that beveled points would result in rotation. For this demonstration, he selected a series of a dozen bifaces from the collections of the Smithsonian and hafted them on non-feathered shafts. He then dropped them from the roof of a tower and observed that the shafts rotated as they fell. In addition, he experimented with the bifaces in a rig that could be pulled through a water tank. Again, the bifaces rotated. Finally, Wilson constructed a crude wind tunnel through which he could vary the conditions under which the beveled bifaces were subjected. As in the previous tests, the bifaces rotated and the rate of the rotation varied with wind speed.

Wilson (1898:142) also noted that although some claim that feather fletching on an arrow was more likely to be effective than beveling of the blade edges, few shafts have been found that have fletching that would have caused rotation. By his count, only a dozen shafts out of a thousand that are stored at the U. S. National Museum bear twisted feathers. He (1898:143) also pointed out that an argument based on the “ease of chipping relative to handedness and orientation” argument is spurious as the bifaces could be held in either direction in each hand. Later Morse (1971) would counter by noting this was not true if the point were still attached to a long shaft at the time of resharpening.

Despite Wilson's arguments being the only ones based on experiment and testing, most contemporary researchers have converged on an account for beveling that is primarily related to edge resharpening rather than flight (e.g., Dincauze 1978; Goodyear 1974;Justice 1987; Patterson and Sollberger 1990; Smith 1953; Sollberger 1971). This shift back to explanations related to manufacturing stem largely from acceptance of pseudo-scientific assertions (e.g., Smith 1953) and from the growing interest in lithic production techniques and replication that emerged in the 1960s (e.g., Crabtree 1966, 1967, 1972, 1973; Sollberger 1971). A focus on technological accounts resulted in the broad consensus among researchers that bifaces that exhibit patterns of unifacial edge flaking on opposite sides indicate edge rejuvenation. Relative to bifacial sharpening of an edge, it is claimed that removal of flakes from one face per side minimizes loss of raw material (Sollberger 1971). This property of beveling would lengthen the use-life of a biface as it could be repeatedly resharpened for longer than would be possible with bifacial flaking.

Generally speaking, edge sharpening forms the basis of most contemporary accounts about beveling (e.g., Justice 1995:5). In fact, arguments to the contrary are often met with swift admonishment. Smith (1953), for example, strongly chastises Campbell and Ellis (1952) for describing several projectile points found in the Rio Grande valley as "rotary." Similarly, Dincauze (1978) in response to a review of the history of lithic experimentation by Johnson (1987) derides Wilson's experiments and argues there is no utility for rotating projectiles even if bevels could be shown to cause rotation, which she argues they cannot. It is essential to note that these rejections are not based on new experiments or measured flaws in Wilson's protocols. Apparently, Wilson was a liar.

While the beveling is now routinely described as "beveled resharpening," (e.g., Justice 1987) the conclusions reached by Wilson (1898) cannot be easily ignored: his admittedly crude experiments show that beveled points do rotate during flight. His observations, while less controlled than one might wish, do falsify claims that rotation is not possible. In this sense, Wilson's work remains a benchmark. While many have argued that bevels are unlikely to cause rotation, few have conducted controlled experiments to evaluate this claim. Smith (1953), for example, describes several of his own efforts to observe rotation in projectiles. But Smith's experiments were far less controlled and reliable than those conducted by Wilson: they consisted of launching an arrow straight up into the air and attempting to watch it spin on its descent and descriptions of arrows as they were shot in front of an observer. Neither of these "experiments" reasonably qualifies as a substantial or replicable test of the rotation hypothesis for beveled bifaces.

Another consideration when evaluating the claims made by Wilson is that not all pointed bifaces were tips for arrow shafts. In comparison to late 19th century investigators, we now recognize that pointed bifaces play roles in spear, javelin, dart and bow and arrow technologies, each of which has different requirements in terms of shafts and the weights, sizes and shapes of their pointed ends (Bettinger and Eerkens 1999; Christenson 1986; Hughes 1998; Lyman et al. 2008, 2009; Miller II 2009; Thomas 1978). We now know that beveling primarily appears in non-arrow projectiles: darts and javelins. This recognition effectively nullifies some of the comments made by those early investigators (e.g., Holmes 1896) who discounted beveling as a feature of flight due to the larger-than-arrowhead size of the bifaces. The rotation hypothesis must be evaluated in the context of these several classes of projectiles rather than solely from the context of bow-and-arrow.

This position, in fact, is consistent with what we know about the chronology of beveling relative to introduction of the bow-and-arrow as well as the earliest stone tool technologies in North America. Beveling is most prevalent on pointed bifaces that pre-date the bow-and-arrow. In addition, it only occurs on bifaces that post-date Clovis and its relatives. From an evolutionary point of view, these observations suggest that beveling appears as a response to a particular set of technological, performance and/or environmental conditions unique to this period of time. Thus, it is appropriate that we revisit the approach taken by Wilson in the late 19th century to examine the degree to which beveling might result in rotation of a projectile and to study the conditions under which this rotation might be beneficial. To do this task, we can now make use of the knowledge of aerodynamics developed since Wilson's early work as well as controlled modeling using simulations and wind tunnels.

## PROJECTILES AND ROTATION

Our starting place for the investigation of beveling is the determination of any functional advantages for a beveled biface that rotates. Some of the earliest lithic analysts recognized an advantage that a rotating projectile would have in terms of its flight path (e.g., Wallace 1887). When a projectile flies, any asymmetry that exists in the shaft will result in a torque on the projectile increasing the offset angle and resulting in a curved flight path. By making the projectile spin around its axis the curved flight path is converted into a helical path as the 'bias' is rotated in all directions. This approach works equally well with all projectiles, all with different biases and the result is more precise targeting. Figure 2 illustrates the effect of rotation on projectile flight path. To understand the full benefits of rotation, however, one must consider the mechanics that cause the projectile to spin in the first place.

To describe how beveling can cause a projectile to spin, consider the simple case when airflow moves directly along the shaft, i.e., the projectile flies perfectly straight. In this situation, shear drag acts at right angles to the cross section of the projectile (Figure 3). Shear drag is a result of the projectile moving through the air and the kinetic energy required to move the air out of the way so that the projectile can pass. Shear drag is proportional to the velocity of the object and the size of the cross section. The hafted points at the distal end of a projectile, the part called the “pile,” usually form the largest cross section.

Bevels present a face on the pile that is at an angle and, consequently, the drag force is no longer normal to the shaft (Figure 4). A component of the drag force on the bevel acts to slow the projectile down and a component generates a torque on each bevel at a right angle to the bevel face and this torque acts to rotationally accelerate the projectile. Importantly, this rotation occurs using the same drag that would be present without the bevels. Thus, in this sense rotation comes for “free” since the drag that causes the spin exists even if the bifaces had symmetrically-flaked edges. In contrast, the use of feathers for fletching to cause the rotation adds to the overall drag and thus shortens the potential distance of the flight path.[1]

Using this model of shear drag, we can generate expectations as to how spin rate relates to velocity. Spin rate (rotations per minute, RPM) increases as the projectile accelerates from its resting position as a function of bevel size and the angle of orientation relative to its trajectory. As the projectile flies through the air it slows down due to drag effects caused by the cross section of the pile. Initially, the direction of the net airflow onto the bevel is along the path that is parallel to the arrow shaft. As the projectile spins faster, however, the bevels move faster and faster relative to a right angle to the shaft. The net airflow direction is the sum of the air velocity and the bevel velocity. As the spin rate increases the net air flow direction rotates until at some combination of projectile speed and projectile RPM the direction of the net air flow will be parallel to the bevel faces at which point the spin acceleration will be zero. The projectile will have reached a 'terminal' RPM and will not spin faster at that velocity. Thus, our model specifies that rotation rate increases as a function of velocity, bevel surface area, and angle of intersection.

Here, we can also see that increased rotation rate provides an additional benefit to projectiles beyond providing precision in flight paths. If the projectile is spinning the shaft begins traveling in the turbulent airflow caused by the bevels and the width of the biface. Projectile shafts that travel through turbulent flow have lower shear drag than those that pass through laminar flow. This situation is identical to the flight of golf balls and why all golf balls have dimples on them to cause turbulent flow at the surface. Thus, spin can contribute to precision and distance of a flight path, while adding no extra drag.

## MODELING ROTATION ON BIFACES USING COMPUTATIONAL FLUID DYNAMICS

Given this simplified understanding of aerodynamics, it is clear that beveled edges should produce forces that result in rotation. We do not know, however, whether or not the shape and size of beveled pointed bifaces are adequate to produce this effect in the real world. Sellers (1886) and Smith (1953), for example, have both argued the bevels simply would have no measurable impact on the flight of a projectile. One way of evaluating this assertion is to model the forces involved to create a series of empirical expectations. To do this, we can make use of computational fluid dynamic (CFD) models to simulate and measure the parameters of air moving across bifaces shapes at varying speeds. CFD is a means of studying the properties of fluids using numerical methods to approximate complex conditions involved in the flow of fluids (e.g., gases, liquids) around solid objects. The fundamental basis of CFD is a set of equations known as the Navier-Stokes equations that can be used to define any single-phase fluid flow. Navier-Stokes equations are based on the application of Newton's second law of thermodynamics to fluid motion and are expressed as nonlinear partial differential equations that have the useful property of modeling rates of change (Acheson 1990). These equations form the basis of aerodynamic engineering and allow researchers to study phenomena such as lift in airplane wings and the efficiency of automobile shapes traveling at variable speeds.

Consequently, CFD is ideally suited to studying the properties of beveling on variability in how shape impacts flow parameters for projectiles such as pointed-bifaces.

The most direct approach to solving turbulent flows is direct numerical simulation, which iteratively solves Reynolds-averaged Navier-Stokes equations for points on a surface modeled in terms of a mesh. Reynolds-averaged Navier-Stokes equations are time-averaged and simplify the solutions for turbulent flow (Acheson 1990). Even this simplified procedure consists of many thousands of calculations that previously required large mainframe computers. Fortunately, new generations of hardware have enabled the development of software packages that can run the simulations on desktop computers. For this project, we used COSMOSFloWorks[2] and SolidWorks[3] to provide a means of conducting the simulation and visualizing the results. SolidWorks is capable of constructing and rendering three-dimensional representations of bifaces (Grindley 2007) and COSMOSFloWorks is a fluid-flow simulation tool that integrates with the SolidWorks modeling application.

In our experiments, we created models to represent beveled pointed-bifaces using the measurements from bifaces obtained by the senior author (Figure 5). We then subjected these models to CFD simulations where wind velocity directed along the long axis of the bifaces was systematically increased from 5 to 60 meters per second, a range that covered the known velocity of arrows, darts and spears (Hughes 1998:352). We measured airflow trajectories in directions perpendicular to the long axis as a means of detecting the potential for biface rotation. Figure 6 presents simulation visualizations of flow trajectories. Areas of increased wind pressure (measured in pascals [Pa], equivalent to 1 $N/m^2$ ) occur in the locations that are expected from the shear drag model previously described.

Figure 7 shows a cross section of air velocity measured relative to the y-axis of the model direction when airflow is set to 30 m/s relative to the z-axis (or long axis of the biface). The red and yellow colors highlight areas of increased relative wind velocity, while the blue colors reflect areas of decreased relative wind velocity. As predicted by our shear drag hypothesis, the opposing directions of air velocity on opposite sides are consistent with expectations of airflow that would result in rotation. This result is also shown in an examination of the forces acting on the beveled faces. Figure 8 displays the total force (measured in Nm) acting in the normal direction on each of the beveled faces as we increased wind velocity from 5 to 60 m/s. Note that consistent with our shear drag model, the forces on each bevel are in opposing directions and value. Thus, the force of the wind creates measurable forces that can potentially cause spin in these projectiles.

## WIND TUNNEL EXPERIMENTS

The results of our CFD simulations support the idea that the presence of beveling on bifaces is potentially capable of producing the forces required to cause rotation at speeds consistent for prehistoric projectiles. We still need to show that real-world projectiles also work this way. To evaluate this question, we ran a series of experiments using modeled and prehistoric beveled bifaces in a low-speed wind tunnel with a maximum generated wind speed of 30 m/s. Initially the experiments were to be carried out at Mississippi State University but for a variety of reasons were ultimately conducted at California State University Long Beach (Figure 9).

For our initial experiments, we created simplified model bifaces from acrylic that matched the dimensions of prehistoric examples used for the CFD simulation (Figure 6). Wind velocity was measured using an ultrasonic anemometer and rotation rate was recorded using a handheld electronic tachometer. We increased wind velocity systematically from 0 m/s to 30 m/s in even increments, the fastest speed for which our wind tunnel could produce laminar flow. The results of the experiment are shown in Figure 10. The results meet the expectation of the shear drag model. Our initial hypothesis is, therefore, not falsified; rotation rate increases as a function of wind velocity, bevel surface area and angle of intersection. Beveled points do rotate when propelled through air.

## EXPLANATION OF BEVELING ON BIFACES

The experiments point to a functional explanation of beveling for at least some pointed bifaces: it is an attribute that causes rotation and positively impacts performance by increasing trajectory precision and decreasing overall surface drag of attached shafts. The resharpening explanation is effectively falsified; beveling does alter performance. Since beveling has performance advantages for projectile ballistics, we might expect that once invented, the variant would quickly go to fixation for all pointed bifaces used as tips for ballistic missiles. This does not appear to be the case. First, beveling is heavily skewed toward large projectiles as already noted. Second, beveling is most prevalent in North America during the earlier Archaic and found only sporadically thereafter often when the association with ballistic missiles is doubtful. These are not fatal flaws in the rotational thesis. Rather they allow us to hypothesize the conditions under which such rotation actually increases fitness. While the demonstration of those conditions is beyond current data, their development can serve to guide research.

As just noted, beveled pointed bifaces are relatively large in size especially when compared with points used in bow-based projectiles. Size may not be the key feature as size is strongly correlated with mass in lithic tools. Mass is more likely the functional parameter but point descriptions usually relate information only on size, not mass. Further the larger shafts associated with darts and spears (e.g., Corliss 1972) increase the overall weight of the missile. Based on this observation it is possible that there is a range of weight for which beveling provides the greatest benefit to the projectile and below which there is no advantage. Alternatively, since large points tend to be early in the archaeological record, it may be that the apparent association is coincidental with separate causes driving beveling and large size. The key here is to elucidate a mechanism that can link mass to rotation that also explains the association between “size” and beveling in ballistic tips.

Weight of the projectile has its greatest impact on the acceleration of rotation. Larger shafts and pile masses have greater inertia that must be overcome. So, while larger and heavier projectiles will rotate in the same way as small projectiles, their rotation rate will increase slower. We can demonstrate this effect by simulating the rotation of projectiles over time given the same physical configurations and starting speed but varying the mass of the pile. We can iteratively calculate the rotation rate over time by using the principle that angular acceleration is equivalent to torque divided by the moment of inertia. Figure 11 presents these results from this simple model. As expected, the rotation rate is inversely correlated with mass; heavier masses increased rotation more slowly than lighter masses.

While lighter projectiles reach their terminal spin rate faster than heavier projectiles, they also have lower momentum relative to drag. Thus, given the same launch velocity, lighter objects travel less distance than heavier projectiles (compare the distance traveled for a thrown soda straw versus a shovel). The shorter the distance that a projectile travels serves to mitigate the benefits of improved accuracy gained by spin. As projectiles get heavier, however, their momentum increases relative to overall drag to result in longer flight times and longer distances travelled. In these cases, rotation will make a greater contribution to accuracy. Objects that have masses that are too large, however, will have decreasing rates of rotational acceleration such that there will be too few rotations before impact to affect accuracy positively.

Figure 12 demonstrates the relation between velocity and rotation. In this example, we measure the rotation and velocity of projectiles of varying masses after they have travelled a distance of 10-meters from their launch point with the same initial speed. Velocity at any position is determined by the relative drag of the objects relative to momentum; larger objects are still travelling fast but lighter projectiles have slowed considerably due to drag. In contrast, lighter objects have a considerably higher rate of rotation than heavier objects at this point in their flight paths. This demonstrates that the trade-off between velocity and rotation rate results in optimum projectiles that are neither too large (as they will not rotate many times over the course of travel) nor too small (as they will not travel particularly far). Although further work needs to be done to evaluate complications due to differences in shape and drag, the optimal payoff for rotation comes in projectiles that range between 100 and 220 grams. This range of masses falls well within the range of darts and thrown spears (Hughes 1998:352). Thus, it would appear that the association between mass ("size") and beveling is a functional linkage rather than a coincidence. This conclusion needs to be explored with actual measurements of tip masses, a measure only rarely made and/or reported.

### *Temporal Dimensions*

It remains to be explained why beveling is seemingly limited to the earlier Archaic. Beveling first appears with Dalton points, not all of which are beveled (unbeveled points were initially called Meserve points) and which come in many regional (e.g., Hardaway), temporal (e.g., Searcy), and both variants (e.g., San Patrice). Gradually, i.e., with numerous intermediate forms, two successive lineages of points develop from this Dalton base, a notched branch (e.g., Thebes, St. Charles, Lost Lake, etc.) and a stemmed branch (e.g., Hardin, Bolen, etc.). Daltons and these derivatives are frequently serrated, a feature that reappears much more frequently later on than beveling but which appears associated to beveling initially (though mechanically connected).

While a definitive functional analysis of early projectile points has yet to be done, the following hypotheses seem plausible based on current incomplete and undoubtedly biased data. The Clovis "point" and its variants would appear to have functioned much as the Paleoamerican "Swiss Army knife," i.e., while the characteristic bilateral symmetry argues strongly for a casting function, its great variability in size, especially length, tip sharpness (often quite blunt) and other characters makes it clear that they did work in actions such as stabbing and cutting. The presence of basal-edge grinding argues strongly for the need for a haft that could stand up to considerable abuse as is required in cutting. The lanceolate shape likewise argues strongly for the importance of being able to easily withdraw (and reuse rapidly) the points from bodies (i.e., stabbing). It is not surprising that beveling does not appear on Clovis points; accuracy, the principal selective pressure fixing beveling, it not an issue with what we construe to have been basically a stabbing instrument.

Dalton points share many of these features with Clovis points: lanceolate shape, basal-edge grinding, and great variability in size (though this may be more bimodal than in the Clovis case). Many are even fluted. They differ from their predecessors in the occurrence of beveling and serration. Also the hafted area (as marked by edge grinding and the length of the basal thinning flake) is smaller proportionately, which may signal either a change in function that placed less stress on the haft and/or a more competent hafting technology. The more or less continuous variability in tip sharpness of Clovis points is replaced by a single mode skewed towards a highly acute tip angle (although many ‘broken’ Daltons are reworked into scrapers and other tools and Dalton-type hafts are common on an expanded range of bifacial tools such as drills either as a consequence of reworking or as originally manufactured). Thus, the conditions under which an innovation like beveling, which rotates in-flight projectiles, appear to be part of a broader trend toward increasing functional specificity within bifacial tools generally, and specifically the evolution of a true projectile point, the principal function of which was to tip cast projectiles. These hypotheses would be readily testable with the collection of appropriate metric and use-wear data on individual points in adequate numbers of well-dated cases.[4]

This scenario addresses only the appearance of beveling. Its abrupt decline is just as important to be able to explain. An obvious possibility is that some change in casting technology made rotation less advantageous or, alternatively, rotation was achieved by some other means. Reduced accuracy has a very low *a priori* probability of enhancing fitness so long as casting remains the primary function. Nonetheless, if some other innovation, itself incompatible with rotation, conferred even greater benefit then beveling might be lost even in casting tools. If the function did change, it should obvious from other changes in successor point design or in detailed use-wear studies. The former does not appear to be the case as many beveled-serrated forms (e.g., Lost Lake) smoothly grade into sequent forms (e.g., many Kirks); direct evidence through use-wear is not testable within the current knowledge base. A third possibility remains. Projectile rotation may have been accomplished by some other mechanism. Fletching immediately comes to mind. But if fletching were responsible, then one would expect to see a concurrent reduction in the size of projectile points. The large size of early points is best attributed to the need to locate the center of gravity of the whole projectile forward of the midpoint to prevent tumbling. Fletching solves this problem differently by providing lift at the rear of the projectile.

These possibilities cannot be resolved at the present time; more data on well-dated pointed bifaces, their design, use-wear characteristics, and breakage patterns as well as the shafts to which they were attached and any machines used in casting are required. The point here is that quite a number of plausible mechanism exist to account for the apparently rapid diminution of beveling

## CONCLUSIONS

We have shown that beveling causes pointed bifaces to spin in flight. This has been demonstrated both theoretically and by wind-tunnel experimentation. In-flight rotation offers benefits in the form of increased accuracy for ballistic shafts that have a mass range consistent with thrown spears and atlatl-launched darts sufficient to explain the fixation of this trait. Further, larger and smaller projectiles do not gain a sufficient benefit from rotation to fix these features as parts of ballistic systems.

In the cultural context of the eastern United States, beveling appears to be an early, if not the first, adaptation to transform the long-handled knife/stabbing tool represented by the Clovis point and its kin into an efficient casting instrument. Other modifications to the ballistic system near the end of the Early Archaic made beveling superfluous. The precise nature of those modifications, however, remains elusive for want of data on pointed biface variability and chronology. Nonetheless, we hope we have shown something of the insight that can be gained by pursuing lithic studies within an explicit theoretical framework, namely evolutionary theory, and that others will be stimulated to collect those data necessary to test the hypotheses suggested here.

## ACKNOWLEDGMENTS

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## NOTES

[1] For this reason, modern archers must balance the benefits of stability that larger fletching sizes provide with the cost of shorter distances that results from the greater drag.

[2] http://www.solidworks.com/sw/products/cfd-flow-analysis-software.htm

[3] http://www.solidworks.com/.

[4] By adequate dating we do not mean the usual dating by loose association with $^{14}$C-dated materials but strong association (e.g., dating a fire that burned a point) or direct dating as in TL, OSL or obsidian hydration). When association dating is employed, the association fixes the precision of chronological assignment, which, per force, periodizes any chronology.

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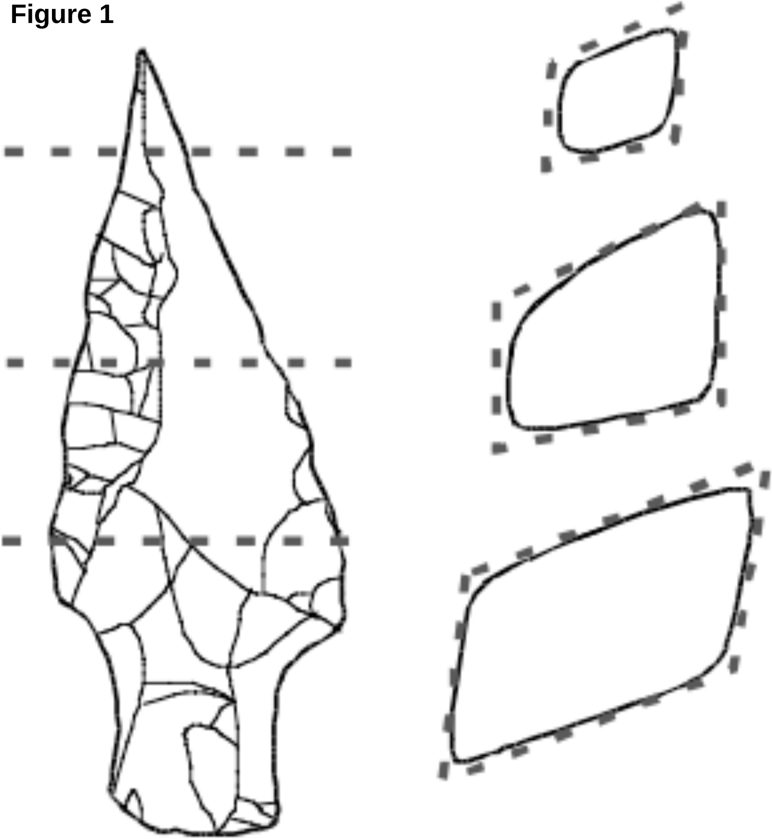
**Figure 1**



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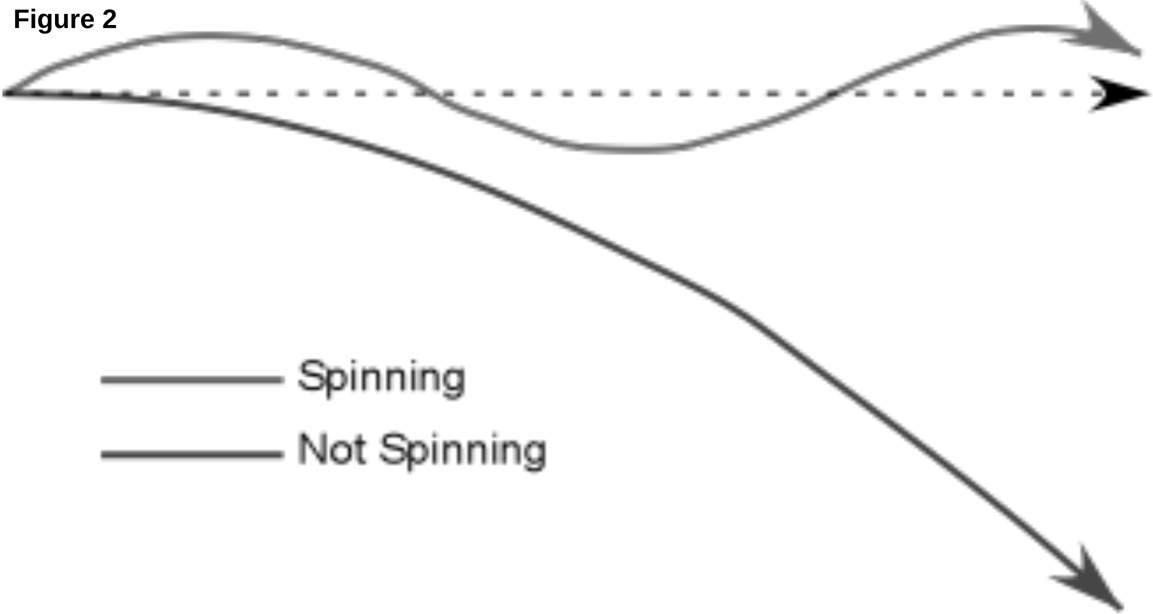

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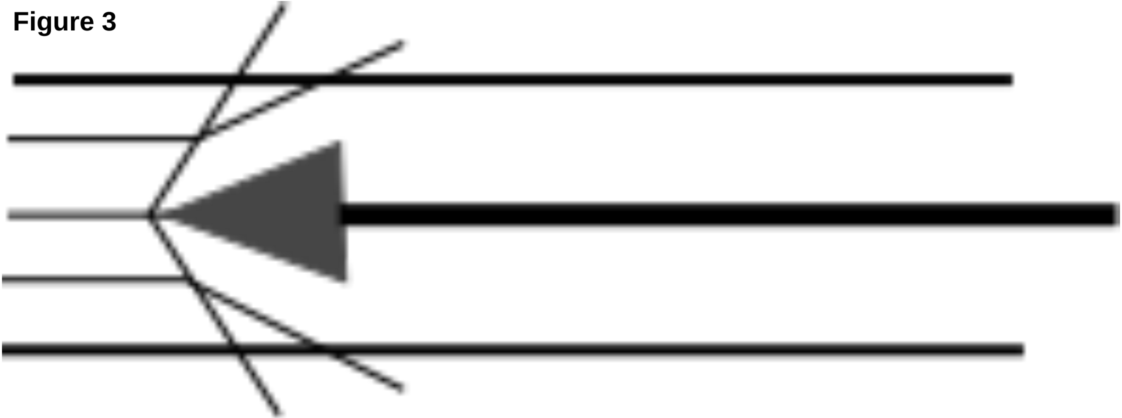

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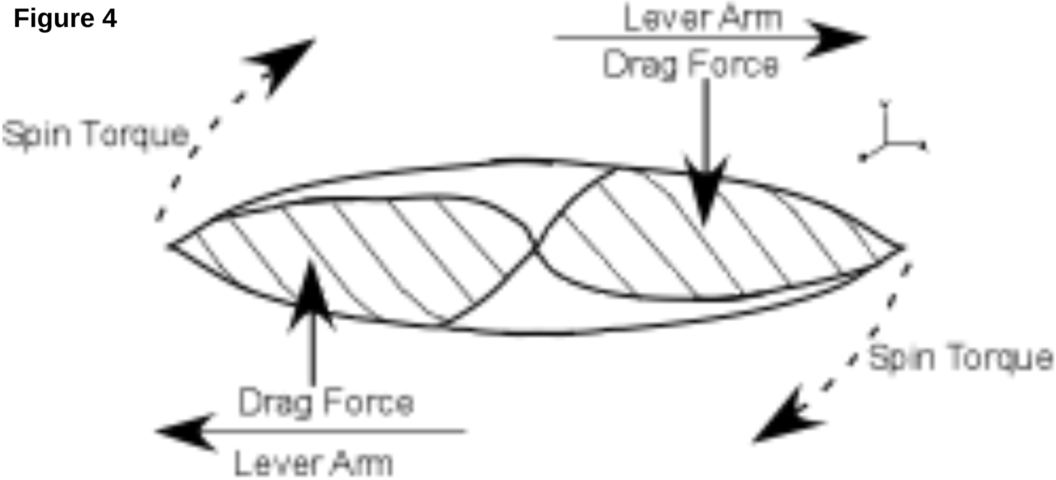
Lever Arm
Drag Force
Spin Torque
Spin Torque
Drag Force
Lever Arm

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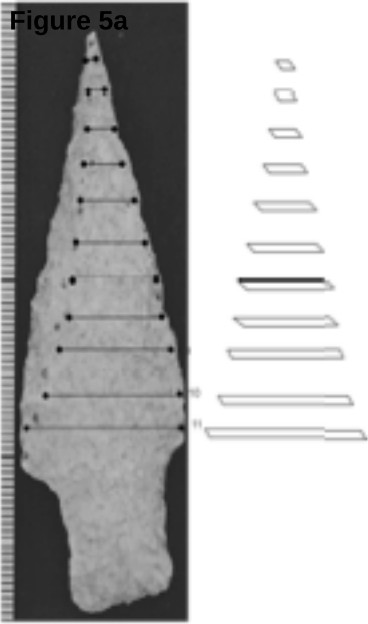

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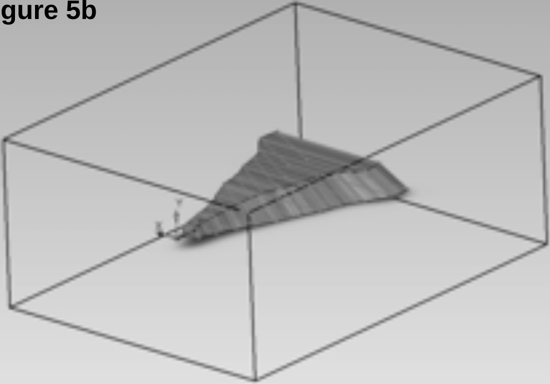
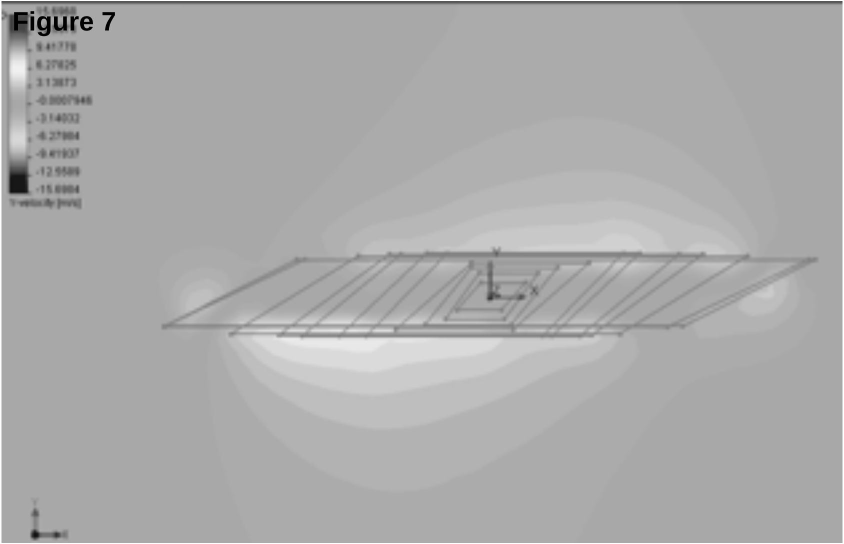


Figure 6a

Figure 6b

**Figure 7**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9.41779
6.27825
3.13873
-0.0007946
-3.14032
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-9.41937
-12.5589
-15.6984
Y-velocity [m/s]
Y
X
Y
X

**Figure 8**

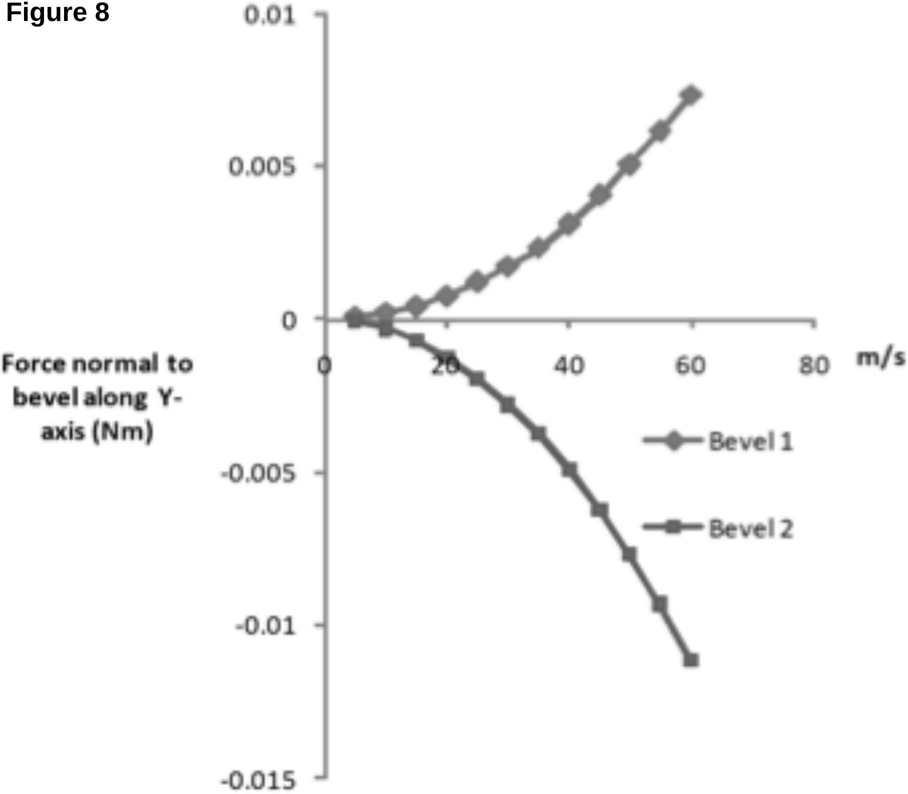
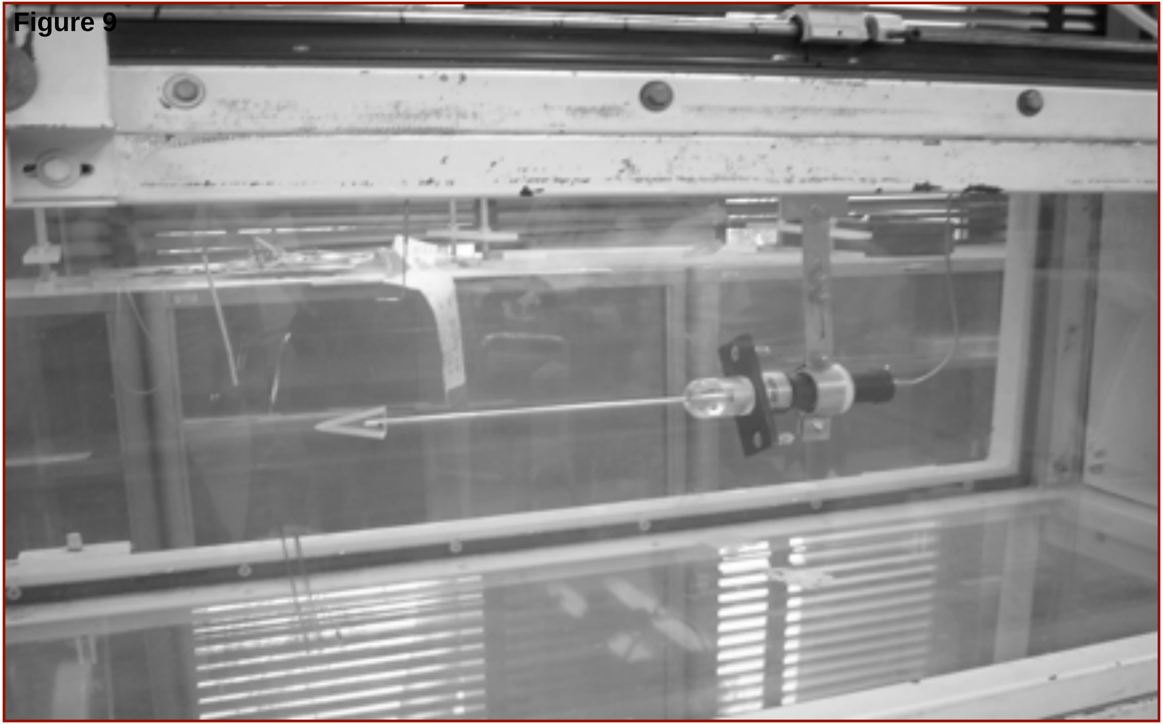

0.01
0.005
0
-0.005
-0.01
-0.015
Force normal to bevel along Y-axis (Nm)
0
20
40
60
80
m/s
Bevel 1
Bevel 2

Figure 9



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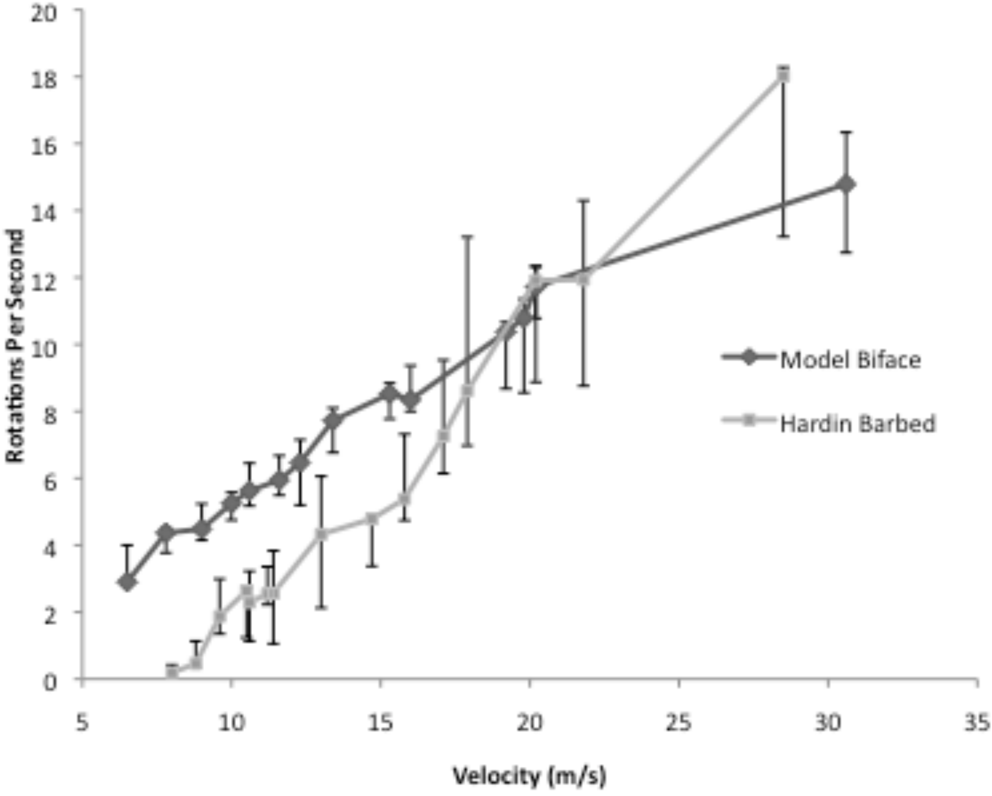

Rotations Per Second
20
18
16
14
12
10
8
6
4
2
0
5
10
15
20
25
30
35
Velocity (m/s)
Model Biface
Hardin Barbed

**Figure 11**

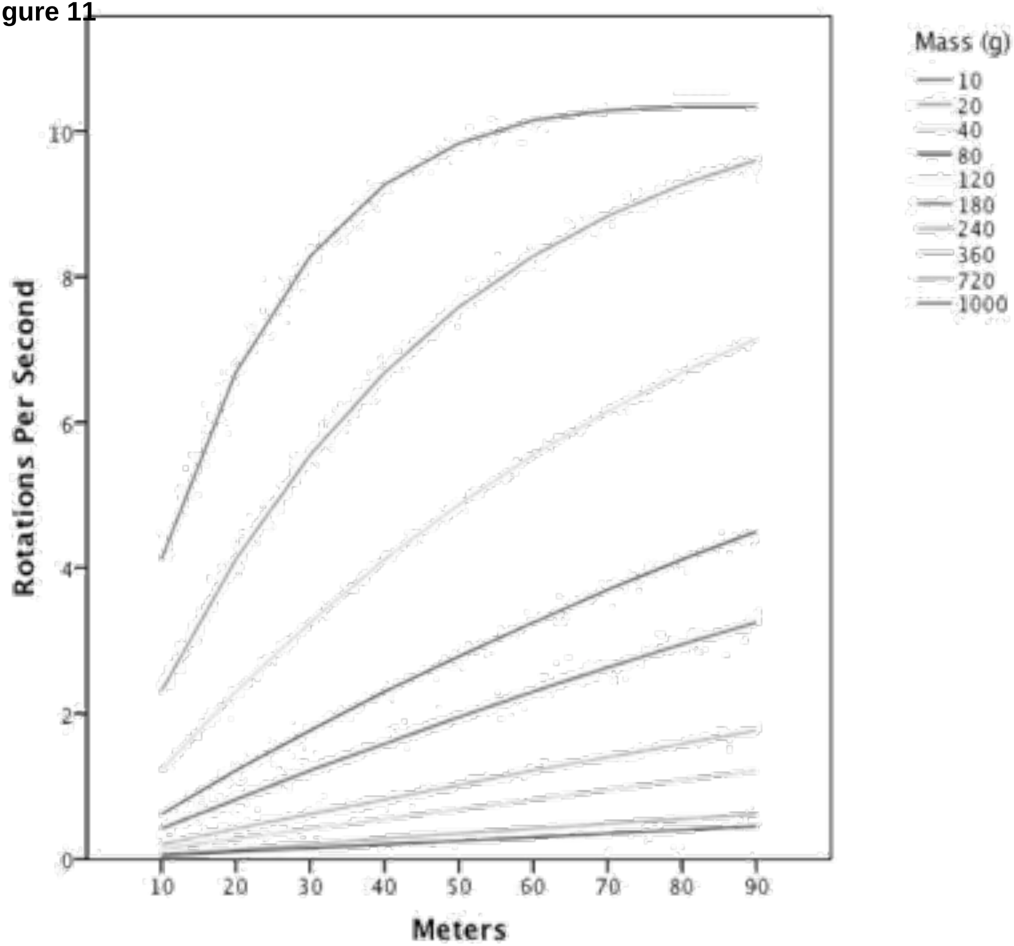
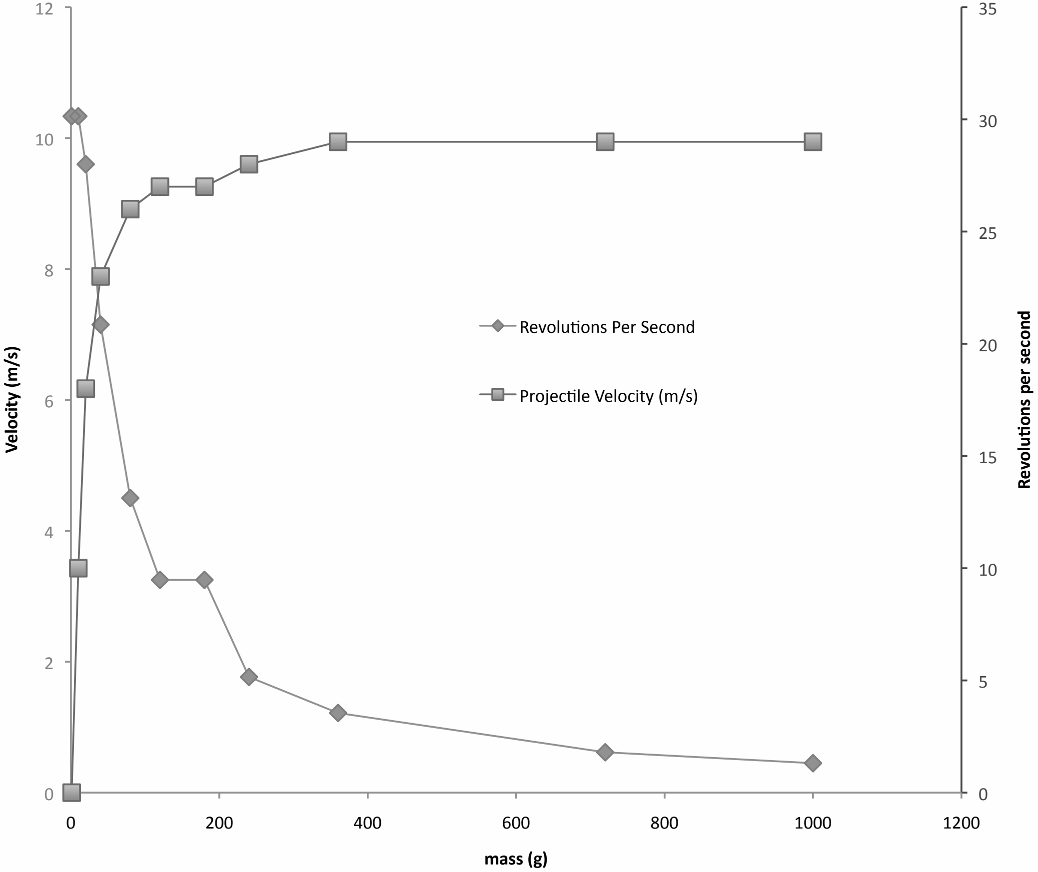

Rotations Per Second
0
2
4
6
8
10
10
20
30
40
50
60
70
80
90
Meters
Mass (g)
10
20
40
80
120
180
240
360
720
1000

**Figure 12**



Velocity (m/s)
12
10
8
6
4
2
0
Revolutions per second
35
30
25
20
15
10
5
0
0
200
400
600
800
1000
1200
mass (g)
Revolutions Per Second
Projectile Velocity (m/s)

Figure 1: Sketch of beveled biface and three cross-sections, illustrating how the angle of bevel changes along the blade.

Figure 2: The effect that spinning has on a projectile's path (dashed line). The rotation of the projectile averages out variability caused by asymmetric shafts and points.

Figure 3: Shear drag is caused by the interaction of the projectile cross section and wind velocity.

Figure 4: Shear drag on the beveled faces produces torque that causes spin.

Figure 5: Model of a biface. Using measurements made from a prehistoric beveled bifaces (A), we created a model for the SolidWorks COSMOSFlowWorks CFD simulation (B).

Figure 6: CFD simulation visualizations of flow trajectories. Simulations were run using wind velocity of 5-60 meters per second in 5 m/s increments. Green lines in images in A and B show the trajectories of air across the biface at 30 m/s. The red and yellow colors highlight areas of increased wind pressure (measured in pascals [Pa], equivalent to 1 Newton/$m^2$ ). Increased air pressure occurs along the beveled faces as would be expected by the shear drag model previously described.

Figure 7: A cross section of airflow trajectories along the y-axis of the model when air flows along the z-axis at 30 m/s. The red and yellow colors highlight areas of positive velocity along the y-axis while blue colors reflect negative velocity along the y-axis.

Figure 8: The total amount of force (Nm) on each beveled face of a pointed biface as wind velocity is increased from 5 to 60 m/s during the CFD simulation.

Figure 9: A simulated beveled biface in the low-power wind tunnel at California State University Long Beach.

Figure 10: Rotations per second measured in wind tunnel experiments on a model biface (blue) and a Hardin Barbed beveled biface (red)

Figure 11: Rotation speed over distance for projectiles of different masses. All projectiles start with 30 m/s velocity. Note that the small masses reach rotation much quicker than the large masses.

Figure 12: Rotation (blue) and velocity (red) after 10 meters for projectiles varying by mass. All projects begin with same velocity. Light projectiles have a high spin rate but low velocity due to low momentum relative to drag. Heavy projectiles have high velocity but low spin. Projectiles between 100 and 225 grams, however, provide the best payoff in terms of velocity and rotation rate.