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Experimentation in Sling Weaponry: Effectiveness of and Archaeological Implications for a World-Wide Primitive Technology

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Experimentation in Sling Weaponry:

Effectiveness of and Archaeological Implications for a World-Wide Primitive Technology

by

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EXPERIMENTATION IN SLING WEAPONRY:

EFFECTIVENESS OF AND ARCHAEOLOGICAL IMPLICATIONS FOR A WORLD-WIDE PRIMITIVE TECHNOLOGY

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The sling is a simple, cheap and effective weapon that was widely distributed among prehistoric and historic populations. Well-known archaeological and textual evidence attests to its widespread military usage in Europe, South America and Central America. However, ethnographic and archaeological evidence also suggest that the sling was widely distributed among Native American populations. Experimentation presented herein suggests that previous scholarship and experimental efforts have significantly underestimated potential velocity, range and potential damage to target organisms. Given the world-wide distribution of sling technology, revision of basic assumptions of weapon capability can have a profound effect on interpretation of archaeological problems internationally and in contexts ranging from warfare to small-game hunting and children’s play.

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Preface

The first time I ever used a sling I was around 11 years old. My grandfather made it for me from a set of leather boot laces and a section of leather cut from an old purse…one of my grandmother's old purses, so apologies are probably overdue. Heedless of our grievous crime, I proceeded to throw around railroad ballast for a few hours, managing to consistently toss the rocks forward, though not much else. Over the next few months I would periodically bring the sling out to throw landscaping pebbles out of my parent's yard (which was probably, in retrospect, also not appreciated). That sling is long since lost, and I went through my undergraduate education, a few years of CRM archaeology, and started my graduate education without a passing thought of slings or slinging.

This interest was rekindled as a project for a primitive technology class, where, honestly at a loss for other ideas, I began building and using slings once again. That project more than anything taught me that I was a very poor slinger, but I've been improving ever since. That first project was in the fall of 2010, and it wasn't until the summer of the following year that I had the muscle-memory epiphany that made slinging click. What had been an awkward and often frustrating movement was transformed into a motion of organic simplicity as my body finally adjusted to the addition to my throwing arm. Whereas before I would cast projectiles weakly and more or less randomly in front of me, now the rocks sang out the pouch with the loud buzz of an angry hornet as it spun through the air, speeding off to get lost in the Colorado pines. It was then that I realized that I had passed over the hump that sling users often reference in online forums and that researchers have too often stopped short of. Suddenly the ancient claims, and the claims of hobbyist users, began to seem far more credible than the scholarly experimentation.

In closing I would like to remind the reader, as I hope to continually do throughout this thesis, that I am not an expert slinger. In any skill there is a continuum of proficiency, and though I have no way of knowing for certain where I lie, I suspect it is in the lower half. All that I have done is get over the initial learning curve (some may liken it more a learning wall) that prevents recognizing the potential of this weapon system. The results I report here are in no way a definitive statement of sling capabilities–the human factor is the limiting one in slinging and I certainly limit the sling a great deal. I have used this technology for about three years, and only half that time in earnest. My capabilities are just that, my own, and it far more reasonable to regard the data presented here as a practical minimum of effectiveness rather than an average. What I hope to demonstrate is that even this “practical minimum” is substantially different from past experimental results, and let this serve as a wake-up call to the need for experimental studies using a large and diverse body of slingers and a variety of slings and projectiles in order to properly evaluate the effectiveness of this tool in a range of applications.

Chapter 1: Introduction

Archaeologists have long sought to understand primitive technologies in order to better understand the traditional societies that used them. While ethnography can provide much of this understanding, some technological systems are amenable to experimental methods. The present study does both; reviewing ethnographic and historical evidence in addition to providing new and significantly improved experimental data to the problem of sling capability.

It is difficult to overestimate how important a revision of our basic understanding of the sling could prove. Slings have been used on every inhabited continent except Australia, dating back an unknown period of time but at least to 5000 years ago and likely further. They have been a hunting tool, a military weapon and a herding aid for shepherds. Its use has spanned massive territories and a plethora of cultures. An accurate understanding of the basic technological capabilities of the sling is essential to forming interpretations about its role in hunting, warfare and other topics. The aim of this thesis is to begin to define sling capabilities through measured experimentation and suggest how these data can be applied to archaeological problems. These problems are suggested by a search through the archaeological and ethnographic record, which I have conducted with a focus on North America, occasionally drawing examples from other regions of the world. In looking at sling effectiveness, it is important to recognize the gulf between previous experimentation and other lines of evidence. Reading classical and ethnographic sources, scholars state that the sling out-ranged many bows of the time and inflicted grievous wounds, citing ranges of up to 500 m. Experimental archaeologists' efforts have shown a different pattern: ranges of 60-70 m on average and projectile speeds insufficient to pass muster at a high-school baseball pitcher tryout. My own experimental study begins to close this gap and empirically demonstrates the potential effectiveness of the sling.

The thesis follows a necessary logical progression from general orientation through previous experimentation to the results of the present study, which are laid out in three successive chapters. Chapter 2 explores sling use and distribution in a general sense, while Chapter 3 focuses attention on sling use in North America. General descriptions of use and prior experimentation are reviewed in Chapter 4. The present experimental design, including description of throwing techniques, and velocity results are in Chapter 5. These velocities are used to compute maximum range for a variety of projectiles in Chapter 6. These results in turn inform a biomechanical exploration of blunt projectile impact effects, within contexts of both warfare and hunting, in Chapter 7. Chapter 8 concludes the thesis by exploring additional avenues of research and expands on the discussion of hunting and warfare. This study accomplishes three primary goals: it demonstrates the archaeological and ethnographic importance of slings in indigenous North America, significantly advances our empirical understanding of sling capability, and it lays out avenues for future research in a number of topics related to sling weaponry.

Chapter 2: A General Background to Slings and their Distribution

Introduction.

Before looking at slings in North America, it is necessary to review what slings are, how they are used and where they have been used in a global context. Sling research has been advanced in other regions of the world to a much greater extent than in North America, so this review lays the groundwork for any further discussion of North America in particular. This chapter focuses on the basic elements and design of slings and sling projectiles, the general technique of using a sling, and (briefly) the distribution of sling use around the world.

Sling and Projectile Design.

The designs of slings, though variable in the details, share certain basic characteristics across space and time. The fundamental parts are a pouch and two cords. One cord is designed to be retained through the throwing motion and often ends in a loop to be attached to the wrist or a finger of the throwing hand. The other end of this cord is attached to the pouch. Pouch design can vary in size, shape and whether the pouch solid or split, as in many Peruvian examples (Means 1919; American Museum of Natural History [AMNH] 2011). A second cord is attached to the other end of the pouch. This cord is designed to be released during the throw, thus opening the pouch and launching the projectile. This cord is approximately the same length as the retention cord and is often ended with a knot and/or tassel that aids in controlling the release (AMNH 2011;

Dohrenwend 2002:33; Korfmann 1973:37-38). Construction is straightforward and a variety of materials can be used. I have made multiple slings of braided twine with woven pouches and have found that a sling could be easily manufactured in less than three hours so long as fibers are already processed. Dohrenwend (2002) makes his slings with commercial cordage and a leather pouch and construction time would be considerably less with these materials and design. Low-cost materials, short construction times and low requisite skill in manufacture combine to make the sling an extremely inexpensive weapon compared to systems like the atlatl-and-dart or bow-and-arrow.

Projectiles can be as simple as a pebble requiring no modification or as complex as molded clay, lead shot, or groundstone projectiles. Projectiles also vary in shape. While Korfmann (1973) and Dohrenwend (2002) both advocate use of smooth, water-worn pebbles, experiments by Vega and Craig (2009:1266) used stones that were roughly rectangular and of varied sizes. In other words, while carefully selected or shaped projectiles may be preferable, they are by no means required to be functional. The shape of projectiles has also varied, showing preferences that change by region and through time. Pecked stones in Bagor, India were described as perfectly spherical (Misra 1973:105). Around 3500 B.C., teardrop-shaped clay projectiles were used in the unsuccessful defense of a city in what is now Syria (Reichel 2009); this design is also suggested by Xenophon, who recorded that the “wide head and tapered tail” of sling projectiles made extraction from the body very difficult (Gabriel and Metz 1991:75). Aside from this shape, researchers in the Aegean have found many spherical projectiles but also biconical bullets, suggesting an evolution of projectile design and material (Vutiropulos 1991: 281). The American Museum of Natural History (2011) and York and

York (2011) document a large ethnographic and archaeological collection of biconical stone projectiles from various areas in the Pacific islands. Greek and Roman slingers used similarly shaped lead projectiles extensively (Dohrenwend 2002; Greep 1987; Korfmann 1973; Lee 2001) and mathematical modeling has shown that these dense projectiles would have an advantage in lethality over stone bullets (Skov 2011). Projections of sling lethality are expanded upon in Chapter 6 of this text.

How a Sling Works.

The modern researcher has difficulty studying slings due to the unique way in which the projectile is cast. In the bow and arrow, compression and tension store mechanical energy in the stave and release this energy to the arrow on release. The rubber band slingshot stores energy in the form of elasticity. Similarly, a gunpowder firearm releases chemical energy and propels the bullet by means of expanding gases. In each case, stored energy is transferred to the projectile, converting potential energy to kinetic motion. In contrast to these commonly known systems, more primitive weapons such as the spearthrower (atlatl) and sling do not store energy in a static system. Rather, energy is built in the projectile through the motion of the body and the weapon. This energy is not released to the projectile as a separate action but as a part of the same motion that built the energy in the first place. This fluidity of motion has been a major challenge to controlled experimentation, which has led to dearth of understanding in how these weapon systems actually work. Essentially, with the fluid motion weapons it is difficult to separate the capabilities of the weapon from the skill of the user. One effect of this is that the body mechanics of differing throwing techniques can produce vastly different results. While this problem has received attention by researchers concerned with the spearthrower (to name only a few such references: Raymond 1986; Whittaker and Kamp 2006, 2007), comparable work is lacking for slings.

Previous authors have stressed that a greater length of sling imparts a greater velocity to the projectile (Dohrenwend 2002; Finney 2005, 2006; Korfmann 1973; Skov 2011). This implies that the primary mechanical advantage has been thought of in terms of extending the arm. If a throwing motion is thought of in terms of rotary motion, the sling and arm together form the radius of a circle. For any given rotary velocity a larger radius results in a greater tangential velocity along the outer edge of the circle. A projectile released at a higher velocity will travel farther, reach the target more quickly and strike with more energy than a lower velocity projectile (The Physics Classroom 2013: http://www.physicsclassroom.com/Class/vectors/).

Practice with the sling has shown that explaining the sling's advantage in terms of simple leverage is inadequate. Using most techniques, the arm does not inscribe as large a throwing motion as when objects are thrown by hand. Motions which are most effective in casting projectiles with the sling do not seek to maximize the total of sling and arm length but to controllably accelerate and release the projectile. While extending the throwing lever does happen to some degree in slinging, the primary advantage seems to be an ability to bypass some biomechanical limitations of the human arm and body. Small impulses sent from the wrist and forearm can easily rotate a loaded sling at relatively high speeds. During the final motions of a sling throw the pouch can be accelerated to a still higher velocity as the projectile is cast. Precisely how the sling and body coordinate during a cast and how different techniques confer mechanical advantage could be further researched utilizing high-speed photography, which should be a great aid to resolving these questions. See Chapter 5 for further discussion of different slinging techniques and the perceived advantages and disadvantages of each.

The Distribution of the Sling.

The most widely known evidence for sling use comes from the Old World. A Late Mesolithic town in India contained probable pecked-stone sling bullets (Misra 1973:105). Iron Age hillforts across Britain have been found with caches of slingstones and molded clay projectiles (Finney 2005, 2006). At Hamoukar, an urban settlement in modern-day Syria, archaeologists documented extensive use of clay projectiles by both attackers and defenders when the city was stormed around 3500 B.C.E. (Reichel 2009). Egyptian, Greek, Assyrian, Judean, Roman and Persian armies all used slingers historically (Dohrenwend 2002; Echols 1950; Korfmann 1973; Lee 2001). Cast lead bullets were recovered in quantity at the site of Olynthos, Greece, which was stormed in 348 B.C.E. (Korfmann 1973; Lee 2001).

Slings were also used extensively in Oceania, where European colonialists have often recorded instances of sling use (Crump 1901; Judd 1970; York and York 2011). A large number of ethnographically collected slings can be viewed through the AMNH website, as can a selection of biconical groundstone projectiles. York and York (2011) discuss the distribution of slingstone finds throughout Oceania in some detail.

In the New World, slings were used extensively in South America, where they were a principal military armament through the Contact Period (Dohrenwend 2002:32; Means 1919; Vega and Craig 2009). A large number of slings have been preserved in

Peru (see AMNH 2011), and hilltop fortresses throughout the former Incan empire contain caches of stone projectiles (Means 1919; Vega and Craig 2009). Arkush and Stanish (2005) have defended this interpretation of Andean 'forts' as military defensive structures in the face of a pervasive denial of full scale warfare by many archaeologists in the region. Conquistadores in Mexico also encountered native military slingers (Means 1919:317-318). Driver (1969:326) describes the incorporation of slings within Aztec military equipment and training.

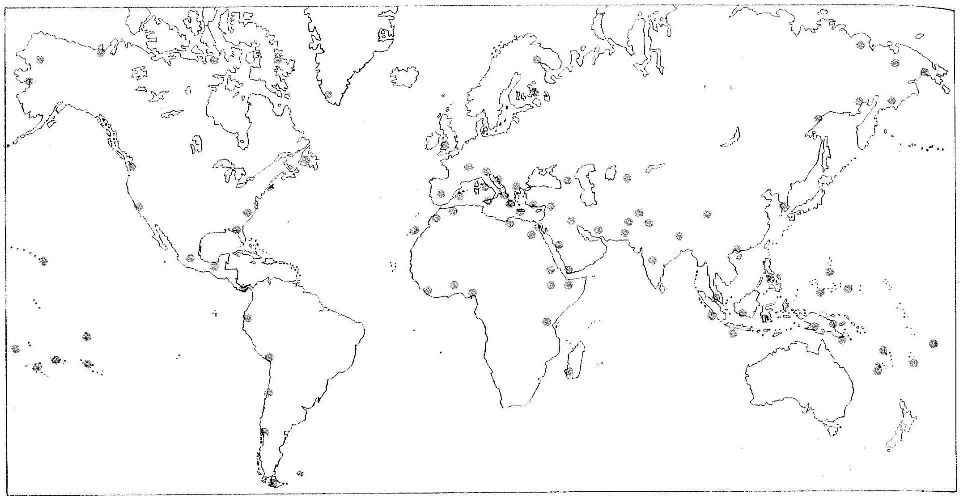


Figure 1. Distribution of the Sling Worldwide. (Korfmann 1973:42)

To date slings have not been documented in Australia, but have been found on every other continent excluding Antarctica. Archaeological evidence of sling use, on the other hand, is relatively scarce in North America. This has led to a lack of recognition among archaeologists and other researchers, the vast majority of whom have some familiarity with other weapon technologies such as the bow and arrow, the spear/lance or the atlatl and dart. As current trends in research (re)gravitate towards warfare and the importance of small game hunting and other less 'prestigious' activities, researchers can gain valuable insights into specific cultures of study through an understanding of the basic capabilities of their projectile weapon systems.

Conclusion.

The sling has been an effective tool in warfare and hunting applications throughout the world. We are only beginning our exploration of this technology, and the topics introduced will be expanded upon later in the text. This brief overview serves as a basic orientation to sling technology, useful as we begin to focus our discussion of North America.

Chapter 3: The Sling in North America

Introduction.

Sling use in North America is supported mostly through ethnographic, rather than archaeological, evidence. This is unsurprising, since slings themselves are constructed entirely from biodegradable materials and sling projectiles may often be difficult to recognize within archaeological contexts. After reviewing the archaeological and ethnographic evidence, this chapter will explore sling use and variation utilizing ethnographic databases.

Archaeological Evidence.

Direct and unmistakable archaeological evidence for pre-contact sling use is extremely sparse. One preserved sling has been reported. Heizer and Johnson (1952) document a sling recovered from the grave of a six-year-old male, from Lovelock Cave, Nevada, and dated to 2482 ± 260 years BP. York and York (2011) cite subsequent re-dating of the Lovelock Cave stratigraphy, which dates this artifact to over 3,200 years BP. Nearby Humboldt Cave also contained preserved sling pockets, dating to ca. 2000 BP.

These finds are the most unequivocal evidence of prehistoric sling use in North America, but probable sling projectiles have also been identified in archaeological contexts. Means (1919:317) mentions that, “[it has] been assumed that the clay pellets found in some of the California sites were sling missiles.” Biconical groundstone and clay artifacts—strikingly similar to sling projectiles in the Pacific Islands—were also found in Lovelock Cave. These sorts of artifacts have been discovered all over the California and southern Oregon coastline. Dating for these artifacts has not been resolved, but may extend as far back as 13,000 BP. These objects have not previously been interpreted as slingstones; they are often referred to as gaming stones, charmstones or bola stones (York and York 2011). Since sling projectiles are often merely unmodified stones, identification of manuports (especially in concentrations) of a suitable size and shape may indicate possible sling use. Future research could focus on the reinterpretation of known caches of stones or clay objects. York and York (2011) suggest such a reinterpretation for some Poverty Point Objects.

Peter Bleed (personal communication, 2011) has suggested a review of rock art imagery as another research approach that may reveal slings in the pre-contact past. Depictions of slings and slingers have been found in other areas where slings were known to have been used (Finney 2005, 2006; Korfmann 1973; slinging.org/image gallery 2012), so finding such imagery in North America may be probable. York and York (2011) have tentatively identified one such petroglyph, “slinging man,” near China Lake, CA.

Figure 2: “Slinging Man”, Little Petroglyph Canyon, China Lake, CA. (York and York 2011)

Another set of possible slinger petroglyphs has been identified by Golio and Golio (2004), which are more ambiguous but may depict either slingers or bola users. York and York (2011:93) cite communications claiming the prevailing current interpretations of these glyphs as either dancers or snake handlers.

Art interpretation is unlikely to become less ambiguous, and researchers will need to be cautious against over-interpreting imagery. As an admittedly somewhat distant example, Trajan’s Column in Rome contains a depiction of multiple slingers operating with very short slings, large stones and in a seemingly close formation. Multiple authors concerned with Old World sling use have interpreted this image at face value, suggesting that underarm slinging with short slings allowed for the use of close formation and suggesting that large, spherical ammunition was in common use within the Roman military at that time (Dohrenwend 2002:45; Ferrill 1997:25). This interpretation does not take into account the limitations of the medium or the intent of the monument—factors which undoubtedly influenced the relief sculpture. The perceived close formation is more likely a combination of the desire to depict a large number of figures to convey the might of the armed force, the angle of the viewer on the flank of the formation, and the difficulty of portraying depth when sculpting in shallow relief. The need to convey important details at a distance could explain the large projectiles.

Figure 3: Detail of Slingers on Trajan's Column. (Slinging.org 2012)

Ethnographic Evidence

Means (1919) acknowledged the widespread presence of slings in the North American ethnographic record, but stated that due to a lack of archaeological evidence, it could not be established that slings predated European contact. This position was undermined by the Lovelock Cave find, and Heizer and Johnson's (1952) map synthesizes the ethnographic information from the Great Basin into an effective argument for widespread distribution of the sling in this region (map is reproduced below in Figure 4). Cultures for which the sling is documented are signified with a concentric circle symbol, cultures without knowledge of the sling are signified by a dot. Heizer and Johnson (1952) also state, however, that in many groups the sling had fallen into disuse or was known only as a toy. Writing in 1969, Harold Driver (85) states that the sling is reported for approximately half the North American tribes. Coffin and Driver (1975) found that 164 of 244 North American tribes had knowledge of the sling. York and York (2011:73) claim to have added to this total in their review of North American sling use. In spite of this evidence, Colin Taylor's (2001:59) review of Native American weaponry states only that the sling "was used… by some of the Californian coastal tribes such as the Miwok and Pomo."

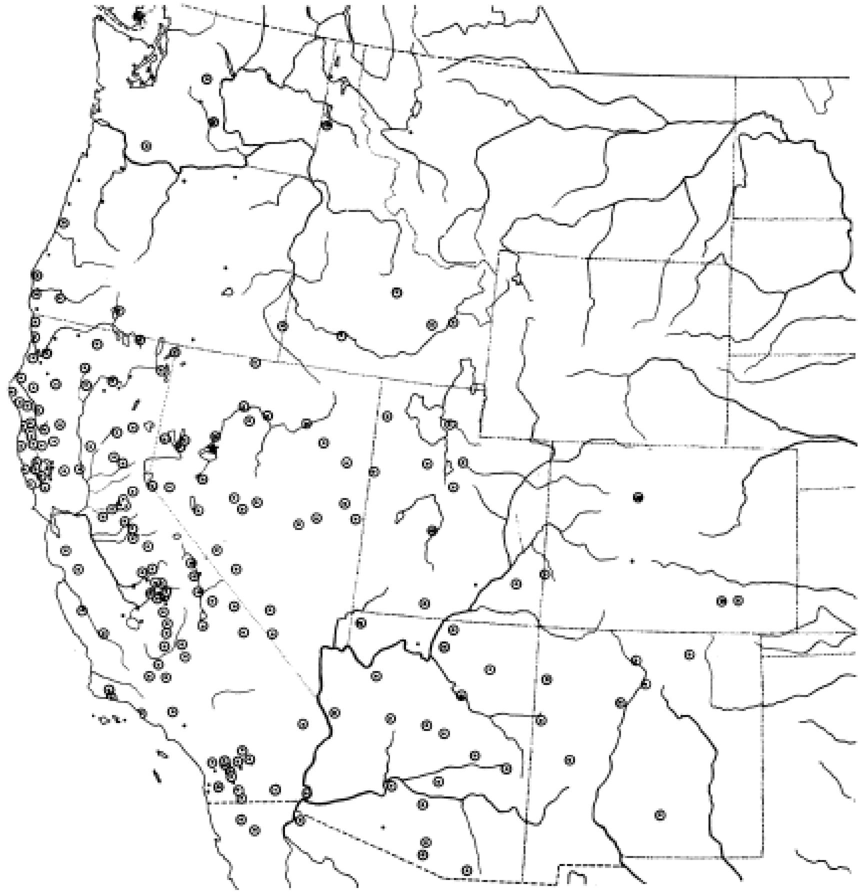


Figure 4: Distribution of the Sling in the Great Basin, American Southwest and West Coast. (Heizer and Johnson 1952:Figure 68)

These general statements make it clear that among researchers focused on sling technology, evidence of its use is fairly ubiquitous. These reviews have not, however, influenced perceptions of non-specialist researchers, who generally have much less knowledge of this technology's distribution. That this gulf between specialists and general archaeological practitioners has persisted is probably due to the scarcity of publications on this subject in the last several decades (York and York 2011).

At present, the archaeological evidence can only attest to knowledge of the sling on the continent well before European contact. The prehistoric distribution of the sling remains unknown and will likely never be fully resolved. It is possible that some native groups adopted the sling following contact, receiving the technology either directly from Europeans or from other native groups. Nonetheless, given the difficulties of detecting sling use in the archaeological record (unmodified projectiles and decomposable slings), ethnography may offer the best opportunity for evaluating sling distribution and use in immediately pre-Columbian times. Archaeological evidence, early contact accounts and a general pattern of declining use following contact are all cited as evidence that sling use in the ethnographic record is not a result of European contact.

Evidence from the Human Resource Area Files and the American Museum of Natural History.

York and York (2011) have written extensively on sling distribution in Oceania and the New World, and this section is not intended to match those efforts. This analysis will instead explore variability in slings and their uses across North American cultures.

Two databases have been identified that may add to the record in this manner. The first is most familiar to anthropologists: eHRAF, or the Electronic Human Resource Area Files, searches a set of 258 cultures from across the globe. Of 42 North American cultures, the eHRAF search revealed a variation of “sling” in 29 cultures’ ethnographies. Only 22 of these cultures’ ethnographies actually contain mentions of sling weapons, the rest describe baby slings, rifle slings or use sling as a verb. Ethnographies for a 23rd culture, the “Copper Inuit,” mention only improvised use of tumplines as slings; no specialized slings were manufactured by this group.

The second database is maintained by the American Museum of Natural History (AMNH) and contains photographs of their ethnographic collections. A search through their collections yields 21 records for “sling,” but only 12 of look to be genuine slings, the remainder being carrying slings, bolas, or other technologies. The AMNH provides some information that can be useful in studying sling distribution and technological variation, but the methodologies behind some of these data are unclear, making interpretation of some variation impossible.

Photoanalysis of the AMNH Records.

To use photographs as ethnographic evidence it is imperative that as much context as possible be gleaned from the graphics themselves and from any associated documentation. Therefore the information assembled from the photographs and captions were organized in a table format, which allows for quick reference to the information provided in each photograph and allows for comparison between them.

Photographs at the AMNH are ‘record’ photographs taken in front of neutral backgrounds. The object is separated from any visual representations of context, and any photo editing is minimal, intended only to enhance the image. The photograph’s context cannot be ascertained visually but must come from the captioned information provided with each artifact. Captions are standardized—probably for ease of collections management—so a comparable set of data is available for each artifact. These are reproduced in Appendix A for reference. Additional information on sling components was ascertained visually where possible and is also listed in Appendix A.

Information garnered from these photographs suggest that some aspects of technological variation across geographic space could be traced in a future effort. Such an effort would require a significantly larger sample (The AMNH has only 12 North American slings). York and York (2011) provide examples from the Chicago Museum of Natural History and suggest that additional slings may sit unrecognized in fiber collections around the country. This is only the first of several difficulties. The AMNH states no methodology for how slings were measured during the photo archiving process. It appears likely, but is unverifiable from the information given, that width and height refer to the dimensions of the pouch in most cases. Similarly, the measured length sometimes appears to be a reference to the full length of the sling from retention end to release end, but in other cases is most likely a measurement from one cord end to the center of the pouch. The North American collection, in contrast to the South American collection, does not include a scale or color card, which would enable resolution of this issue via photogrammetric techniques. Some of the slings are shown bundled or folded, or are taken at angles which obscure details of interest to the analyst. Each artifact has only one photograph, so issues that could be resolved if multiple viewpoints were available must instead remain unanswered for the time being. In light of these limitations, a full analysis of sling variability would require direct access to the materials.

Even so, analysis of the photographs did reveal the use of what I have called a ‘toggle,’ a release aid that I have not heard mentioned in any previous texts nor seen in any other photographs. In one case the toggle is a separate scrap of leather sewn into the release thong, which is wider and appears to also be thinner to aid in gripping the release cord. In the other case, a knot is tied below two pieces of leather thong. From the picture it cannot be determined whether one thong was stitched into the release cord (also of leather thong) or if an additional scrap was simply tied on. Unlike the first case, it is not obvious that the thong would be the release node (the part held during throwing) or if the knot would serve this purpose. In the latter case, the ‘split toggle’ could be referred to as a tassel instead. Direct examination of the artifact could probably resolve this issue.

It is easier to analyze the materials used. The captions only list materials involved in the entire artifact, but it is usually possible to visually distinguish which elements are made up of what material. In many cases the slings were produced from a single material, which obviates this difficulty entirely. Pigment is difficult to detect in any of the photographs provided, though it is listed as a material component or possible component in four slings (a full 1/3 of the sample). A total of three material components are listed as questionable. Without direct access to the collections it would not be possible to determine these cases one way or the other.

The context of acquisition is documented for all slings in the assemblage. These listings do not detail the exact conditions of the original collection, but do offer some approximation. It could be hypothesized that ethnographic artifacts better reflect the prehistoric past if they were collected sooner after contact rather than later. The earliest artifact in the collection dates to 1895, and the latest to 1916. This dates the period of collection well into the post-Contact period, and casts some doubt on their authenticity as expressions of prehistoric methods of manufacture. The items least tainted by this suspicion are those from the Canadian West Coast and the two Inuit (Eskimo) slings since these were collected relatively early from areas that had more limited contact with

Europeans. In contrast, most other slings were collected after a long period of contact and in some cases displacement to reservations.

In some cases the circumstances of the collection are listed in parentheses. ‘Expedition’ contexts seem more likely to find unaltered material culture, but the purpose of these expeditions is not established here. Two expeditions were led by military men, but does this actually suggest venturing into unknown territory? Two other slings were purchased, while an additional one was a gift. Without more context than these simple one-word descriptions it isn’t possible to parse this reliability issue any further.

Some additional insight can be gained by looking into the professions of the donors and, where listed, the collectors. Most importantly, however, is the context of the artifact’s creation, which is not referenced by the AMNH at all. Was the sling manufactured on the spot for the ethnographer? Was that ethnographer paying or trading for artifacts, creating a financial incentive to offer up novel specimens? If the artifact was in the community prior to the ethnographer’s arrival, what had been the use-life of the artifact? Once again, the analysis conducted here stops short of that required for a full investigation, which should delve into the full array of primary documents associated with these expeditions and ethnographic collecting excursions.

Figure 5
Nootka (Clayoquath) war sling
(AMNH, 16/2022)

The sling is composed entirely of plant fibers. The cords are braided, while the pouch has braided and netted elements. There is a possible retention loop, but resolution was insufficient to confirm this.

Figure 6
Kwakiutl sling
(AMNH, 16/9278)

Sling has a tassle on the end of the release cord and a finger loop on the retention side. Cords are braided leather, the pouch is diamond-shaped and solid

Figure 7
Zuni sling
(AMNH, 50.1/276)

This sling is composed of leather, with leather thong cords and a solid, concave-edged diamond pouch. Small holes are cut along the fold in the pouch and are barely visible here. The sling once again has a finger loop for retention and a 'toggle' forms the release node.

The limitations inherent in the use of photographs as ethnographic evidence are primarily concerned with the context of the artifact in question. The written ethnographies explored here could potentially provide context but are separate from the AMNH photograph records. For this reason, ethnographic accounts are treated as a separate section of evidence. Of the 23 sling-using cultures uncovered through eHRAF, the Navaho and Pomo each provide a relatively detailed account. Appendixes B and C organize pertinent information distilled from the eHRAF accounts. The amount of information available for the Navajo and Pomo allowed these cultures to be analyzed individually as well. In these cases, selected traits were compared between sources to help parse variation in the ethnographies.

Cross-Cultural Comparison.

This section primarily aims to document variation in sling material culture and sling usage by looking for presence of selected traits within these categories cross-culturally. Material culture traits that were included in the analysis are: material of cords and pouch, retention design and retention cord length, release design and release cord length, pouch dimensions and shape, and projectile material, size and shape.

Sling usage was divided into the following categories: warfare; ritual combats, games/training; large game, small game, bird and waterfowl hunting; child's toy; crop protection; herding aid; and use from boats. Ritual combats are defined following the suggestion of Arkush and Stanish (2005:11) as "contained, festive combat." This is distinct from warfare, which is "potentially destructive" in that it can have gross demographic or political consequences. The category of "Ritual Combat" is also treated here as distinct from the "Games/Training" category in that the latter is within groups while the former is between groups. Either of these categories could be explored using signaling theory: Ritual Combats are preponderantly group signaling whereas Games/Training are predominantly individual-level signals, though there could certainly be variation and significant overlap between the two. These categories can also carry different expectations of lethality: while death can occur from violent training games, such outcomes are not regarded as ideal (Goodwin and Goodwin 1942), whereas in ritualized combat with other groups the intent may well be to seriously injure or kill members of the opposite party (Arkush and Stanish 2005; McIlwraith 1948; Vega and Craig 2009).

Hunting was divided into four categories but it should be noted that there is some significant overlap between some of these. Large game hunting is a purely distinctive category, and no groups report hunting large game with slings. Among groups that use the sling for hunting smaller game, the prey seem to be targets of opportunity—often without distinction between small mammals or birds. Waterfowl hunting is included as a separate category because waterfowl-hunting strategies employed by the Pomo involved unique adaptations of sling technology (Barrett 1952; Kniffin 1939; Loeb 1926; Powers 1877; Theodoratus 1971). In at least one culture, sling technology also appears to have been adapted to support agricultural and pastoral economies. Using slings to drive pests away from crops could be an indigenous adaptation, while use of slings as a herding aid certainly originated post-contact and could have been imparted by the Spanish directly. Though evidence of such uses is presently scarce in North America, these variations on "typical" sling use are interesting examples of adaptation of material technology to a changing cultural environment.

Warfare. Use in war is documented for 9-11 cultures of the 23 cultures that used slings. This includes the Alutiiq (Birket-Smith 1953), Cherokee (Gilbert 1978), Havasupai (Cushing 1882; Spier 1928), Mescalero Apache (Opler 1969, 1983), Navajo (Kluckhohn et al. 1971), Nuu-chah-nulth (Drucker 1951; Fleisher 2011; Koppert 1930), Nuxalk (McIlwraith 1948), Pomo (Barret 1952) and Yuki (Foster 1944; Gifford 1965); and possibly the Tlingit (De Laguna 1960) and Zuni (Cushing 1896).

Further information than this is only available for a few of these cultures. Among the Havusupai, Cushing (1882) states that slings were at that time regarded mostly as toys, but were used as weapons previously. Spier (1928:249) writes that the sling was not "seriously considered a weapon." He also relates the account of Sinyella: "The last time the Yavapai came I was a young lad. I made a sling and threw rocks at them. I do not know whether I hit any or not; I was high up near the top of the red cliff."

Kluckhohn and colleagues (1971) relate conflicting accounts from Navajo ethnographic interviews. While some informants claim that slings were weapons of war, others claim they were scarcely suitable for hunting. The Navajo and Pomo accounts are parsed further in a later section.

The Nuu-Chah-Nulth told Drucker (1951:334) that slings, "have not been used in war for a long time, but…elders taught them that the slings were very effective before firearms." Koppert (1930) similarly finds that the sling probably used to be a weapon although at that time it was only a toy.

McIlwraith (1948:341-342) tells us that Nuxalk warriors would use slings from their canoes. Slings were also used from the shore against oncoming canoes, as “large shields of moosehide…[were] held up by the bow paddler as the craft neared the shore to protect him and those behind from arrows and stones cast by slings.”

Barrett (1952) records that the Pomo used slings in warfare, and that their war slings differed from the slings they used for waterfowl hunting. Loeb (1926), however, claims that the slings used for waterfowl hunting are the same as for other activities. This discrepancy is discussed below in the section dealing specifically with ethnography among the Pomo.

In open battle the Yuki would use slings and bows during the approach and then use clubs and knives in close-quarters (Foster 1944). Powers (1976:129), however, states that battle lines rarely made contact; enemies would “shoot at each other until they ‘get enough,’…and go home.” Gifford (1965:52) says the sling could be “effective against a man up to one hundred and fifty feet” (46 m).

Regarding the use of the sling as a war weapon by the Tlingit, De Laguna (1960) states only that investigation was unable to establish whether the sling had been used in war. In Zuni mythology, a message was wrapped around a slingtone and flung towards the enemy, who were convinced by it to offer peace terms to the beleaguered Zunis (Cushing 1896). This tale implies that slings were at least part of the warriors’ equipment, though it does not necessarily imply that it was ever used in combat.

Ritual Combat. Sling use in ritual combats was only recorded for the Nuxalk (McIlwraith 1948:383-384). Rival villages would, before the arrival of muskets, commonly arrange fights when they were provoked but not to the point of warfare. A notification would be sent to the rival village stating where the 'attack' would take place and how many canoes would be sent. The opposing canoes would pair off in combat, each trying to beat the other side into submission with stones. A man positioned in the bow of each canoe would hold a moose-skin to block the stones. Once a canoe abandoned the fight they were not pursued, nor would the victor move on to other enemies. Men never left the canoes, so combat never became hand-to-hand. Casualties "…consisting chiefly of broken heads, were sometimes almost as serious as on a foray, but no revenge was ever claimed in case of death so caused" (McIlwraith 1948:384; see also Arkush and Stanish 2005:12-13 for description of Andean *tinku*, a ritualized combat with slings).

Games/Training. Slings are used in games or training exercises by five to six cultures in the sample, including the Hopi (Dennis 1940), Nuu-Chah-Nulth (Arima and Dewhirst 1990; Sapir and Swadesh 1955), Nuxalk (McIlwraith 1948), Ute (Smith 1974) and Western Apache (Buskirk 1986; Goodwin and Goodwin 1942) as well as possibly for the Klamath (Spier 1930). Spier mentions that the Klamath used the sling "only in sport" (1930:84), but it is unclear whether this can be interpreted to include organized games.

The Hopi played a combat game wherein boys would divide themselves into an attacking 'tribe' and a group of 'Hopi' defenders. The leaders determine who picks their warriors first by seeing who casts a stone the farthest. The boy who casts farther gets first pick and usually elects to be the attacker. The defenders would position themselves on high ground while the attackers (representing the Navajo, Apache, Ute or Havasupai) approach from below. The boys would throw rocks by hand as well as by sling, and would use heavy blankets as shields from the rocks. Once the battle closed to hand-to-hand, the game changed to a wrestling contest. In spite of the shields, participants were often injured (Dennis 1940:62-63).

Arima and Dewhirst (1990) record that Nuu-Chah-Nulth children would engage in stone throwing contests and slinging, but provide no details on how such contests were organized. Sapir and Swadesh (1955:35) say Nuu-chah-Nulth young men used to "shoot at each other with slings at long range…They too ended the game when someone got hurt by being hit on the side of the head." Sapir and Swadesh (1955) also describe a game similar to the Hopi combat game but using slingshots. It is possible that slingshots replaced slings in this game, but this is speculative.

The Nuxalk would also test bow paddlers before the ritual combats previously described.

> To test their endurance, each [bow paddler] took his place and the canoes were paddled towards the shore while all the other inhabitants, lined up on the beach, showered stones on them. On this first test, six of the twenty fell beneath the avalanche of projectiles and were accordingly considered too feeble. Their places were taken by six others who were tested the same way the following day, and the same procedure was repeated until the twenty strongest men in all Kimsquit had been found. (McIlwraith 1948:383)

Among the Ute, boys would have contests in slinging for distance (Smith 1974:113), while the men would sometimes sling stones at each other "'just for fun'" (Smith 1974:233).

The Western Apache also used slings in mock battles amongst themselves (Buskirk 1986; Goodwin and Goodwin 1942). The game was limited to older boys and was meant to imitate real warfare. The men would observe and sometimes even fire their guns overhead to add to the realism. Goodwin and Goodwin (1942) also relate the direct accounts of two informants. John Rope was one such participant:

> We used to divide into sides and make war on each other. Each side held a war dance, just like the real thing. There always used to be an old man at these dances who would direct us in carrying it out properly. One boy was chosen as chief on each side, a boy who was not afraid. .. When we started in to fight each other, the chiefs led us. After the battle started, one or two would be captured. We would whip them with sticks and make them bring rocks to us for our slings… One time when we were set to have a battle these two boys [the chiefs] each made their men line up behind them. Then they walked out in front and prepared to fight each other singly with slings. The [other] leader threw first, but our chief ducked and the rock went over his head. Then he got up and made believe he was about to throw at the [other] chief. The latter ducked, and, when he did, our chief really threw and hit him right in the back of the head. He was knocked unconscious and bled a lot. All our boys thought he was dead. We were scared and ran off. (Goodwin and Goodwin 1942: 485)

Neil Buck's account comes from 1893-1903, well into the reservation period in that area. He was never a participant but observed the game as a child:

> Down at Dewey Flats, the Eastern White Mountain camps were on one side of the river, the Western White Mountain camps on the other. The boys from each side played this game against one another. They fought with slings and stones. The Yavapai, camped on the river below us, fought the Arivaipa boys near them in the same way. Big boys and sometimes men took part. (Goodwin and Goodwin 1942: 486)

In this account, the game is played between groups rather than within them, blurring the line between these combat games and ritual combats. There is no suggestion that the intent of participants was any more violent, however.

Combat games seem to have been relatively common across cultures and would have prepared participants for true warfare. These games could be violent, resembling the ritual combats described previously, but violence was more mediated. Usually participants were limited to sub-adult males, unlike in Nuxalk ritual combat where the strongest men were selected. These games would also end if serious injury resulted, whereas in Nuxalk ritual combat the bombardment would continue until all the canoe occupants decided to yield.

Hunting: Large Game. No cultures were reported to have used the sling for large game hunting. This is probably due to the blunt impact wounding mechanism of sling projectiles, which I argue to be ineffective for bringing down larger animals (see Chapter 7).

Hunting: Small Game. Small game hunting with slings was recorded for seven to ten of 23 cultures. This includes the Mescalero Apache (Opler 1969), Navajo (Kluckhohn et al. 1971), Nuu-Chah-Nulth (Drucker 1951), Pomo (Barrett 1952), Ute (Smith 1974), Western Apache (Basso 1983; Buskirk 1986; Goodwin and Goodwin 1942), Yuki (Foster 1944; Miller 1979) and possibly the Yokuts (Kroeber 1953) and Tlingit (De Laguna 1960; Kraus and Gunter 1956) and Zuni (Leighton and Adair 1963). Again information on the Tlingit is inconclusive, as De Laguna (1960) discovered little at all and Kraus and Gunter (1956:125) only say that the sling was "another hunting device." Small game or birds are the most likely targets for slings, however, so it is likely that the Tlingit used the sling in this manner. Among the Yokuts the sling was "used only by boys" (Kroeber 1953) but other accounts suggest that boys frequently engage in small game hunting, so it is reasonable to expect that some amount of small game hunting with slings took place here as well. Leighton and Adair (1963) say that slingshots are used from early childhood by Zuni boys to hunt small animals, but whether this statement should read "slings" rather than "slingshots" is unclear.

Small game hunting is frequently associated with adolescents, but may also provide significant caloric benefits to the family unit. Basso (1983:469) stresses the importance of small game to the Western Apache during the December to March raiding season. Other sources are consistent in reporting that boys were encouraged to hunt from a young age in this society (Buskirk 1986; Goodwin and Goodwin 1942). Aside from providing additional subsistence, this process also helped to train the boy into an effective hunter.

Though other ethnographies do not make the importance of small game hunting by adolescents as explicit, they agree that it was encouraged from a young age. Among the Mescalero Apache the sling was used "by boys…in hunting small mammals…" (Opler 1969:171), while Nuu-Chah-Nulth boys "are said to be quite accurate with it, killing birds, squirrels and the like…" (Drucker 1951:334). Ute boys would "try to kill rabbits or sage hens" (Smith 1974:113) and Yuki men and boys were both said to use the sling in killing small animals (Gifford 1965).

Hunting: Birds. The hunting of birds is in many cases tied to the hunting of small game generally. Small, edible animals were likely regarded as targets of opportunity regardless of whether mammalian or avian. The six to ten cultural groups who hunted birds with the sling are nearly identical to the list for small game hunting: there is no mention of bird hunting for the Mescalero Apache, while Copper Inuit children were reported using their tump-lines to throw stones at birds (Jenness 1922). Comanche boys used slings to kill night hawks (Wallace and Adamson 1952) but it unclear whether this was for food or amusement. Otherwise, bird hunting may be considered synonymous with small game hunting.

Hunting: Waterfowl. Waterfowl hunting with slings was recorded only for the Pomo but was documented across several sources. The quantity of evidence available in this case has warranted a more detailed analysis (see below) but a brief synopsis is provided here. The Pomo manufactured specialized waterfowl slings and clay ammunition that was designed to skip on the water (Barrett 1952; Loeb 1926). These were used from a boat made of tule, which could be paddled to within the 50 yard preferred range without disturbing the targets (Barrett 1952). A single projectile skipping through the sitting flock could hit multiple birds (Barrett 1952; Loeb 1926). There is some disagreement on the preferred shape of the projectiles (Barrett 1952; Kniffen 1939; Loeb 1926; Theodoratus 1971) but flattened disks were most likely used.

Child's Toy. The ethnographies of 12-15 cultures state the sling was used as a toy. This is reflective both of the lengthy training process required to acquire proficiency with the sling and the declining importance of the sling post-contact, as many sources state that the sling is now "only a toy" or something similar.

Crop Protection. Only among the Navajo did ethnographers note slings being used for crop protection (Hill 1938:38; Kluckhohn et al. 1971). The effectiveness of this tactic is not noted.

Herding Aid. Once again, the Navajo were the only culture in the sample to be recorded using slings in this way (Newcomb 1940:53-54). This pattern of use is certainly a post-contact development, as sheep were introduced during the long period of Spanish occupation of the American Southwest. Spanish herders apparently used slings in this same manner until recently (Santiago n.d.).

Use from Boats. Both Pomo waterfowl hunters (Barrett 1952) and Nuxalk warriors (McIlwraith 1948) used slings from boats. Pomo waterfowl hunting is described below, and makes the case that hunting from a boat is advantageous given the dense shoreline vegetation. For Nuxalk warriors the close confines of a canoe, occupied with multiple warriors and their gear, make sling use seem hampered, yet there may also be an advantage: the whirling motion of a sling might act to gyroscopically stabilize the sling while on an unstable platform. Slinging from watercraft is certainly not unique to North America. The Greeks and Romans both used slingers in naval warfare (Ferrill 1997; Korfmann 1973), and Ferrill (1997:87) provides a depiction of a slinger perched in the crow's nest during an Egyptian naval battle. Additionally, York and York (2011) provide accounts of sling use in naval battles among Polynesian groups, including the use of so-called "canoe breakers"—large stones launched with the purpose of punching holes through the enemy vessel.

Analysis of Pomo and Navajo Ethnographies.

Though ethnographic information was limited for most cultures, in two cases sufficient information was provided to allow a more detailed analysis. Among the Pomo, a unique system of waterfowl hunting has drawn the interest of a series of researchers, necessitating an evaluation of the resulting competing claims. Among the Navajo, a spatial and temporal patterning of accounts allows for an analysis of smaller-scale cultural variability and cultural adaptation. In each culture, the material culture manifested by these adaptations can also be evaluated.

Pomo. Analysis is focused on the waterfowl sling, since this is the most unique aspect of Pomo sling use known. Among the Pomo, the sling's use for hunting waterfowl is documented across several sources. Of eight sources, only six have anything to say about hunting with slings at all and all these sources agree that clay projectiles were used for waterfowl (Barrett 1952; Kniffen 1939; Loeb 1926; Powers 1877; Theodoratus 1971). Where sources make any mention of it, they also agree that stone projectiles were used for other game or for warfare. There is some disagreement on the size and shape of clay projectiles and what sort of sling they were thrown with. Loeb (1926) says projectiles were a round ball 1.5 – 1.75 inches (3.8 – 4.4 cm) in diameter. Kniffen (1939) says clay pellets were 1 inch (2.5 cm) in diameter. Theodoratus (1971) mentions "clay balls," again implying a spherical projectile. Only Barrett (1952) presents contrary evidence, specifically stating (seemingly in response to Loeb 1926) that projectiles were 1.5-2 inches (3.8 – 5 cm) wide and flattened to allow the projectile to skip over the water. Sources agree that projectiles were meant to skip over the water. Goldsmith (Barrett 1952) states that a single stone might strike five to six birds. Barrett gives this number as four to five in his discussion, while Loeb (1926) says three to four. Loeb specifically states that clay was preferred over stones because the lighter clay would "skate along the water" (1926:184). Since stones can also be made to skip it is readily apparent that the shape is a more important variable than the material. Barrett and Loeb both include photographs of sling projectiles, but the quality of the 1926 image is so poor that no interpretation of shape is possible. Barrett's image also contains a sling and a tule basket, making shape interpretation more difficult, but these projectiles are certainly flattened. This debate may seem pointlessly trivial until it is realized that the clay projectiles would likely be the only part of this technological adaptation to survive in an archaeological context. Deliberately flattened projectiles have not been noted in other parts of the world, and likely are related to this specific strategy of skipping projectiles.

Only Barrett states unequivocally that waterfowl slings were different than other slings, though Goldsmith does refer to "the mud-ball sling" (Barrett 1952:418), which implies a special type. Loeb (1926) is directly contradictory, stating that waterfowl hunting employed the same sling as other activities. Powers (1877), Kniffen (1939) and Theodoratus (1971) make no distinctions whatsoever, and only refer to "slings." These same sources give no details on throwing technique, sling measurements or materials and may generally be regarded as simply less-detailed on this subject. Once again, Barrett included photographic evidence. The tule sling pictured is precisely measured and the process of manufacturing and using these slings is also carefully described.

There is no reason to doubt Barrett's observations but reconciling his data with the Loeb's statements is difficult. One possible answer lies in the different dates of their publications and the dates of their field work. Though Barrett published 26 years after Loeb, his field dates (information standard with eHRAF sources) dated to 1894-1915, while Loeb was present from 1924-1925. Another possibly related explanation derives from the greater detail present in Barrett's account of waterfowl hunting. In fact, Loeb's (1926) description of the Eastern Pomo sling is attributed to "Miss Greiner," whose credentials are not given. Nonetheless, it appears that Loeb did not observe any native sling users and measured one sling, while Barrett's (1952) account commonly mentions "informants," implying multiple native inputs. In short, the later publication date is misleading, because Barrett had two decades of contact with the Pomo before Loeb had done any fieldwork.

In his general description of waterfowl slings, Barrett (1952) mentions that the strings were made of milkweed fiber but does not provide average length measurements. The sling pictured was measured, however, and the sling would have been over a meter long while being swung and would extend to around 2.3 m during release. Such a design imposes practical restrictions on use. At this length, the sling would almost have to be swung on a horizontal or tilted plane. Loeb and Barrett both agree that sling users did this: Loeb (1926) says there were two overhead rotations, while Barrett (1952) says there were three to four rotations around the head. This "sidearm" delivery may also required if projectiles are to be expected to skip along the water. A sling of this length, however, would have required a large amount of open ground to use, which may be severely limited in many environments. Slings used in warfare or other hunting are also described by Barrett (1952) and these are shorter, two to three ft (.61 - .91 m), than the waterfowl sling. The space requirements of the longer waterfowl sling are obviated by launching the projectiles from a boat. Barrett describes this process in some detail, noting how the tule boats could be unstable, so the hunter had to position the boat carefully. The common range to the targets is listed at around 50 yd (or 46 m), and Barrett describes how mudhen diving behavior was exploited by repeatedly causing the birds to go underwater until they were too exhausted to flee as the hunter paddled up and dispatched them. No other source makes mention of using the sling from boats or of this mudhen exhaustion technique. The logistics of waterfowl hunting, however, seem to require a boat (or a dog trained to retrieve, as among modern-day waterfowl hunters) to collect the killed birds. Additionally, the shores of Clear Lake are described as being thick with tule: this dense vegetation would make using a sling nearly impossible, especially with a sidearm delivery.

A final point for the Pomo concerns carrying the sling. McLendon (1977) states that *slingshots* (emphasis added) are often tied around the forehead. McLendon is primarily concerned with types of headdress, so her description is brief. Slingshots, however, are not the same thing as slings. In a 1978 edited volume by McLendon and colleagues this paragraph is repeated verbatim except that “sling” has been substituted for “slingshot.” This change immediately sends up a red flag, but the likely explanation is simple enough. It appears that the use of “slingshot” was an error of vocabulary. Firstly, the rubber-band and forked stick slingshot is not indigenous to North America and is not mentioned in any other Pomo ethnographies. Secondly, a slingshot is not nearly as suitable for wrapping round the forehead as a sling and would likely be painful. Finally, the 1978 volume was edited by Heizer, who was the discoverer of the Lovelock Cave sling. The most parsimonious explanation of this discrepancy in the sources is that McLendon was alerted to the error and the paragraph was corrected accordingly. It is also possible, however unlikely, that Heizer assumed this statement was in error and corrected the text without the author’s knowledge.

Navaho. The primary source for analysis of Navajo sling use, Kluckhohn and colleagues (1971), was divided into five sections to aid analysis. Four of these describe the regions for Kluckhohn's reporting, with a fifth "general" column supplying information that is not attributed specifically to any of these four regions. Most reporting comes from Ramah, but other regions supplement this data. In Kluckhohn's comparative discussion, he cites Gifford 1940, who divided his informants into eastern and western Navaho. These mentions are included in the "general" category, since it is not known if the exact study areas delineated by Gifford in 1940 and Kluckhohn in 1971 are the same. In general, the detail found in Loeb's 1926 and Barrett's 1952 accounts of the Pomo are lacking. Kluckhohn's 1971 work is the most detailed available and even that is a summary. Complicating this investigation further is the inconsistent use of "sling" and "slingshot" between and within the ethnographies. Three issues can be explored: technological variation and sling uses, the decline/replacement of the sling after contact, and confusion with slingshot (this is related to the issue of replacement).

There is remarkably little technological variation reported, but this could be linked to the low amount of detail provided. Material used was reported only at Ramah and West locations of Kluckhohn's study. These agree that deerskin leather was the material used. Cords of these slings are described as leather thongs, but while central Navaho informants reported that "if greater than 3 feet (~1 m), [slings are] difficult to shoot efficiently" (Kluckhohn et al. 1971:54), the western Navaho cut thongs only about 1 ft (30 cm) long. The pouch is described as "diamond-shaped" at Ramah (Kluckhohn et al. 1971:53), but only as "a wide piece of deerskin" (Kluckhohn et al. 1971:54) among the western Navaho. Preferred ammunition is only recorded at Ramah, and only states that round pebbles “of a certain size” (Kluckhohn et al. 1971:53) are used; no dimensions or weights are given. Other sources have no input on this subject. The only variation that we can likely draw from this limited information is that slings tended to be shorter among the western Navaho. Analysis of the uses of the sling supports this interpretation, as western Navaho informants consistently give low estimations of sling effectiveness.

Several possible uses of the sling are detailed in Appendix B. Of these, only “large game hunting” has no affirmative evidence. At Ramah, informants said slings were never used on large game, while the western informants provided further information, stating that slings were “not large enough or strong enough,” (Kluckhohn et al. 1971:54) to be used on large animals. This finding is not surprising as, to the best of my knowledge, the use of the sling on large game has not been documented in any culture. Concerning small game, sources agree that slings could be used for hunting (Kluckhohn et al. 1971; Newcomb 1940). The lone exception to this is one of Gifford’s informants, who adamantly stated that slings were not used on foxes and rabbits but were instead weapons of war, a use that was in turn denied by Gifford’s western informant. Western informants in Kluckhohn’s study, perhaps not incidentally, are the only ones to mention “stunning” animals (1971:54). One informant, listed as IJun, stated that slings were toys and “not effective for hunting” (Kluckhohn et al. 1971). This western informant is the only one to deny all hunting use so categorically. Estimates of sling effectiveness seem to correlate with accounts on the length of the sling. Among western Navaho, where slings were apparently shortest (though we do not have data for all regions reported) the usefulness for small game hunting is doubted and we see the only mention of “stunned” animals. This is also the only region where use in warfare was categorically denied. At Ramah, informants said slings were sometimes used after arrows were expended (Kluckhohn et al. 1971:53), and Gifford's eastern informant says slings were for warfare but gives no additional details (Kluckhohn et al. 1971:54).

Other uses are of interest for documenting the versatility of sling technology for application in a wide variety of settings. As an agricultural aid, slings were used to frighten or kill pests marauding the corn. Hill (1938:38) says cornfields were defended at night by a slinger who "threw stones about the field to scare them [coyotes, foxes and dogs] away." Gifford's informants agree that slings were used to kill birds to protect crops, while the central Navaho specifically mentioned scaring birds and other animals from the fields (Kluckhohn et al. 1971). Against this evidence, Newcomb's (1940) documentation of taboos against killing birds seems to be missing a description of periods or circumstances where these taboos were not applicable. As a pastoral tool, slings were used to aid in sheep herding. Central Navaho informants say the stone could be cast near the animals for "turning sheep during herding" (Newcomb 1940:53). Franciscan missionaries also described this use in 1910 (Newcomb 1940:54). Finally, it is widely agreed that slings were used as toys (Newcomb 1940). This is not surprising, since sources agree that proficient slinging requires long practice, preferably beginning in childhood (Dohrenwend 2003; Korfmann 1973).

The decline of sling use is seen in the changing demographics of use and replacement by the slingshot attested to by informants at Ramah. At Ramah, the sling is described as "no longer an adult weapon" and Kluckhohn and colleagues say users are mostly boys (1971:53). They also state that slings were no longer in use at Ramah, but that some informants knew how to use them. Of these, two informants said they had used slings as children and one said his father had made it for him. Given the sling's simple construction, it is likely that manufacturing techniques have not been lost, but Kluckhohn makes no mention of this. Kluckhohn summarizes the changing use of sling by stating that it has "declined in use except as a toy" (1971:440).

Confusion with the slingshot is especially difficult to parse because the slingshot is described well enough to see that this is no error of vocabulary. The slingshot was present among the Navajo. Downs (1964:57) links its use as a boy's toy to training for the demands of a shepherd's life. The rubber slingshot had arrived at the Franciscan mission by 1910 (Kluckhohn et al. 1971:54) and at Ramah the sling had been replaced by the slingshot "a few years ago" (Kluckhohn et al. 1971:53). Mentions of the slingshot have to be parsed individually to eliminate possible confusion with slings. Use of "slingshots" at Ft. Defiance in 1881 is doubted because the Franciscans date the arrival of rubber slingshots to later than this. In this case, Kluckhohn's reference Bourke may be in error and it is probable that "slings" was meant, not "slingshots" (see Kluckhohn et al. 1971:54). Kluckhohn's statement that the slingshot replaced the toy bow is likely accurate (1971:24). He also describes a blind used in conjunction with the bow to defend corn. He states that the arrivals of the gun and slingshot have made this blind obsolete (Kluckhohn 1971:16).

Conclusion.

This overview has not drastically altered our knowledge of sling distribution, but it has suggested some research questions that could be analyzed through wider study.

Different uses of the sling can be compared cross-culturally, and it is likely that uses from boats, in waterfowl hunting, or in herding are not unique adaptations Similarly, elements of sling construction and projectile shape, size and material can be compared across cultures and across geographic space. These and other topics related to sling technological variation and use could be profitable avenues for future research.

One example is the use of flattened clay projectiles, which provides a technological and behavioral marker that may be seen in the archaeological record. Means (1919:317) suggests that clay projectiles have already been found in Californian archaeological contexts–presence of flattened disks near lakes would seem to directly link observed Pomo hunting techniques to the prehistoric past. The use of slings in waterfowl hunting may be documented more widely in the ethnographic record and may also provide a plausible interpretation of clay objects found in other locations. A survey of archaeological reports may locate possibilities to apply this ethnographic knowledge to the benefit of the prehistoric record.

For present purposes, these different uses of the sling suggest parameters for defining sling effectiveness or ineffectiveness. As we explore the technological capabilities of slings, the data (in terms of range and impact energy) can be applied in ways that are relevant to warfare and the hunting of small or large game. These ‘performance characteristics’ (Bleed 2001; Schiffer and Skibo 1997) of slings in general can help to explain behavioral choices between slings and other weapon systems. Range and impact effects are also computed for different projectile material and shape, which illustrate the performance characteristics influencing the design and material choice of projectiles.

Chapter 4: Sling Use and Previous Experimental Studies of Sling Range

Introduction.

There is a long history in archaeology of investigating weapon capability through experimentation. For example, *The Atlatl* is populated with a long list of such efforts. In addition, Anan Raymond (1986) sought to establish the effect weights have on atlatl performance, and evaluated maximum distance, velocity and accuracy in a series of detailed experiments. Miller and Bergman (1986) explored the evolution of archery in the Near East. Using modern replicas, they were able to show that later bow forms were more efficient machines, able to attain higher velocities than earlier bows. While these studies looked at general weapon systems, archaeologists have also investigated more specific technologies. George Frison (1989) used Clovis-tipped darts to evaluate the lethality of that technology on African elephants–using the elephants as a reasonable substitute for extinct mammoths and mastodons. His experiments showed that Clovis weaponry could be lethal against extremely large mammals. Adam Karpowicz (2007) investigated the efficiency of Ottoman composite bow design, and used the data to estimate draw weight and performance of museum specimens. These interpretations informed his discussion of Ottoman military tactics and his comparisons to contemporary weapons. This chapter reports on previous attempts to experimentally evaluate sling range and effectiveness and addresses the failings of these earlier studies.

Textual Sources.

Sling researchers have often begun their research by looking for textual evidence of sling effectiveness or range. Xenophon is an especially popular source, writing that his Rhodian slingers could outrange Persian archers (Dohrenwend 2002; Ferrill 1997; Finney 2005, 2006; Gilleland n.d.; Korfmann 1973; Vega and Craig 2009). These same sources also cite Vegetius, who stated that archers and slingers practiced on targets placed at 200 yards (182 m). Following the quotation from Xenophon, Thom Richardson (1998; note: Not all references cited here by Richardson were located and verified) has this to say of range estimations:

> This has inspired remarkable claims for the maximum range of the sling. The more conservative estimates area around the 200 m mark (Ferrill 1985:25), Connolly suggests 350 meters (1981:49), Korfmann estimates 400 m (1973:37) while Demmin and Hogg go to 500 m (1893:876; 1968: 30). The few accurately recorded observations are rather different. Reid records 55 m with a 227 g stone, and 91 m with 85 and 113 g balls (1976:21). Burgess threw stones with his reconstructed Lahun sling between 50 and 100 yds, but admits to being unskilled at the art (1958:230). Korfmann observed Turkish shepherds sling ordinary pebbles, 'in 5 out of 11 trials the pebbles reached 200 m, and the three best casts were between 230 and 240 m (1973), while Dohrenwend has himself thrown beach pebbles over 200 yds. (1994:86)

Vega and Craig produce the most succinct summary of this data (2009:1265), including references from Classical history and ethnography, estimations and experimentation. Several of these, however, list the range at which some feat was accomplished, rather than a maximum range attainable. For instance, one range cited is 30 m[1] and is a colonial account from Peru. This is actually the range at which a stone broke the sword in a Spanish soldier's hand; the table also contains a mention of a 50 m range from Fiji/Hawaii, which in fact references the range at which users could hit sticks

Comment [U1]: Usual practice is to report units in metric with English units in parentheses; I suggest when you first start talking about range, include a footnote or endnote that indicates that your sources used a variety of units to report range and, for ease of comparison, have converted all of these reports to metric.

[1] For ease of comparison, distances have been converted to metric where originally given in English units. Velocities are given with miles per hour (mph) in parentheses to provide a more vernacular unit.

placed in the ground as targets. Yet another ethnographic account from Arabia gives a range of 27-45 m, which is the distance at which small game was hunted (Finney 2005:178-179).

Table 1. Sling Ranges. From Vega and Craig (2009:1265)

Range (m)	**Location**	**Observation Type**	**References**
27	Inca Empire	account	Keeley *et al.* 2007:73
27-45	Arabia	ethnographic	Finney 2005:178-179
30	Peru	colonial account	Finney 2005:178-179
40-90	Britain	exploratory attempt	Griffiths and Carrick 1994:7
46-91	Britain	exploratory attempt	Burgess 1958:230
50	Fiji/Hawaii	ethnographic	Finney 2005:178-179
55-91	-	exploratory attempt	Dohrenwend 2002:42
60	Britain	estimate	Cunliffe 2003:68-69
60	Peru	ethnographic	Finney 2005:178-179
69	Madagascar	ethnographic	Lindblom 1940:26
69-183	Old World	general statement	Gabriel and Metz 1991:75
80	Britain	exploratory attempt	Time Team 2002, Finney 2005:178-179
91	New Britain	ethnographic	Finney 2005:178-179
91	Nigeria	ethnographic	Finney 2006:178-179
100-400	Greece	general statement	Keeley et al. 2007:73
110	England and Wales	general statement, for downhill cast	Dyer 1992:23
180-200	Majorca	ethnographic	Hubrecht 1964:93
183	Old World	literature review	Dohrenwend 1994:86;
183	New Guinea	ethnographic	Finney 2005:178-179
183	Ancient Rome	reference: Vegetius	Echols 1950:228, Ferrill 1985:25
200	North Africa	ethnographic	Lindblom 1940:11
200	Turkey	ethnographic	Korfmann 1973:37
274	Tibet	ethnographic	Lindblom 1940:34
349	Old World	experiment and literature review	Dohrenwend 2002:42
350	Old World	general statement	Connolly 1981:49
366	Rhodes	reference: Xenophon	Echols 1950:228; Ferrill 1985:25
457	Old World	general statement	Hogg 1968
500	Old World	general statement	Demmin 1877:466, Cowper 1906:227

*In some cases multiple references cited were reduced to save space. Not all references were independently verified.

Finney reviews a limited set of this data and concludes that observations are unreliable, citing the difficulty of estimating range and the tendency of slingstones to bounce on impact.

> Non-empirical experimentation [informal survey?] has shown that a majority of individuals with limited knowledge of the sling's capabilities consistently estimate the range to be between 100-150m. This is certainly in excess of what experimentation indicates is achievable, and shows the difficulty in observing ranges rather than making any form of measurement. (Finney 2005:179)

I disagree with this conclusion on the grounds that there is no extant evidence with which these observations are dismissed and that the experimentation performed up to and including Finney's study was generally by untrained researchers. The far simpler explanation is that the observations are accurate to within a reasonable margin of error, and the limited experimentation Finney cites report lower ranges due to lack of skill with the weapon.

To the data previously presented by other researchers one further source can be added, conveniently compiled by members of www.slinging.org. The data is self-reported, so relies on considerable trust, but arguably no more than when citing early ethnographic accounts. The first five entries are current or former world records. These have been measured and reported (presumably with witnesses) to a more exacting standard than was *necessarily* present for the other entries. In spite of the limitations of utilizing user-generated data, the value of such a body of knowledge and experience cannot be understated. Future research should endeavor to obtain data from diverse and experienced slingers, possibly identified through this organization.

Table 2. Modern Slinger data.

Adapted from www.slinging.org/index.php?page=sling-ranges (Accessed 8/17/2012)

Slinger	Projectile Type	Projectile Mass (g)	Sling Length (cm)	Range (m)
Jerzy Gasperowicz	bipointed lead			505
David Engvall	Dart	62	127	477
Larry Bray	Stone	52	130	437.1
Melvin Gayloor		212.6		349.6
Vernon Morton		283.5		258.2
LoboHunter	Foos ball	42.5	109	88.2
LoboHunter	Egg-shaped stone	85	109	177.3
LoboHunter	Clay glande	85	109	148.6
LoboHunter	Weighted golf balls	162	109	196
LoboHunter	Lead egg sinkers	170	109	198.2
Alsatian		90	~60	~60
Alsatian		90	~100	~100
Alsatian		90	~120	~120
Zorro	Stones		84	~100
Douglass	Heavy stone	500		~90
Douglass	Lead glande	85		~250
MammotHunter	bipointed clay	34	94	101.5
Thomas	Softball	312		95
Thomas	hard baseball	148	129	~120
Oscar	Golf balls		91	171.3
NonkinMonk	Stones	70	91	182.9
Sammy Atif	ice-filled plastic egg			~90
Jerzy Gasperowicz	light stones	25		~250
Jerzy Gasperowicz	ice balls			~120
Jerzy Gasperowicz	snow balls			~90
Tint	golf ball		48	~170
Tint	golf ball		167	~195
David T	golf ball			~230
David T	cement ball	164		~150
Mike Greenfield	Stone	82	85	~100
Col Walker	Orange	454	122	~130
Col Walker	Stone	112	64	~107
Crater Caster	Stone	113	60	~107
Curious_Aardvark	Stone		58	~210
Curious_Aardvark	Stone	57	~74	~220
Funslinger	Stone	85	208	~219
SEB	Stone	300	130	~220
SEB	Stone	100	80	~173
Naiyor	lacrosse ball	142	66	~160
Naiyor	salt flour glande	56	66	~80
Leeds_Lobber	lead ball	42	175	~180
Zorro	spherical stone	40	71	~119
Africa_Slinger	golf ball	45	107	~200
MammotHunter	golf ball		99	101
Peter van der Sluys	bipointed, clay	11	~50	119
Peter van der Sluys	bipointed clar	6	76	180
Peter van der Sluys	lead fishing weight	10	76	200
Peter van der Sluys	lead fishing weight	15	76	210
Stephen Fitzgerald	smooth stone	70	105	~180
Stephen Fitzgerald	golf ball	45	105	~190
Stephen Fitzgerald	lead egg	57	105	200
Stephen Fitzgerald	1" steel ball	66	105	212
Ben Croxon	golfball-sized rock		90	70
Saulius Pusinskas	bipointed, cement	100	90	220
Saulius Pusinskas	Stone	70	90	220
Sobieski	Stone	90	112	180

It should be noted before transitioning to measured experimentation that slinging is a national sport of the Majorca (formerly the Balearic) Islands. In 2011, the first international sling competition was held there, which drew 35 competitors from nine countries (http://www.tirdefona.org/actas/I%20TIRADA%20INTERNACIONAL%20SOLLER%202011%20EN.pdf). Given the amount of knowledge gained by such competitions among atlatl hobbyists (Whittaker and Kamp 2006), we can hope that such competitions will continue and spread.

Prior Experimentation.

Experiments on sling capability have mainly focused on establishing the maximum range of the weapon. Brian Finney (2005, 2006) found a mean distance of approximately 56 m on level ground. Measurements were made very precisely, but Finney is a self-admitted amateur and his results likely reflect his ability more than the sling's capability (compare this result with those of other users in Table 2). By measuring time of flight, he computed an average velocity for each cast. Finney calculated that drag would be negligible, so this average velocity is used directly as a proxy for initial velocity. (The calculations I have performed for my own experimentation show that drag cannot actually be discounted, creating an additional source of error.) The average initial velocity of 25.48 m/s (~57 mph) was combined with an ideal launch trajectory of 45º to give a range of 65.66 m. This process corrected for errors of launch angle. Finney then used this calculated range to investigate defender advantage at a selection of hillforts across Britain, finding that at many sites the defender's height advantage would result in outranging their opponents by 2:1 or more. Although this modeling is an excellent example of using weapon capability to evaluate fortifications, it will likely need revision as the capabilities of sling weapons are revised.

Margaret Vega and Nathan Craig attempted to address the central weakness of Finney's study by using native Quechua slingers of Peru in their trials. Sixteen different slingers were included in the trial, including one elderly woman, three young adults and twelve adult slingers: five female and seven male (Vega and Craig 2009: 1266). Subjects were approached in the field and asked to sling. Five subjects used their own slings, which implies they are frequent slingers since they had one on their person. Vega and Craig do not identify which subjects these are. Indeed, their definition of an 'experienced slinger' is any Quechua-speaking adult (2009:1268). They find a mean distance of 66 m for all slingers, but 78 m for males and 70 m for adults. These values are slightly higher than those attained by Finney but do not compare with the results of one adult male in the study who consistently threw beyond 100 m (Vega and Craig 2009:1266).

While these Peruvian subjects may have been shown to be better slingers than Finney, Vega and Craig do not adequately establish the skill of their subjects. Assuming proficiency based on age and ethnic identity or occupation (Vega and Craig mention that the Quechua speakers are herders [2009:1264]) is not sufficiently robust. Furthermore, the manner of current sling use among the Quechua is likely different from military sling use. While herders may need slings only at short ranges, using stones to alter the herd's movement or directly firing towards predators, military uses may have included high-trajectory, long-range fire intended to create a barrage of stones (Avery 1986; Dohrenwend 2002:44). It is as yet unknown whether throwing for distance involves the same techniques as aimed direct fire. Even if the same throwing technique is used the release timing would have to be altered to release at the higher angle. These difficulties lead to the caveat that experience in one sort of slinging may or may not be immediately applicable to other types of slinging. Demands for accuracy and velocity are most likely different in military contexts than they are in a shepherding situation. While training methods for ancient military slingers likely highly valued accuracy, power, and distance, whether modern Quechua-speaking slingers stress the same aspects is undocumented.

Other variables in the study are not controlled. Subjects used different slings, yet the measurements of these slings were not measured. Projectiles were also variable and uncontrolled (Vega and Craig 2009:1266). Furthermore, the rectangular stones used would suffer increased air resistance relative to a smooth, rounded projectile, which would decrease maximum range. Vega and Craig (2009:1268) regard their own study as a preliminary trial, and call for more experimentation in the future.

Thom Richardson (1998) performed a valuable series of tests for the Royal Armouries, which has been unfortunately been largely ignored by subsequent scholars. A reconstruction sling was created based on an Egyptian specimen, and multiple types of projectile were tested for both range and release velocity. Richardson’s study was conducted in two stages, in the first the distance of throws was measured and in the second the initial velocity was measured. The experimental slings were reconstructions of an Egyptian specimen from 800 B.C.E., all measuring 1.45 m in length (Richardson 1998). A range of projectiles were used, including lead biconical ammunition, lead spheres and stones of varying weights. Within each category of projectile, an average of experimentally determined range was computed. Average range was greatest for the 40g biconical lead projectile at 145 m, and least for the 85-160 g stone projectiles, which averaged only 82 m. These results show very clearly that drag has an impact on sling projectile trajectory; among categories of roughly equal weight, stones are consistently outperformed by lead projectiles, while comparing only the lead projectiles it seems that the biconical shape has an aerodynamic advantage over the spherical lead shot. However, the significance of these tests cannot be statistically verified because Richardson only provides mean values and gives no information on the number of trials conducted.

Richardson's (1998) tests of velocity have limited value because of the measurement equipment used. In order for the velocity to be read, the projectile had to pass through a one meter wide arc placed three meters in front of the slinger. Richardson notes that in the trials the need to accurately throw through this target necessitated a noticeable reduction in velocity. The average velocities across all categories of projectile were remarkably consistent at 30.3 – 31.2 m/s (67.8 – 69.8 mph). Using standard algebraic trajectory equations (the same used by Finney 2005, 2006), these velocities are insufficient to obtain the ranges found in the range experiment. Since the algebraic physics used do not account for any drag on the projectile, which the range experiment suggests is an important factor, this shortfall is still more substantial than is immediately apparent. The equations used are shown below.

Range equals the initial velocity squared, times the sine of twice the launch angle divided by the acceleration of gravity, or:

$$R = V_i^2 \times \sin 2\theta / g$$

Where $\Theta = 45^{\circ}$, $\sin 2\Theta = 1$, so the equation simplifies to the initial velocity squared, divided by acceleration of gravity, shown here in m/s/s.

$$R = V_i^2 / 9.8$$

Table 3. Sling data from Richardson (1998).

	Measured Range	Measured Velocity	Computed Range
Lead biconical 40g	145m	30.6 m/s	95.5m
Lead biconical 85g	120m	31.2 m/s	99.3m
Lead spherical 38g	114m	-	-
Lead spherical 100g	107m	30.5 m/s	94.9m
Stone 45-75g	90m	-	-
Stone 80-85g	84m	-	-
Stone 85-160g	82m	-	-
Stone 80-100g	-	30.3 m/s	93.7

Average ranges and velocities are shown, deriving respectively from the distance and initial velocity components of the experiment. Computed range is calculated from the measured velocity by the equation shown above, clearly showing that initial velocities were compromised by the equipment used. The 80-100g stone shot can be roughly compared to the 80-85 and 85-160g stone shot categories. Only in these cases does the range without drag at ideal launch angle exceed the range experimentally measured.

Comparing Richardson's (1998) data with Finney (2005, 2006) and Vega and Craig (2009) we see that despite some flaws in the experiment, Richardson's casts with stone projectiles substantially exceed the range obtained by Finney and are slightly further than those by male users in Vega and Craig's study. This speaks again to the error of assuming that skill with slings is necessarily linked to membership within a slinging culture. Though Quechua speakers have retained the use of the sling through to modern times the context of that use has been altered by the changing cultural environment (Vega and Craig 2009).

At the same time it must be remembered that unlike other weapon systems such as the bow and arrow, experimental sophistication cannot be a substitute for skill with this weapon. A long period of practice is necessary to acquire sufficient proficiency to test the weapon and this has led researchers to seek out native slingers (Korfmann 1973; Vega and Craig 2009). Inversely, the assumption that researchers from non-slinging cultures cannot acquire the necessary skill to be comparable to indigenous users is clearly false. All that is needed are multiple years of study and practice.

Table 4. Comparison of previous range experimentation

Study	**Category**	**Measured Range**	**Computed Range**
Richardson (1998)	Lead 38-100g	107-145m	94.9-99.3m
	Stone 45-160g	82-90m	93.7m
Finney (2005, 2006)	Stone	56m	65m
Vega and Craig (2009)	All users	66m	-
	Adult users	70m	-
	Male users	78m	-

Conclusion.

The gap between experimental studies and ethnographic/historical sources requires explanation. Given the shortfalls of prior experimentation it is likely that the capabilities of slings lie closer to ranges reported in textual sources than to the measured trials. The challenges preventing accurate experimentation are not insurmountable, and further studies can begin to close this gap and significantly increase our understanding of this weapon system.

Chapter 5. Experimental Design and Results

Introduction.

The challenge of evaluating sling capability, like many experiments, can be seen as eliminating as many variables as possible and controlling the others. However, without the ability to separate the sling from its user, as is possible with other weapon systems, it is impossible to account completely for the largest source of variability. It is difficult to quantify and I do not know for sure how my level of skill compares to other sling users. I suspect, however, that I am in the lower half of serious sling users. The ethnographic and historical record clearly indicate the serious use of slings in both hunting and warfare, and I can say that I would be next to useless at either of these. The experimental design has sought to minimize the effect my lack of skill can have on the results, yet these still probably represent the low end of sling capability in the hands of experienced users. Nevertheless, sling velocities obtained in this experiment proved to be substantially greater than previous measures.

Experimental Design.

The sling used in the experiment was constructed according to the guide by Bruno Tosso (2009) out of the twisted jute twine common in hardware stores. This material was chosen over other materials because it allows the sling to be braided from natural fibers without needing to collect and twist the fibers myself. The sling has a finger loop for retention and a knot for the release node. The pouch design is a split woven pouch, but the overlapping pouches in effect create a cupped single pouch that can expand or contract to accommodate different sizes of projectile. Length of the sling is 71cm from the release node to the center of the pouch, while the pouch measures 9 x 4 cm. Cotton thread was tied around the retention loop to reduce friction, but this element is not functionally important. It is important to note that this sling design is not based on any ethnographic example, it is merely an effective design that has been used to evaluate sling potential in general.

Projectiles were hand molded from modeling clay into biconical shapes and allowed to sun dry. Dried in this manner the clay retains some water and is therefore denser than if fired. Firing would also necessitate the use of a temper, which could further reduce density. Finally, sun-dried clay is less brittle than fired clay, which by reducing the odds of shattering on impact should aid in the transfer of kinetic energy to the target. Clay projectiles found in Hamoukar were sun-dried (Reichel 2009), while York and York (2011) have documented multiple sites with “baked” clay biconical projectiles in California. Experimental projectiles ranged from 20.4 – 55.2g. This lower limit is approximately equal to the lower limit of lead sling bullets recorded at Olynthos by Korfmann (1973). The upper limit was determined by my own comfort level and a desire to avoid injury. In previous use, I had found that larger weights placed additional stress on the shoulder, which seemed to have been at least a partial cause of some minor tears and strains I had experienced in the muscles around the shoulder, back and neck.

Various methods for measuring either distance or initial velocity were explored, but I eventually settled on a solution that could exploit preexisting systems. Golf simulators track the motion of a golf ball in the fractions of a second between impact and the ball striking the catch screen. While some work by recording the moment of impact in close detail, others function by measuring the position and time of the ball as it passes through two successive infrared screens. This latter system is actually quite flexible and without adaptation can be used to measure the initial velocity of other small projectiles, including sling-launched missiles. Since the enclosure is built to protect the equipment from ricocheting golf balls, there is relatively little liability so long as the slinger can consistently throw forward. The central problem that Richardson (1998) encountered in attempting to measure velocity was the need to throw the projectile through a 1 m wide aperture. Using the golf simulator obviates that difficulty, since the screen is approximately 3 x 3 m and is only around 2-3 m from the tee. This large area makes accuracy a non-issue, which allows the user to throw at full force. Finally, the simulator measures projectile velocity to a 1 mph error, or 0.45 m/s. This error range is more than precise enough for current purposes.

Along with establishing new baselines for sling velocity and range, the experiment also sought to evaluate four different slinging techniques. For each technique, 12 trials were conducted, followed by a five minute break. In each run of 12 trials a range of projectile weights were used, the purpose being to simultaneously evaluate the impact of projectile weight on initial velocity. Because the sun-dried projectiles can vary in weight as drying continues, the projectiles were weighed immediately prior to use. Any projectile that broke on impact (a total of three did) was excluded from any future trials and remaining projectiles were weighed after each session to certify that weight loss through abrasion was insubstantial. After the initial 48 trials (12 per technique), additional throws were conducted to increase data resolution between throwing techniques that piqued interest during the run, with appropriate breaks to reduce fatigue. To further limit the effects of fatigue, trials were conducted in two sessions. In this way, each session could be limited to around an hour. The first session contained 61 measured throws while the second session had 80, for a total sample of 141. Of these, two throws were eliminated because the simulator failed to read the throw, leaving a sample of 139 measured throws. Seven of these throws, all conducted in the second session, were simply thrown by hand (overhand, as in a baseball pitch) to provide a baseline for evaluating the mechanical advantage created by the sling. The session and cumulative throw count were recorded for each throw to evaluate whether these variables had significant impacts on the results.

Techniques Used.

Experimental trials also considered four different slinging techniques. These four techniques are ones that I developed some level of proficiency with during the months before the experiment. Note that in describing the motions of these techniques, the slinger is assumed to be right-handed for simplicity.

My early attempts at slinging were documented in the fall of 2010 (Skov 2011). At that stage, no technique but underhand could be performed effectively. Early experimentation work in 2011 (unpublished), similarly relied on the underhand technique. This seems to commonly be the first technique learned: Finney (2005, 2006) used a minimally modified underhand delivery in his experimentation and the technique also appears to have been used by some participants in Vega and Craig's (2009) study—based on photos available at the www.slinging.org image gallery—and by Dohrenwend

(2002). After learning to use other techniques, however, the underhand delivery seems inefficient and awkward. The use of this elementary technique in experimental studies may be the primary reason for low ranges reported by Finney (2005, 2006) and Vega and Craig (2009). Though Dohrenwend (2002) appears to be using this technique in one photo within his article, he also describes other techniques and claims to have thrown over 200 m. He does not state what technique(s) he prefers for long-distance throws. The underhand release was illustrated by Finney (2005, 2006) and is shown below.

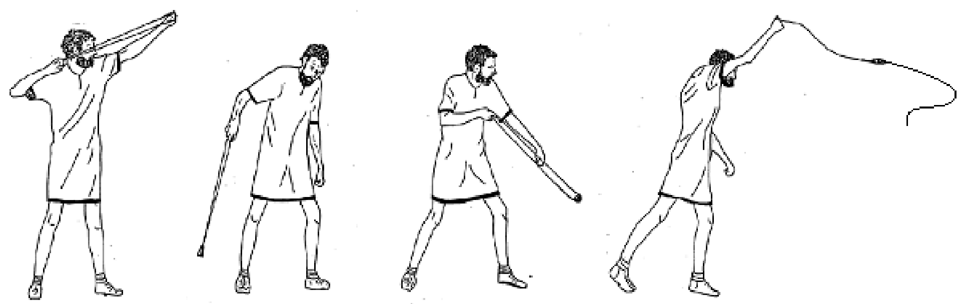


Figure 8. The Underhand Release. Adapted from Finney (2005)

In the first step the sling is loaded and “aimed” downrange. The loaded pouch is then let down to rest at the position shown by the second figure. From here the sling is rotated forward using mostly the wrist but also with some input from the forearm. These rotations are at a constant velocity, speed is only built up on the final rotation. Finney released on the fourth rotation, following the account of Vegetius, which implied that four rotations were the norm (Finney 2005, 2006). In my experiments I chose to also release on the fourth turn to remain consistent with Finney. On the fourth and final rotation the body can be brought into the motion and the throwing arm extended slightly. It is during this last motion that most of the speed is built up. As the pouch reaches a vertical alignment, the release cord is let go. For higher trajectories the release may be delayed slightly.

This release is inefficient because during the final motion of the sling immediately prior to release, the arm and sling cannot be fully extended because the sling would strike the ground. This requires that the slinging arm be kept in close to the body and this further reduces the acceleration of the pouch in the critical final motions. This necessity, moreover, makes the action of throwing in this manner feel as awkward as it appears in Figure 8. This could be compensated for by reducing the length of the sling to the point where it would clear the ground and any vegetation, but this would act to decrease the sling's mechanical advantage. This solution would furthermore not be sufficient if the user found themselves in knee-high grass or brush. It is more likely that users would opt for other techniques that allowed for the use of longer, more effective slings rather than adapting their slings to fit an inefficient technique.

A second technique is a sidearm delivery with a few preliminary rotations behind the back. This technique was learned after witnessing it performed (via a multitude of Youtube clips) by several effective slingers. I have called the style "Balearic" due to its popularity among participants in the Majorca slinging competition held in 2011. This style can be witnessed here http://www.youtube.com/watch?v=F4VwbJ8f7bE&feature=relmfu (David Morningstar [screen name] 2011), which may prove more illuminating than the following description. During the initial rotations the sling hand is held low, approximately even with the elbow, and back behind the body. Though there is some variability among different users, these rotations on an approximately vertical plane. As these more-or-less vertical rotations are transitioned to the horizontal plane (for me only during the last rotation) the slinging hand rises slightly above the level of the shoulder; this change in position is sufficient to ensure the sling passes over the head. At the beginning of the last rotation the slinger should step towards the target with the left foot. As the sling passes overhead the sling arm, which had been rotating the sling using mostly the wrist up to this point, is fully engaged for the final motion. The elbow is allowed to rotate to bring the forearm around behind it, then the entire arm and shoulder can be utilized in the final throw which brings the arm down and across the front of the body.

Though this description makes the technique appear complicated, in actual practice it flows very naturally and is not difficult to learn. Although I was concerned with hitting myself in the head at first, it quickly became apparent that during the motions no special considerations are needed to avoid injury. Furthermore, the technique allows the full extension of the arm during the final motions. This makes the technique feel more unhampered than the underhand release and was predicted to lead to increased velocity. Finally a small caveat: though I have just stated that this technique is not difficult to learn, I only picked up the style after nearly a full year of fairly consistent practice and learning other techniques. The ease with which I adapted to this style may be more related to having learned other styles previously rather than any inherent simplicity in the technique.

In fact, I suspect that the two easiest techniques to learn after mastering underhand are the overhand and sidearm techniques described here. In each case the sling is held similarly to the beginning of Finney’s (2005) underhand sequence: The right hand is near the head while the left holds the sling pouch up high, in front of the body. I have adapted the stance to put the left foot behind the right, a stance deliberately reminiscent of a baseball pitcher during windup. Since the left foot ends the motion stretched out in front—again just like a baseball pitch—this stance allows the whole body to be accelerated forward a greater distance during the throw. In each case I release on the first rotation, but this is a matter of preference more than necessity.

In the overhand delivery, the pouch is dropped with minimal guidance to start it on a backwards rotation that is nearly vertical and directly behind and on the left side of the body. A small motion of the slinging wrist is all that is necessary to maintain this initial motion. The left foot begins to move forward here. As the pouch begins to climb upward, the throwing arm is already in a "cocked" position for an overhand throw. The final motion brings the hand down and across the body to the left knee as the left foot plants and the right leg lifts to allow rotation of the body. The motion is immediately recognizable to anyone who has seen a baseball pitch.

The sidearm delivery is very similar. However, the pouch is propelled to the left by the left hand rather than allowed to drop. As the throwing hand rotates into position for the final effort, the arm tends to be lower rather than cocked back over the shoulder. The final throwing motion is less downward and more horizontal. Otherwise the two techniques are identical. In fact, these do not seem to be separate techniques so much as two ends of a continuum. Using the overhand throw, the final motion is not completely vertical, while the sidearm throw is similarly not completely horizontal and throws intermediary between these two positions are certainly possible.

There are other techniques to launch projectiles which were not evaluated here. Richardson (1998) used a 'whip' technique, which brings the pouch, "…back and down past the right side, until at the rear of the arc the slinger can feel the weight of the slingshot pulling at the second finger. It is then swung upwards and forwards, gathering momentum rapidly [until release].” Dohrenwend (1994) claims that this method imparts greater velocity than either a horizontal or vertical whirl technique.

York and York (2011:46) relate yet another technique, common to at least Tahiti and possibly widely practiced throughout Oceania, described by Reverend William Ellis in 1827, “The sling was held in the right hand, and, armed with the stone, was hung over the right shoulder, and caught by the left hand on the left side of the back. When thrown, the sling, after being stretched across the back, was whirled round the head, and the stone discharged with great force.”

I have tried both techniques, and have found each usable, though I have very little skill with either. The whip technique does not appear to have any advantage over the overhand and sidearm techniques already described, but this could be due to a lack of proficiency. The across-the-back technique, practiced even less than the whip method, seems to give good velocity and should be easy to learn, though I cannot throw with any accuracy yet using this method. Additionally, the technique appears well adapted for the use of longer slings. In the case of each of these techniques, these perceptions are merely preliminary and investigation of their effectiveness would require a lengthy period of practice.

Figure 9. Polynesian Slinging Technique
From York and York 2011:18: Caption reads “French sailor Jean Baptiste Cabri, ‘gone native’ in the Marquesas, ca. 1800, demonstrates a use of the sling.” The technique appears to be the same across-the-back technique described above.

Results.

My experimental trials report slinging velocities substantially higher than previous measures (Finney 2005, 2006; Richardson 1998; Vega and Craig 2009) and estimations (Finney 2005, 2006). The observation that underhand slinging appears to be an inefficient technique is substantiated by the evidence. The raw data is available in Appendix D, and a summary is shown here.

Table 5. Summary of Experimental Velocities by Technique

	By Hand	Underhand	Balearic	Sidearm	Overhand
Number of Throws	7	23	30	33	43
Minimum Velocity (m/s)	24.15	28.6	33.1	31.75	36.7
Average Velocity (m/s)	27.2	32.1	37.5	42.7	43.3
Maximum Velocity (m/s)	31.3	36.7	42.5	50.5	49.6

Technique used was coded as a categorical variable, while session was coded as ordinal. All other variables (projectile mass, velocity and cumulative throw count) were coded as continuous. Data were input into SPSS 17.0 and run through univariate generalized linear regression analysis to test the effects of each of the independent variables and relevant interactions between variables. For this analysis, technique and session were coded as factors, while projectile mass and throw count were coded as covariates. Marginal means were also generated across technique categories and between the two sessions, and the variations between these were analyzed via Bonferroni-adjusted pairwise comparisons. Two velocity readings were anomalously low, and were filtered out of the analysis. Since throws by hand were conducted only using a single projectile weight, they were necessarily excluded from analysis. Confidence thresholds for significance were set at 95%, or α = .05.

The model accounted for 82.1% of the variation in the 129 throws (adjusted R^2 = .795). Technique, projectile mass and throw count were all significant influences, as were the interactions between technique and throw count as well as between technique and projectile mass. Session was insignificant, as were other interactions between throw count, projectile mass and technique.

Table 6. Significance of variables in model predicting projectile velocity.

Variable	**Significance**
Technique used	.000
Throw count	.000
Projectile mass	.000
Session	.133
Technique AND throw count	.014
Technique AND projectile mass	.024
Throw count AND projectile mass	.258
Technique AND throw count AND projectile mass	.716

Strangely, though session is not a significant variable in the model, Bonferroni-adjusted pairwise comparison between sessions finds a significant relationship (p = .015) but this cannot be replicated when either a two-tailed T-test (p = .172) or the Mann-Whitney U test (p = .08) are run on the data. Either of these tests should be more susceptible to a false positive (Type I error) than the Bonferroni analysis (which uses marginal means in analysis, thus accounting for the effects of other variables), so this result is slightly puzzling. Since the preponderance of tests conclude that session was not a significant source of variation (and these included tests deliberately selected to be susceptible to a Type I error) I have discounted this variable from further discussion.

The effect of technique on velocity was immediately apparent during experimentation. This allowed me to focus effort on techniques that were producing similar velocities in order to gain better data resolution. Pairwise comparisons between each of the techniques show that all techniques were significantly different from each other except overhand and sidearm, which were virtually indistinguishable. The estimated marginal means (mean velocity after controlling for throw count and projectile mass) are shown below.

Table 7. Estimated marginal means of velocity, by technique.*

	Marginal Mean	95% Confidence Interval
Overhand	43.07 m/s	42.30 – 43.84 m/s
Sidearm	42.68 m/s	41.82 – 43.54 m/s
Balearic	37.30 m/s	36.38 – 38.23 m/s
Underhand	32.90 m/s	30.36 – 35.45 m/s

*Marginal means estimated using a throw count of 36.67 and a projectile mass of 36.96 g.

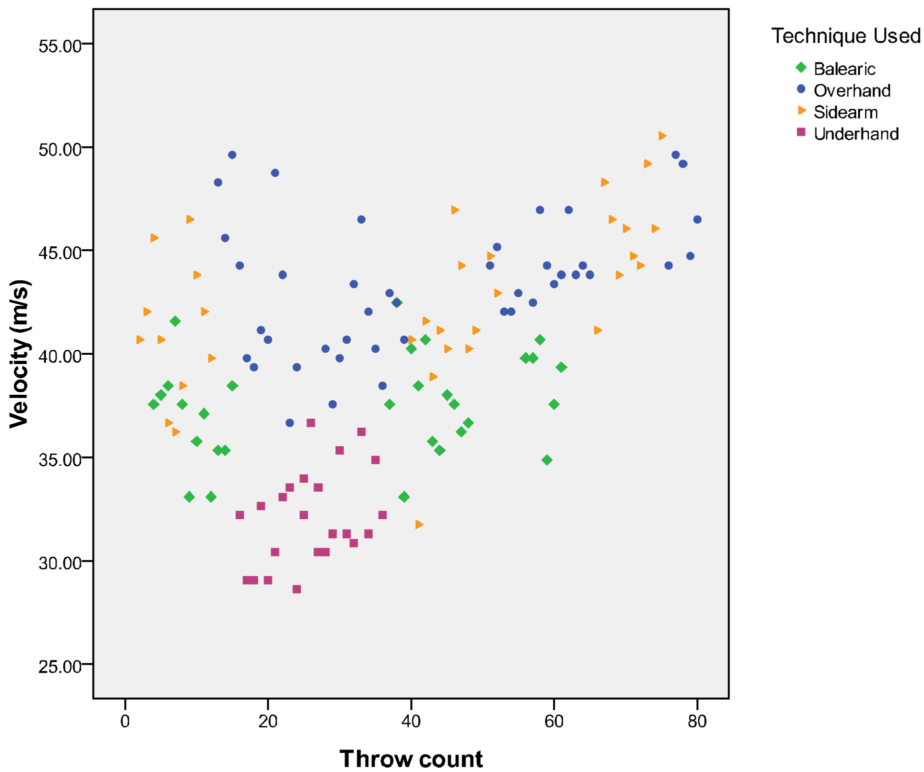
As can be seen in the data above, the only overlapping confidence intervals are those for the sidearm and overhand throws. The expectation that these would show no significant difference while other combinations would be significant was confirmed.

Table 8. Significance of pairwise comparison of techniques

	Overhand	Sidearm	Balearic	Underhand
Overhand	NA	1.000	.000	.000
Sidearm	1.000	NA	.000	.000
Balearic	.000	.000	NA	.006
Underhand	.000	.000	.006	NA

Throw count and the interaction between style and throw count were both significant. After accounting for other variables it is certainly conceivable that velocities improved throughout each session. This is why the order techniques were tested were reversed during the second experimental session. However, this control was abandoned when I decided to improve data resolution on some techniques but not others. The effect was that high throw counts were associated primarily with the more powerful overhand and sidearm throws, while the underperforming underhand technique was never included in these late-session trials. This helps to explain the influence of the throw count variable in predicting velocity, and is further supported by the significance of the interaction between technique and throw count. The scatterplot below shows the interaction between velocity and throw count. Note that the apparent rising trend is in fact due in large part to the reduction in low-velocity throws after approximately 50 throws and that velocities were actually fairly consistent within technique categories shown.

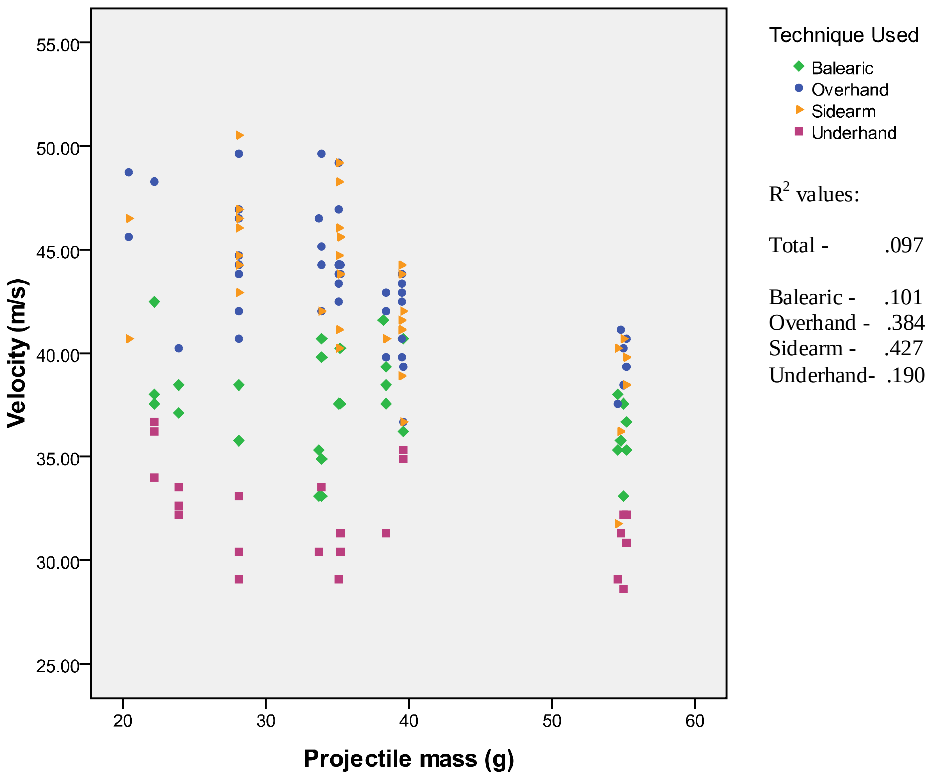
Figure 10. Relationship of velocity to throw count.



The same experimental design issue helps to explain the interaction between technique and projectile mass. Supplemental trials, primarily of sidearm and overhand techniques, were conducted using a more restricted range of projectile weights.

Projectile mass itself showed interesting effects, but not as strongly as predicted. The more powerful overhand and sidearm techniques were far more affected by projectile mass than the other techniques were. Fit lines were left off the scatterplot below to avoid clutter, but the R^2 values are reported.

Figure 11. The effect of projectile mass on velocity.



Conclusion.

These tests have shown that velocities attainable by sling projectiles are substantially higher than has been previously demonstrated in experimentation. Environmental variables were controlled, measured, and accounted for in the statistical analysis, which demonstrated a minimal influence of these variables. The results also show a statistically significant difference in projectile velocity depending on technique, which confirms the hypothesis that some techniques are more efficient than others, all other factors being equal. The velocity data generated here is applied to the questions of sling range and projectile impact effects in the next two chapters. In each case, the results exceed previous experimentation and align the data more closely with ethnographic and historical sources.

Chapter 6: Sling Range

Introduction.

Range can be generally defined as the maximum distance a projectile weapon can be reliably expected to reach, with any expectation of accuracy. Previous attempts to define the range of the sling were explored in Chapter 3 and showed a wide gap between experimental data and ethnographic and historical extrapolations. This chapter applies the velocity data from Chapter 4 to show that experimental ranges can approach those indicated by the ethnographic and historical evidence. Range is calculated using mean velocity and an optimal launch angle, and unlike previous estimations of range, includes drag as a critical component of the calculations. The results clearly show that shape and material density are critical aspects of projectile design, and offer an explanation for the evolution of projectile design.

Calculating Range.

Range was estimated by inputting the marginal mean velocity for overhand throws and then computing total range assuming a release angle of 45 degrees. Unlike previous attempts to estimate range (Finney 2005; Richardson 1998), my calculations have included drag, which is shown to have a substantial impact on the total range of a variety of projectiles.

The force of drag depends on a variety of factors, including the velocity of the projectile, so the force of drag actually varies during the flight of the projectile. To accurately model the flight path of a projectile therefore requires calculus, but the flight path can be closely approximated by computing drag as constant during a short interval, plotting the position at the end of that interval, then repeating the process until vertical position reaches zero. To make this estimate more conservative, I computed the deceleration due to drag at the beginning of each interval and then applied it as a constant during that interval.

The force of drag is a product of a constant of ½, the drag coefficient (C_d), the reference area (A), fluid density (p), and the square of velocity (V).

$$F_d = 0.5 C_d A p V^2$$

I have used the cross-sectional area for the reference area, and fluid (air) density was obtained via FoilSim III, which is an educational wind tunnel simulation program (NASA, Glenn Research Center, 2011). Both biconical and spherical projectiles were analyzed, each across two material classes chosen to represent the full range of likely projectile densities: clay and lead. Mass of the projectile was set to the marginal mean, 36.82g (calculations were done before outliers were eliminated from the data, accounting for this small difference in marginal mean mass). Drag coefficient was more difficult to estimate, but by approximating the biconical projectile as a prolate spheroid, it was possible to conservatively estimate C_d at 0.1 based on wind tunnel studies reviewed and conducted by Joshua DeMoss (2007). The drag coefficient of a sphere was found to vary significantly over the velocity ranges encountered, but these were determined through referencing FoilSim III, which provides values for smooth or rough spheres over a range of velocities (NASA, Glenn Research Center, 2011). To determine the size of the biconical clay projectiles, an existing projectile (not used in the trials) of approximately the same mass was chosen and measured. Spherical projectiles were modeled by dividing the mass by the known density of the materials. After this volume was derived, it was a simple matter to solve for the radius of the sphere. To model the lead biconical projectile, the required volume was determined and cut from modeling clay then molded into a proxy projectile. In each case, diameter was measured and the cross-sectional area calculated.

Table 9. Values used for drag calculation

	Air Density (kg/m^3)	Drag Coefficient (C_d)	Cross-section (cm^2)
Clay biconical	1.20	.1	5.77
Clay spherical	1.20	.151 - .45 (velocity dependent)	9.99
Lead biconical	1.20	.1	2.07
Lead spherical	1.20	.151 - .45 (velocity dependent)	2.61

Terms were then simplified to a constant times the square of velocity. Since force = mass x acceleration, this constant could then be divided by the mass of the projectile to give the instantaneous deceleration due to drag (a). For biconical projectiles, this gives the following equation, where k is the derived constant:

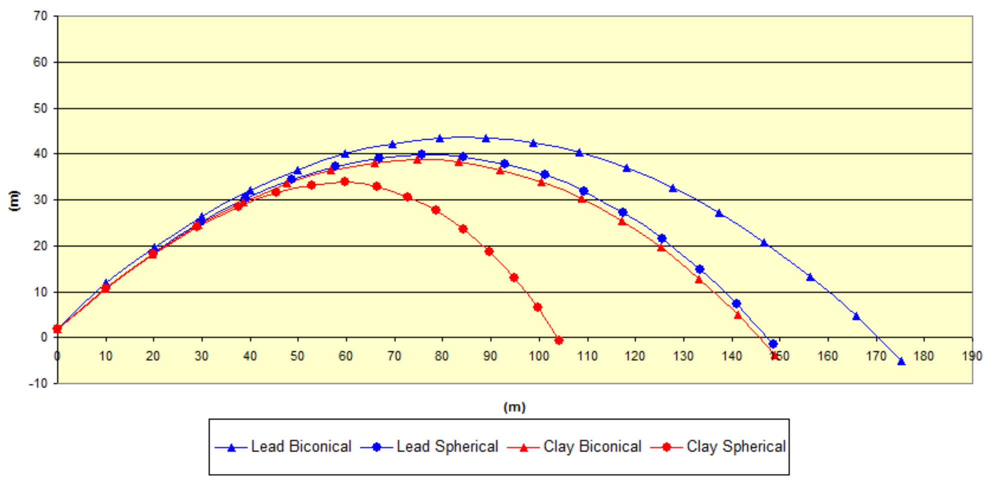
$$a = kV^2$$

Spherical projectiles have a variable drag coefficient, so the equation could not be simplified as far, but was still fairly straight-forward:

$$a = kC_dV^2$$

At this point, the velocity, acceleration and ultimately the position of the projectile must to be divided into its horizontal and vertical components to allow computation of the flight path. This requires trigonometry based on the angle of the projectile at that point in time. Time from release until impact is divided into equal intervals, and the change in velocity is computed and applied to each interval. The velocity can then be multiplied by the length of the interval to compute the change in position. To allow for a reasonably accurate computation, I set the interval at 1/3 second. The deceleration is figured based on each interval’s original velocity, and then applied to the whole interval, making the calculations deliberately conservative. Since 45 degrees provides for the optimal flight distance without drag, that same angle was chosen as the release angle in this study. These cumulative calculations were entered into spreadsheets and can be viewed, along with full explanation, in Appendix E. The calculations allow us to plot the position, angle and velocity of the projectile at 1/3 second intervals. The flight paths for the four projectiles were plotted and the range estimated based on the x-intercept.

Figure 12. Calculated flight paths of 36.82g projectiles launched at 45 degrees, at 42.9m/s.



The data clearly demonstrate the importance of aerodynamics in sling projectile performance. In a vacuum, projectile shape and density would not affect range, so the variability seen here shows the effect drag has on various projectile designs. Range in a vacuum given this launch velocity would be approximately 187m, so even the most aerodynamic of projectiles was significantly affected. In spite of a deliberately conservative model, the ranges derived are substantially greater than previous experimental studies. Only Richardson (1998) had average ranges that overlapped the results of this study, and then only when comparing across projectile types.

Table 10. Comparison of results across experiments

Study	**Category**	**Measured Range**	**Computed Range**
Richardson (1998)*	40g lead biconical	145m	96m (no drag)
	38g lead sphere	114m	-
	45-75g stone	90m	-
Finney (2005, 2006)	Stone	56m	65m (no drag)
Vega and Craig (2009)	All users	66m	-
	Adult users	70m	-
	Male users	78m	-
Present study (2012)**	Lead biconical	-	170m
	Lead sphere	-	147m
	Clay biconical	-	146m
	Clay sphere	-	105m

*Categories selected from Richardson to allow direct comparison to present results.
**Based on 36.82g projectile launched at 42.9m/s.

On the assumption that only the highest velocity throwing technique would be used when throwing for distance, range was not computed with drag for the other throwing styles. As a way of comparison, however, range without drag effects is computed below. It should be kept in mind that these are overestimates, since drag is not considered.

Table 11. Range without drag based on marginal mean velocity

	Marginal Mean Velocity	Calculated Range
Overhand	43.07 m/s	189 m
Sidearm	42.68 m/s	186 m
Balearic	37.30 m/s	142 m
Underhand	32.90 m/s	110 m
By hand*	27.20 m/s	75 m

*Throws by hand are not based on marginal mean, but on the mean of 7 throws using a 55g projectile.

One source of variation from the range data presented here was not measured and could be the focus of future experimental efforts. The spin of a projectile can act to create lift as it passes through the air. A useful way of thinking of this phenomenon is to imagine that the surface of the projectile lightly “grips” the air as it passes through. If the projectile has a backspin, the top of the projectile is retreating relative to the direction of motion and the bottom of the projectile is advancing. Thus the “grip” of the projectile surface acts to push the air along over the top of the projectile and to hinder its motion along the bottom. This creates a situation similar to the lift generated by an airfoil: according to the Bernoulli Principle, since air is moving faster along the top of the wing, the air pressure is lower, creating lift. The term lift is something of a misnomer, however, because if the projectile is released with a top spin the “lift” will be generated in a ground-ward direction.

In actual practice it is possible to control the rotation of a sling projectile in order to gain this advantage. If in an overhand release the palm of the hand is kept facing forward during the final release this causes the sling to open in such a way as to roll the projectile out with backspin. I have, subsequently to the measured experimentation, launched more or less spherical stones in just such a manner and they visually appear to be generating lift. Golf balls are typically driven with a significant amount of backspin, so the visual appearance of a projectile flight path with lift is readily available to any curious person with internet access (the same is also true in baseball, especially long throws from outfield that appear to have a nearly flat trajectory). At this point the phenomenon is only supported by this anecdotal evidence, and, though widely appreciated among slinging hobbyists, has yet to appear in scholarly publication. Measurement of flight path with Doppler radar (such as are used in sport applications already) or some forms of golf simulator could be a profitable direction for future research.

Conclusion.

These experimentally derived ranges exceed those of previous empirical attempts and more closely align results with ethnographic and historical sources, though some gap between these remains. It should be remembered that the results presented here are those of a single, amateur user and that sling capabilities may be greatly in excess of my capabilities. This study should serve as a beginning point for a wide-scale analysis that can include many slingers and begin to look at other aspects of performance, such as sling length and pouch design. Avenues for future research are explored further in Chapter 8.

The initial and downrange velocities from the calculations presented above are utilized in the next chapter to evaluate the likely effects of projectile impacts on human and animal targets. In contrast to previous research, these analyses show a potential to cause the sort of devastating wounds indicated by the ethnographic and historic record.

Chapter 7: Sling Projectile Impact Effects

Introduction.

The previous chapter presented experimental determinations of sling range for a variety of projectiles. This chapter build on that information by investigating another aspect of the effectiveness of sling technology, that of impact effects. The potential of sling projectiles to do damage can be approached from several angles, including historical and ethnographic sources, medical texts dealing with blunt injury and biomechanical experimentation. These insights are mutually supporting, as experimental models can be used to test the plausibility of historical or ethnographic claims while biomechanical predictions can be compared against documented injuries. These multiple approaches suggest that the lethality of slings may be greater than widely appreciated.

Historic Sources.

Among a modern American audience, the most widely known historical account of sling use is undoubtedly that of David and Goliath (Gilleland n.d.). “And David put his hand in his bag, and took thence a stone, and slang it, and smote the Philistine in his forehead, that the stone sunk into his forehead; and he fell upon his face to the earth” (Samuel 17.49). There is some discrepancy among various translations whether the stone was a killing blow, as David subsequently decapitated his opponent, but all agree that the projectile hit the forehead and sunk in. The translations are also consistent in stating that Goliath was quickly incapacitated by the strike. In the light of the evidence to be presented here, these events are by no means an anomaly; there is nothing necessarily miraculous about a lethal result from a sling.

The sling was a widely used military weapon in Europe and Southwest Asia up through the Middle Ages (Dohrenwend 2002; Harrison 2006; Korfmann 1973). This ubiquity as a military arm speaks to the sling's effectiveness as a weapon, but a few accounts from this period speak directly on the effects of slings on human targets. Vegetius (1.16) says that "Soldiers, notwithstanding their defensive armor, are often more annoyed by the round stones from the sling than by all the arrows of the enemy. Stones kill without mangling the body, and the contusion is mortal without loss of blood" (Gilleland n.d.). This passage suggests that sling stones can kill through non-penetrating blunt force trauma, but the physician Celsus suggests that sling stones could also pierce the human body (7.5): "There is a third type of weapon that sometimes needs to be removed, a leaden bullet or rock or something similar, which breaking through the skin lodges inside in one piece" (Gilleland n.d.). Xenophon also stated that projectiles could penetrate the body (Gabriel and Metz 1991: 75). Finally, Thucydides suggests that armor provided (at least some) protection against stones (2.82.8) "…using their slings against them from a distance and distressing them; for it was not possible for them to stir without armour" (Gilleland n.d.). Taken together, these ancient sources are not as contradictory as may be thought. The primary means of injury seems to be blunt trauma, but the projectiles can sometimes penetrate the body. Armor can sometimes prevent injury, especially at long range, but the energy of the impact can nonetheless sometimes transfer into the body with lethal effect. Gabriel and Metz (1991) tallied the wounds and deaths recorded in the Iliad, which although a work of fiction can be expected to at least have been believable to its audience, who were familiar with the weapons involved. A total of 147 wounds are recorded, the vast majority, 106, with the spear, 17 with the sword and 12 each with the bow or sling. Spear wounds are 80% lethal in the tale, sword wounds 100%, while arrows prove 42% mortal and slings were 66% lethal (Gabriel and Metz 1991).

Ethnographic Sources.

Leaving Classical history behind, evidence of sling lethality abounds in other areas of the world. An archaeological find in Guam included a skull, bones completely shattered by impact, with a biconical slingstone still embedded in the wound (York and York 2011: 23). European chroniclers were impressed by the lethality of Marianas sling users (York and York 2011:22):

> They are very skilled at using the sling for which they fashion marble slingstones that fly as through bewitched. These resemble very large acorns that are flung from their slings in such a way and with such force that it is as through they were fired from an harquebus. They always hit the target with the point of the slingstone and strikes with such force that, if it hits the head or the body, it will penetrate (Driver 1989:19).

York and York (2011:22-23) also relate that, "They can throw stones from a sling with such dexterity and strength that they are able to drive them into the trunk of a tree (Higgins 1968:46)," and "They whirl and shoot those [slingstones] so violently, should it make an impact upon a more delicate part, like the heart, or the head, the man is flattened on the spot (Lévesque 2000:39)."

Slings were also used extensively among Fijian, Tongan and Samoan islanders. An observation by Reverend Thomas Williams around 1858 is especially poignant:

> I have been led to think that the natives [Fijians] throw stones and other missiles with extraordinary force…During the conflict [attack on Koro na Yasaca] a stone struck the barrel of this musket… shattered the lighter part of the stock; made and indentation in the barrel 1/8 inch in depth, and … drove the barrel 7/16 of an inch out of the straight line. I have since learned that this stone was thrown from a sling. (York and York 2011:38)

On Samoa the sling was in use around 1838-45 and could apparently cause horrific injuries.

> The sling was always considered a very formidable weapon, and old warriors have repeatedly assured me that a wound from a stone hurled from a sling and thrown with force was often much worse than one received from a musket ball. If a stone struck the arm or leg, it was difficult to heal, since the bone was usually smashed to pieces, and caused much suffering. (York and York 2011:44)

York and York suggest that this claim could be exaggerated or that the reference could refer only to the very large (“grapefruit sized”) slingstones occasionally found on nearby island groups (2011:44). However, biomechanical data (see below) tend to confirm that even the relatively small projectiles, probably launched at lower velocities than those attained by skilled warriors, used in the present study could fracture most human bone even at extreme range.

In my own use of the sling, I have many times put a stone (unmodified water-worn cobble, all un-weighed but probably on the order of 40 -75 g) completely through a slightly rotten board of 3/8” thick plywood I use as a target. More commonly penetration does not occur, but visible dents conforming to the shape of the end of the stone are left even in the non-rotten 2x4” planks which supplement the target’s construction. Stones have several times fractured from the force of impact against even these relatively soft targets. When practicing against logs or living trees (mostly lodgepole pine) I have often seen the bark fracture violently outwards from the point of impact, though I have never observed a stone embedded in the trunk afterwards.

Biomechanical Investigation.

Biomechanical studies have been used in military, forensic and medical applications (to name but a few) to predict the cause of existing injury or the likelihood of injury from an experimental stimuli. These studies have been adapted to historical and archaeological problems by researchers interested in warfare and other forms of interpersonal violence (e.g. Gabriel and Metz 1991). Previous attempts to directly model the effects of sling projectile impacts have focused unduly on trauma to the skull (Finney 2005, 2006; Skov 2011). While the skull is a favored target (Judd 1970), a large percentage of impacts would undoubtedly fall on the torso or limbs. Due to the proliferation of blunt trauma injuries in modern societies (especially as a result of automobile collisions and the widespread use of body armor in military conflicts) a large body of experimental research has been conducted in recent decades to investigate how blunt impacts produce injuries in soft tissue (Clemedson et al. 1968; Cooper and Taylor 1989; Cripps and Cooper 1997; Viano and King 2000; Widder et al. 1997).

These studies have found that high energy, low momentum impacts can initiate compressive waves within the body which produce effects that may support Vegetius' assertion that sling projectiles can produce lethal internal injury (Gilleland n.d.). The potential of sling projectiles to break the skin and cause a penetration wound have been modeled previously (Dohrenwend 2002), but will be revised here based on a more comprehensive biomechanical model (Sperrazza and Kokinakis 1968). Finally, based on fracture thresholds for a wide variety of human bones provided by Gabriel and Metz (1991), the potential to directly break bone can be evaluated.

For any impact there are therefore three kinds of impact effects to evaluate: fracture, penetration and soft tissue blunt trauma. For any injury, it is posited that one of these mechanisms will dominate and which mechanism takes precedence will be largely dependant on the location hit. For instance, a shot that strikes the forehead will produce injury primarily through direct fracture of the frontal bone, possible penetration of the skin would be of little importance in this instance. Conversely, if a shot hits the torso penetration is potentially traumatic but whether or not penetration is achieved soft tissue injury through blunt trauma may still result.

Direct Fracture. Direct fracture injury from blunt force trauma is a well-established archaeological signal for interpersonal violence (Lovell 1997; Wells 1962). A study of ancient warfare by Gabriel and Metz (1991:57, 95) lays out a series of energy thresholds required to initiate fracture on various bones in the human body. Impact over areas with greater amounts of overlying soft tissue, such the thigh, would dissipate the impact over a larger area and likely a longer impact time, making direct fracture comparatively unlikely. Therefore, these analyses are most applicable for impacts to the skull, limbs and joints. The measurements were given in footpounds per square inch (ftlb/in^2), but have been converted to metric (J/ cm^2) for consistency. One footpound is approximately 1.356 Joules, while one square inch is 6.4516 cm^2.

Table 12. Energy thresholds per unit area to initiate fracture of various human bones.

Bone	Imperial Threshold (ftlb / in^2)	Metric Threshold (J / cm^2)
Frontal bone	90	18.9
Temporal / Parietal bones	45	9.6
Zygomatic bones	18	3.8
Produces unconsciousness	56-79	11.8-16.6
Most post-cranial bones	67.7	14.2

To evaluate sling projectile impacts, all that is then necessary is to compute the kinetic energy contained within the sling projectile and the impact area. For impacts on hard tissues, I estimated impact area conservatively as being the cross-sectional area 5mm distal from the point of impact. For spherical projectiles this was measured from a to-scale drawing, while for the biconical projectiles the actual projectiles were measured (the same as used for aerodynamic computations). Kinetic energy is simply ½ the product of the mass and the square of the velocity.

$$KE = 0.5MV^2$$

Since the velocity of the projectiles changed through the flight path, this measurement was taken at release and at maximum range. The greater drag some projectiles experienced is directly reflected in their lower maximum range kinetic energy, as they lost more of their velocity. It should be understood that shots over medium ranges would be launched at lower trajectories and so should impact at speeds intermediary between launch and maximum range impacts. To evaluate the potential of projectiles heavier than the marginal mean, an average combined overhand and sidearm velocity was obtained for the projectiles between 54.6 - 55.2 g. This heavier projectile was launched at a lower velocity but the increased cross-sectional density allowed it to retain velocity better than the lighter clay biconical projectile. Maximum range was therefore 131 m, only 15 m short of the smaller projectile.

Table 13. Impact Energies of Projectiles.

Projectile Shape and Material	Projectile Mass	Impact Cross-section	KE at Launch	KE at Max Range	Launch KE / area	Max Range KE / area
Lead biconical	36.82 g	0.79 cm^2	33.88 J	28.00 J	42.89 J/cm^2	35.44 J/cm^2
Lead sphere	36.82 g	2.01 cm^2	33.88 J	21.28 J	16.86 J/cm^2	10.59 J/cm^2
Clay biconical	36.82 g	1.29 cm^2	33.88 J	21.28 J	26.26 J/cm^2	16.50 J/cm^2
Clay sphere	36.82 g	4.52 cm^2	33.88 J	11.51 J	7.50 J/cm^2	2.55 J/cm^2
Clay biconical	55 g	1.50 cm^2	41.23 J	26.43 J	27.49 J/cm^2	17.62 J/cm^2

When the kinetic energy per unit area is compared the critical values needed to initiate fracture, it rapidly becomes apparent that projectile design has a grave influence on wounding potential. In general, the more impact is concentrated over a small area, whether by projectile shape or material, the more lethal the projectile is. In the table below, impacts that exceed critical values for fracture are signified by an “x.” If a projectile exceeds critical value at launch and max range velocities, there are two “x” markings. Clemedson and colleagues (1968:192) note that when threshold energies are exceeded by 10-20%, “the skull is completely demolished.” To denote these highly destructive impacts of at least 20% over the threshold, the x symbol is capitalized.

Table 14. Wounding potential of projectiles

	Frontal	**Most post-cranial bone**	**Produces unconsciousness**	**Temporal / Parietal**	**Zygomatic**
Critical value for fracture	**18.9 J/cm^2**	**14.2 J/cm^2**	**11.8 – 16.6 J/cm^2**	**9.6 J/cm^2**	**3.8 J/cm^2**
Lead biconical	X X	X X	X X	X X	X X
Lead sphere	- -	x -	X -	X x	X X
Clay biconical	X -	X x	X x	X X	X X
Clay sphere	- -	- -	- -	- -	X -
55g clay biconical	X -	X X	X x	X X	X X

(x denotes fracture, X denotes impact exceeding fracture threshold by at least 20%)

Penetration. The second mechanism of sling projectile wounding is penetration. Although it seems unlikely for a blunt object to penetrate the skin, Celcus' medical texts document that surgical extraction of sling projectiles was at least occasionally needed. In fact, it takes a surprisingly low amount of energy to puncture human skin. Gabriel and Metz (1991) and Dohrenwend (2002), both cite studies claiming that only around 2 ftlb/in^2 are needed, or approximately 0.42 J/cm^2. I have previously argued (Skov 2011) against the use of this measure because it predicts such absurdities as the penetration of skin by a moderately quick fastball. However, experiments conducted by Sperrazza and Kokinakis (1968) on cadaver skin samples found a more complex relationship which was related to momentum rather than kinetic energy. They also tested penetration of US army winter uniforms consisting of 6 layers of garments, which may be a reasonable analog for traditional cold-weather dress or possibly some types of flexible cloth-based armor. Lighter clothing would almost certainly require velocities intermediary between those for skin and for winter clothing. In each case, velocity threshold for penetration is determined by a robust linear equation.

Winter uniform: V = 261(cross-sectional area / projectile mass) + 73.5 m/s
Skin: V = 125(cross-sectional area / projectile mass) + 22.0 m/s

Velocity threshold was determined for each projectile and compared to velocity at launch and at maximum range impact to evaluate penetration potential. Sperrazza and Kokinakis (1968) noted that critical velocities to penetrate isolated skin preparations tends to be slightly higher than when subcutaneous tissue is included, so the following evaluation errs slightly on the side of caution.

Table 15. Penetration capability of projectiles.

	V threshold: winter uniform	V threshold: skin	Penetration of uniform?	Penetration of skin?
Lead biconical	88.2 m/s	29.0 m/s	- -	X X
Lead spherical	92.0 m/s	30.9 m/s	- -	X X
Clay biconical	114.4 m/s	41.6 m/s	- -	X -
Clay spherical	144.3 m/s	55.9 m/s	- -	- -
55g Clay biconical	110.0 m/s	39.5 m/s	- -	- -

(x denotes penetration, X denotes impact exceeding penetration threshold by at least 20%)

Blunt Force Trauma to Soft Tissues. The third wounding mechanism, soft tissue damage through blunt force trauma, has not been previously explored in any previous treatment of sling technology. Indeed, even Gabriel and Metz’s (1991) evaluation of a wide range of weapons dealt only with penetration and bone fracture. The importance of blunt force trauma has been recognized in full body deceleration events such as car crashes for some time (Clemedson et al. 1968), but in recent decades biomechanical research has begun evaluating topics such as less-than-lethal projectile impacts (Clare et al. 1973; Widder et al. 1997) and the transfer of energy after a bullet is stopped by body armor (Cannon 2001). In the process researchers have discovered that there are three classes of injury created by blunt trauma, differentiated by the velocity of body wall compression (Viano and King 2000). The velocity of compression is related to the relative momentum of the impact compared to the kinetic energy.

When the momentum of impact is high, such as in car crashes or injury from falls, the velocity of body wall displacement is low and injury is related to the peak compression of the chest. At high rates of compression, ribs begin to break under the stress and major organs (the liver is especially susceptible) or blood vessels can rupture. Viano and King (2000) found that chest compression rates below 34% were sustainable, beyond which the risk of multiple broken ribs, a flailed chest, and direct loading onto the chest's internal organs increased dramatically.

At the other extreme, blast injuries are produced by very rapid body wall displacements of very low amplitudes. In the middle range are viscous injuries, which moderately compress body tissues, but at rates that exceed the tissue's ability to deform without ruptures. In some cases injuries through the viscous mechanism can exceed those produced by even large rates of compression over lengthier time intervals. Cooper and Taylor (1989:60) illustrate this principle by comparing the difference in severity of lung contusions in pig test animals using a 17 millisecond, 10cm displacement impact, which produced only minor contusions, and a 1.2 millisecond, 4 cm displacement impact which produced major contusions over the majority of the impacted lung. These different kinds of injury can occur at different times during an impact event, so multiple mechanisms may be involved in a single blow (Viano and King 2000).

In a series of projectile experiments against anesthetized animal targets, two models for predicting injury have emerged. The first relies on direct instantaneous measurement of compression velocity and proportional compression. The model is variously referred to either by the variables: VC or CV (that is, Velocity Compression or Compression Velocity), or it takes its name from the injury mechanism, the viscous model. When the product of these measures passes a certain threshold (which varies by the location and aspect of impact) the risk of serious injury by the viscous mechanism rapidly increases to a near certainty. For instance, the probability of serious injury from a blow to the anterior chest is 25% at a VC of 1.0 m/s, but rises to 50% at 1.08 m/s and nearly 100% at 1.5 m/s (Viano and King 2000). The threshold for 25% injury risk was provided by Viano and King (2000) for both compression and viscous injury for a range of body locations and aspects.

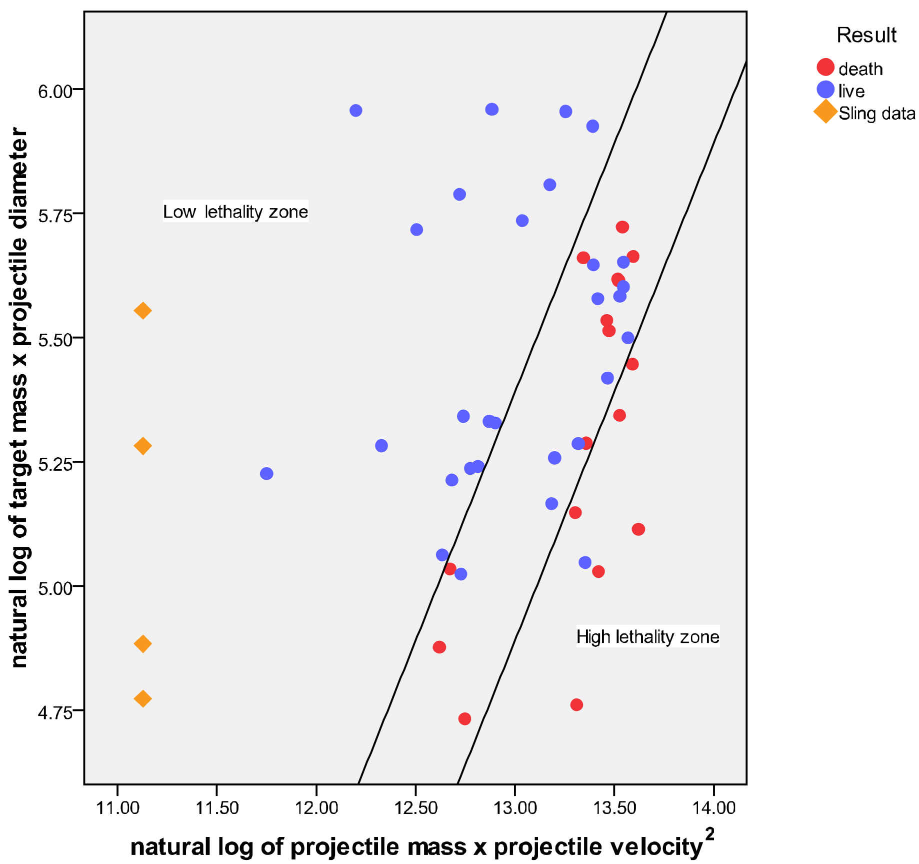
Table 16. Injury Probability for Blunt Impact

	25% chance of serious injury through compression	25% chance of serious injury via viscous mechanism
Frontal impact to chest	34%	1.0 m/s
Lateral impact to chest	38%	1.5 m/s
Lateral impact to abdomen	47%	2.0 m/s
Lateral impact to pelvis	27%	-

This method, however, requires measurement of the body wall during impacts and to date VC measurements have not been related to the type of impacts that cause the rates of compression necessary to cause injury. Because VC is computed as an instantaneous measure (the peak value is the one noted), measurements of total compression and total time of the impact event are insufficient to compute the relevant measure, yet these are often the values reported. Utilizing data from Cripps and Cooper (1997), total VC from a series of 31 trials on anesthetized pigs is consistently in excess of 4.0 m/s, yet injuries resulted in only 20 of these cases, several of which were only fairly minor contusions to the small intestine. Cripps and Cooper (1997) did not compute peak VC, but did note that small intestine injuries only occurred when impact velocities exceeded 40 m/s. Because peak VC has not been reported in projectile impact studies, the necessary link between the type of impact and the type of bodily response has not been established. This shortfall renders the Viscous Model only useful as a heuristic for understanding injury from projectile impact, a significant failure considering its (purported) potential to empirically evaluate impact effects (Widder et al. 1997).

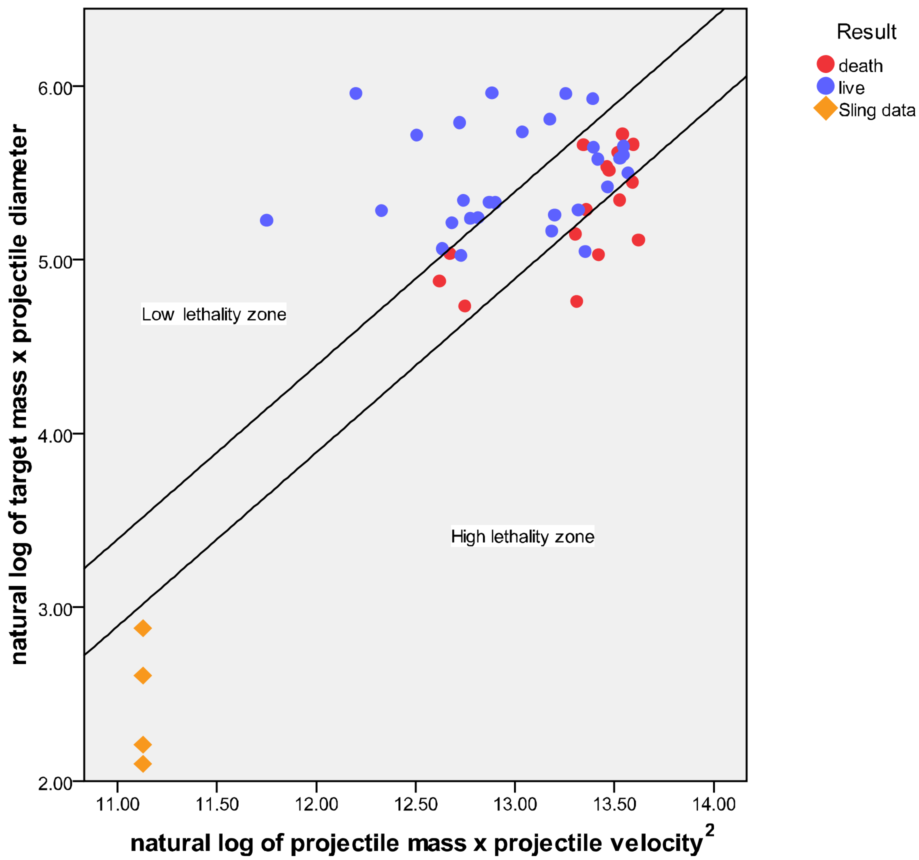
The competing model has been developed by the Edgewood Arsenal (Clare et al. 1976) and relies on the interaction of projectile mass and diameter, impact velocity and the mass of the target. When the natural log of the product of mass and velocity squared is plotted on the horizontal axis, and the natural log of the product of target mass and projectile diameter on the vertical axis, a scatter plot of the impact events can be generated. These were coded by whether lethality resulted within a 24 hour period. Two discriminant lines ($y = x - 7.61$ and $y = x - 8.11$) could then be drawn through the data, separating impacts into low, medium and high lethality ranges. Forty-six animal tests were used to generate this model, with 0/17 lethal impacts in the low lethality category, 11/22 in the medium and 6/7 in the high lethality grouping. All impacts were to the anterior wall of the thorax. The resulting model was then tested against independent data, which add 93 animal tests and a range of projectile weights, types and velocities. Despite a few outliers and with necessary adjustments for differences in the experimental procedure (for instance, Lovelace Foundation tests euthanized the target animals after 30 minutes rather than 24 hours, accounting for the lower lethality of those tests) these data further confirmed the predictive power of the model. Utilizing the marginal mean overhand velocity and projectile mass, and assuming an average target weight of 72.57kg (160 pounds), the predicted lethality of various projectiles was plotted alongside the results of the initial 46 animal tests.

Figure 13. Projected Sling Lethality Against Targets of 72.6 kg, with Animal Testing Data for Comparison.



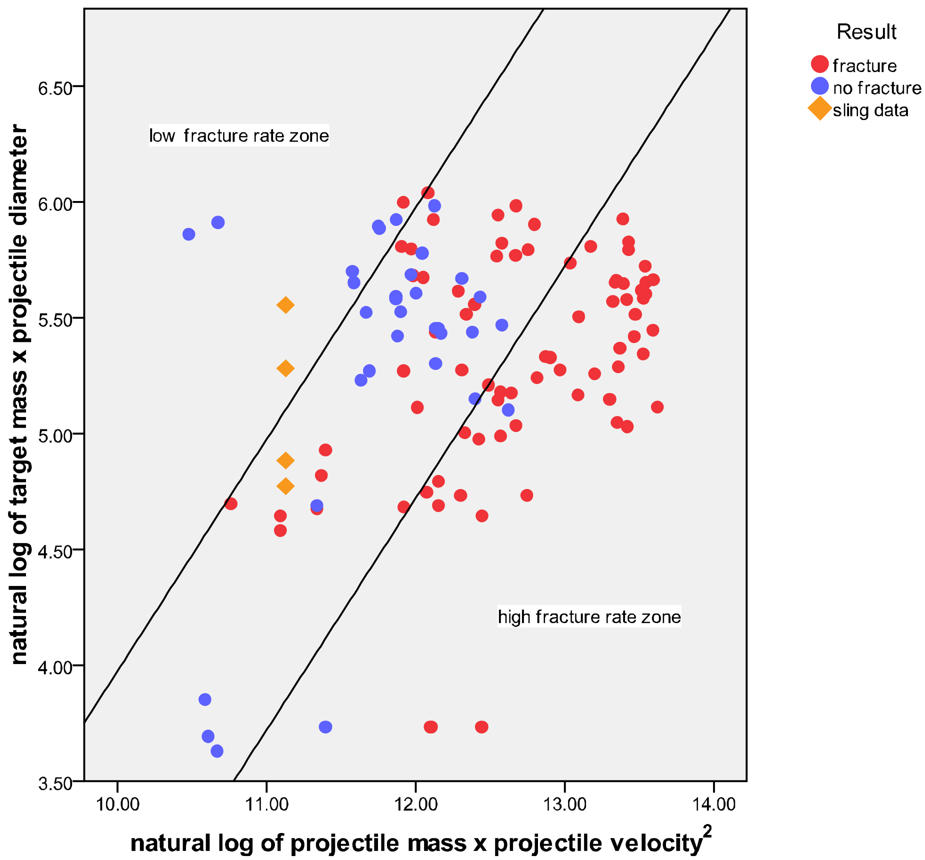
The sling data differs only in projectile diameter, so the clay sphere is uppermost and the lead biconical projectile lowest. Still, all projectiles fall unquestionably in the low lethality zone. When the same projectile data is applied against a 5 kg target, however, the sling's usefulness for small game hunting is made apparent.

Figure 14. Projected Sling Lethality Against Targets of 5 kg, with Animal Testing Data for Comparison.



The model was also adapted to predict liver fracture probability. As previously mentioned, the liver is particularly susceptible to blunt injury, making this organ of some interest to designers of less-than-lethal projectiles or of body armor. The same four variables are used, and the model differs only in the y-intercepts (-6.026 and -7.28) of the discriminant lines. Once again, sling data assumes a target mass of 72.57kg, is projected alongside the animal testing experiments, and the sling projectiles are the clay sphere at the top and the lead biconical at the bottom.

Figure 15. Projected Liver Fracture Probability Against Targets of 72.6 kg, with Animal Testing Data for Comparison.



Two factors are at play in the apparent increase in sling projectile effectiveness. Firstly, the discriminating criteria is the presence or absence of organ fracture “regardless of severity" rather than death of the animal within 24 hours (Clare et al. 1975). It is unknown how lethal these impacts would have proven, as the liver is both especially susceptible to fracture compared to other organs and is capable of recovery from severe injury.

Application of the Data to Warfare.

The results of these experiments fall short of a vindication of sling lethality, since most of a presented target consists of the thorax and abdomen. This seems to relegate the sling's effectiveness as a weapon, as Gabriel and Metz (1991:75) put it, to producing a barrage of projectiles, "most of it harmless…experienced soldiers quickly became used to it, and it caused little damage." Other authors, however, have given cause to doubt whether the results of the Edgewood Arsenal study (Clare et al. 1975) can be extended to targets of human dimensions or to projectiles vastly different from those used in the study. Widder and colleagues (1997) list projectile shape and "compliance" (industry code for material compressibility) as additional variables in predicting impact effects. Furthermore, they note the non-linearity of complex bodily reactions to blunt force trauma and doubt that results on one body type maintain the same linear relationship to other body sizes. Cripps and Cooper (1997) note that in small projectile impacts the entire body mass of a person is not engaged in the exchange of energy. This makes intuitive sense: when a batter is struck by a baseball (or a player struck by a soccer or tennis ball, or any other such incident) the player is not thrown bodily backwards by the impact. Rather, that portion of the anatomy absorbs the impact while the rest of the body is (relatively) unmoved. Thus using the total body mass large target organism as a variable to predict impacts from small projectiles is inappropriate. It may be that using the weight of the chest cavity or some other fraction of total body weight may be more appropriate, but this remains to be answered.

Similarly, the mass and shape of the experimental projectiles was quite different from sling projectiles. Projectiles used in the animal tests, for both impact models, are either compliant projectiles such as beanbag rounds or are metal cylinders. In either case the full diameter of the projectile makes contact with the body surface almost immediately. Only six data points from Clare and colleagues (1976) study had hemispherical impact surfaces. In contrast, sling projectile impact surfaces range from hemispherical to conical. These impact with a smaller portion of their full cross-section, which may affect the speed of body wall deformation since energy is initially concentrated on a much smaller portion of the body's surface. Total diameter of sling projectiles are also less than the range of projectiles used in the animal testing experiments. While the sling projectiles range from 1.62 to 3.56 cm, the projectiles used in testing vary between four to eight centimeters diameter. Finally, the mass of the projectiles used is substantially higher in the biomechanical study. The marginal mean mass of 36.67 g was used in calculations for the sling projectiles, but biomechanical projectiles ranged from a minimum of 50 g to a maximum of 200 g. When one considers the projectile diameters as well, it becomes clear that the biomechanical study is based on projectiles of a quite different span of cross-sectional densities than are represented by sling projectiles.

Finally, Cripps and Cooper (1997) argue that the relative mass of target and projectile are important for determining the type of bodily response to the impact. Larger mass projectiles (and larger diameter projectiles) are more likely to cause slower body wall displacements of a greater magnitude–a mechanism more amenable to producing shearing injuries. Small mass projectiles (and those of small diameters) should produce quick body wall displacements of smaller magnitude that produce primarily viscous mechanism injuries. Clare and colleagues (1976) seem to be investigating primarily shear injuries, certainly their investigation of liver fracture seems to indicate this sort of injury (see Cooper and Taylor 1989 for depiction of direct localized shear injury to the liver) yet sling projectiles may be more likely to cause viscous injuries. The investigation of soft-tissue trauma has not brought the clear results any researcher would hope for, but there is clearly a direction forward.

In any case, we are left with fairly robust predictions of the effects expected when sling projectiles impact exposed skin or bony surfaces. These clearly show the importance of projectile shape and material as aspects of design that have a functional importance in sling performance. Significantly for archaeological detection of sling projectiles, design parameters that act to increase the localization of energy on the target are irrelevant to small game hunting (explored below). Therefore, where biconical and/or abnormally high-density projectiles occur they are likely related to warfare, though not all warfare would have used such specialized projectiles. York and York (2012) note that though the sling was a principal military weapon among the Inca they did not manufacture specialized sling ammunition. Incan slingstone caches have therefore been identified by their provenience within 'defensive' areas, and by their statistical similarity, rather than by any distinguishing individual characteristics of the projectiles (York and

York 2011:76). Similar methods will have to be employed in order to document North American sling use, since shaped projectiles have only been documented in a few areas.

Application of the data to hunting.

Sling effectiveness for hunting can also be explored from the data presented. Though critical values for the fracture of different animal bones or for the penetration of different hide surfaces are unknown we can make a few justifiable assumptions that allow for application. Fracture thresholds should be higher for the bones of animals larger than humans and less for smaller animals. This follows from the primary function that skeletons perform: providing support to the body mass. Where skeletal features have evolved under the influence of addition factors the skeletal strength may be higher or lower than initially predicted based on mass. For instance, in many species of mammals with high amounts of male-male competition skull bones tend to be reinforced, at least in the males of that species. Thresholds for fracturing the skulls of such animals would be correspondingly higher, and sling effectiveness in wounding these animals decreases. Birds present an opposing example. The demands of flight have led to an evolution of generally lighter skeletal components and hollow long bones. Bird bones should be easier to fracture than bones from an equivalently sized mammal.

Animal skin should prove less vulnerable to penetration, if only slightly, than human skin by virtue of the fur or feathers covering the skin tissue. Recall that using Sperazza and Kokinakis' (1968) model for penetration not a single sling projectile would penetrate the winter uniform, and only two of the four (the lead projectiles) would penetrate exposed skin reliably. If the animal skin is even mildly tougher then penetration is unlikely to be an important factor in evaluating hunting effectiveness.

Finally, looking at the large animal testing studies conducted by the Edgewood Arsenal (Clare et al. 1976), one immediately notes that in these blunt trauma trials the observation period (to see if death of the animal occurred) was 24 hours. The Lovewell data had an observation period of only 30 minutes and lethality was substantially lower than predicted. Blunt trauma does not kill quickly.

From a standpoint of pure practicality, a hunting weapon should kill game quickly, immobilize the animal, or cause a wound that makes tracking the animal easier (Loughlin 1968). These factors reduce energy outputs in tracking wounded game and should also increase game recovery rates. Blunt trauma damage to soft tissues (either through shearing or viscous mechanisms) does not appear meet any of these requirements. Time until death in controlled experiments is quite long and since by definition penetration is not achieved, no blood trail results from the impact. Whether the blow would immobilize the animal is less clear, though by no means likely. Since the ribcage acts like a soft tissue from the standpoint of these kind of injuries, this means that thorax and abdomen would be ineffective targets for the purpose of hunting large animals. In small game, as the data presented in Figure 14 showed, blunt trauma should be lethal, but the time until death may still prevent the hunter from capitalizing on this. Intuitively it seems that an injury that could prove lethal to a human should be disproportionately catastrophic when inflicted on a rabbit-size creature. The reviewed experimentation did not measure time until death, however, so at present this perfectly reasonable assumption cannot be empirically verified. The notion does get some support from Viano and King (2000), which predicts rapidly increasing chance and extent of injury as relative lateral chest compression passes 38%. Widder and colleagues (1997) estimate total rabbit chest diameter at 75mm, so a 38% compression only needs to move the body wall 28.5 mm, just over 1 inch. Moreover, since velocity of body wall displacement should be high in such an overwhelming impact, VC should be well above the threshold to produce viscous injuries in addition to the crushing injuries resulting directly from compression. While this discussion could turn in yet more circles on itself, bone fracture acts to mitigate this difficulty concerning small game.

The fracture of bones, while not necessarily effecting a quick kill, can act to immobilize the target animal or, by changing the animal's natural gait (by immobilizing a limb), create an easier to follow track and exhaust the animal more quickly. Skull fracture, as in humans, can be expected to bring about more rapid incapacitation. In large game targets, vulnerable bones include the skull and the limb bones, all difficult targets. In small game targets, however, lower threshold values for bone fracture and smaller animal size relative to the projectile diameter virtually guarantees that multiple bones will be hit and broken by any impacting projectile. These multiple breaks should immobilize or drastically slow the animal, essentially rendering mute the (practical, if not ethical) concern over whether blunt trauma kills the animal quickly. This line of reasoning is especially illuminating when considering bird hunting, which has been shown to be as common as small game hunting on the North American continent. As previously discussed, bird bones are on average more easily broken than mammalian bones. Pomo waterfowl hunting (Barrett 1952; Loeb 1926) would skip a clay disk through a flock of waterfowl, often hitting several. A projectile that has lost velocity in multiple impacts with either the water or other birds is unlikely to be killing many mudhens outright, but if it can manage to stun the animal or break a wing then it makes paddling up and dispatching the fowl a relatively simple matter. The prevalence of blunt tips on arrows in small game hunting and the use of boomerangs and throwing sticks further support the efficacy of using blunt force trauma to take small game.

Conclusions.

The review of biomechanical modeling has shown that sling projectile lethality is dependant on projectile material and design. Impacts from effectively designed sling projectiles can be expected to fracture a wide range of human bone, including at long range. Dense lead projectiles can be expected to penetrate exposed human skin at all ranges, and biconical clay projectiles could penetrate skin at close range. The potential for sling projectiles to cause soft tissue blunt trauma is inconclusive, but appears likely based on ethnographic and historical accounts as well as the levels of lethality indicated by the penetration and direct fracture modeling. These lines of evidence show that slings would be effective weapons in warfare and that use in warfare would likely lead to an evolution of projectile design.

Adapting the data to hunting applications, it appears that slings would be less likely to be used against large game animals. The wounding mechanisms slings rely upon are relatively unlikely to quickly kill, immobilize, cause external bleeding or otherwise make a wounded large game animal easier to track down. However, the same weapon would likely quickly immobilize (if not kill outright) small game animals by fracturing multiple bones on impact, making the sling an effective weapon for small game hunting.

Chapter 8: Conclusions and Recommendations for Future Study

The experimental study conducted here shows that slings have significantly greater range than attested by previous studies (105-170 m depending of projectile type). I have also shown that slings could easily produce lethal or debilitating impacts to human and small game targets. In addition, slings have been shown to be a common part of material culture in North America, and we have explored the different uses of sling weaponry. In spite of these gains, this study has raised more questions than it has answers. In an effort to remain focused on the central experiment, I have been forced to gloss over many fascinating avenues of research and the variation of slings and sling use throughout the world. Diffusion is one theme uniting many writers' discussion of slings throughout the world. While other authors have seen the sling's distribution as potential evidence of widespread diffusion (Heizer and Johnson 1952; Korfmann 1973; Lindblom 1940; York and York 2011), I think multiple independent inventions and more limited, regional diffusions is more likely. This topic of debate may have died out for many in the 1950s, but if the study of warfare is any indication, the study of prehistory on this grand scale may also be due for its own cyclical resurgence.

I have coincidentally spent more time devoted to warfare than any other use, both because there is more existing source material and because the topic is experiencing a resurgence of interest in scholastic circles. Knowledge of weapon capabilities will no doubt be intrinsic to understanding prehistoric conflict. This topic naturally leads to comparison to other ranged weapon systems, specifically the atlatl-and-dart and the bow-and-arrow. However, the archaeology of children and the importance of small game hunting to subsistence strategies are also topics that the sling has played a fascinating role in shaping. Even to the modern day the sling has been a tool for herding domesticated animals, and continues to be used as a weapon by oppressed people. Even as the sling has become a symbol of underdog resistance, cultural anthropologists and historians of the post-modern era may benefit from an understanding of the practical abilities and limitations of slings.

Some Further Thoughts on the Sling's Use in Warfare.

The discussion of warfare in this work has so far been limited to the simple aspects of maximum range and the impact effects of different projectile shapes and materials. Most archaeologists, however, seek to interpret beyond simple ranges and expectations of lethality to some understanding of how different weapon systems collectively influenced (and were influenced by) the cultures they are a part of (Arkush 2010; Keeley 1996). For example, modes of warfare are linked with variation in settlement patterns, political organization and the design of settlements and fortifications. The following examples are (nearly) unforgivably brief, but are intended to show the direction sling research could take within various fields of conflict archaeology.

Finney (2005, 2006) analyzed slinging in order to interpret the function and design of British hillforts. In this he actually followed the efforts of Michael Avery (1986) who speculated on the plausible tactics of defense and attack at these fortifications. Hillforts have similarly been a frequent topic of interpretation in the Andes, often dealing specifically with sling warfare owing to the importance of that weapon in the region (Arkush 2005, 2010; Vega and Craig 2009). These efforts are a small part of a wider trend within conflict archaeology which looks at fortifications and settlement patterns as indicative of the scale, intensity and types of warfare practiced–and thence the type of cultures doing the practicing.

Moving to Classical history, researchers have a multitude of written sources to draw from for interpretation. This additional information enables a more detailed level of analysis, delving into specific leaders or campaigns. In a more general sense, within Greece, slingers and other light troops were an important if often under-appreciated arm of the military. Arther Ferrill (1997:155) writes that the Greeks were perennially deficient in light troops, a crucial weakness which caused Xenophon to convert Rhodian hoplites to slingers. Often times the Greeks relied on mercenaries to fill out their light infantry roles rather than raising regular troops, probably because of the skill required to be an effective slinger or archer (Ferrill 1997:151). Though light troops were not able to hold ground against heavy infantry, the more lightly armed, open-order troops could easily outmaneuver the hoplite phalanx, a point further driven home by one instance in the Peloponnesian Wars. In this case, a body of Spartan hoplites was harassed by a larger body of peltasts (light troops armed primarily with javelins) for an entire day without ever being able to close with their opponents. The peltasts were especially effective when maneuvering onto the Spartan's unshielded (right) flank (Ferrill 1997:159). Slingers would have been able to use similar tactics, though they would have also been able to operate at longer ranges.

The Roman military was notably more flexible than the Greek, but continued to rely on heavy infantry. An analysis of the Roman military machine is well beyond the scope of this work, but as an example of what could be done I reviewed *The Gallic Wars* for references to sling warfare. Caesar's *Gallic Wars* are scant on the details of combat, dealing more with the political and strategic than with the tactical aspects of the campaigns. None-the-less, the text contains several references to slings, though many times only mentioning a 'hail of stones and darts' falling on the legions at the commencement of the engagement (The Gallic Wars 2:6, 3:4, 7:81). One could read into this a Gallic tactic of using slingers in mixed units alongside javelin-armed light troops, or that slings and javelins had roughly equivalent ranges, but it could just as easily be an artifact of Caesar's overly succinct writing style. In an additional instance, an officer is wounded in the mouth by a slingstone while rallying his ambushed legionnaires (The Gallic Wars 5:35). Finally, the Gauls used heated clay shot to set fire to the thatch roofs of the Roman's winter quarters (The Gallic Wars 5:43). In addition to these brief examples, Hannibal employed significant bodies of mercenary slingers during the 2nd Punic War (Hawkins 1847), the *funditores* of the Roman Republic were equipped with slings, and lead sling missiles linked to the Romans have been found as far flung as Britain (Greep 1987). Clearly an expanded knowledge of sling capabilities has potential to influence our understanding of Roman military tactics.

Moving away from Europe, York and York (2011: 49-50) provide a series of brief mentions of sling use from David Porter's early 19th century account of conflict in the Marquesas. These suggest that slings were used in ambushes from concealment as well as pursuits and other engagements, and indicate the kind of wounds commonly suffered. Unlike the previous accounts, they give a more visceral feel of the combat.

> Mr. Downes [one of Porter's officers] to rush up the hill; at that instant a stone struck him on the belly and laid him breathless on the ground.
>
> We had two wounded, and one of the Indians [Marquesan allies] had his jaw broke with a stone.

> We entered the bushes and were at every instant assailed by spears and stones. We could hear the snapping of the slings, the whistling of the stones…but we could not perceive from whom they came.
>
> From the thicket…we were assailed with a shower of stones, when Lieutenant Downes received a blow which shattered the bone of his left leg, and he fell.
>
> Three of the men remaining with me were knocked down with stones. The wounded entreated me to permit the others to carry them to the beach.
>
> And our allies pursued in turn, and knocked over with a stone one of the Typee warriors, whose body they triumphantly bore off.

Speaking on a much more general level, Keeley (1996:50) theorized that "Only units disciplined by training and fear of punishment could be expected to traverse the missile zone and close for shock action with an unbroken enemy," which begins to get at the intersection between warfare and culture that has been hinted at previously. Such proclamations do not rule out decisive engagements or high casualties; see Bamforth (1994) for discussion of pre-state warfare which in fact could produce near total casualties and certainly involved "shock action," or hand-to-hand violence. Keeley's statement may hold truer in open battles, where combat was usually low-casualty and indecisive (Bamforth 1994:99). Still, it is clear that technology has an integral role in shaping the conduct of war, as the changing balance of offensive and defensive capabilities brings tactical advantage to one side or another. The balance of capabilities, coupled with warfare's ruthless selection (in the Darwinian sense) for ever more effective implementation, can be a driver of socio-political adaptation. In the same way that technological innovation dramatically altered 20th century warfare, warfare in previous millennia would have been shaped by the interplay of different weapon systems.

Comparison to other weapon systems, especially the atlatl and bow.

In discussing Classical warfare, I have already reviewed how lightly-armed ranged infantry could evade and harass heavy shock infantry with relative impunity. These tactics are obvious and would normally be countered, so it is the interaction between various armaments of light infantry that is the most interesting—where an advantage to one side could lead to harassment of the other side's heavy infantry. This leads naturally to a comparison with the other primary pre-gunpowder ranged weapons: the bow-and-arrow, atlatl-and-dart, and the hand-thrown javelin.

Keeley (1996:51) helps open this argument, stating that Mae Enge warriors are accurate with a hand-thrown javelin only to 30 m, with a maximum range of 50 m, while the Australian spear thrower is deadly within 40 m with a maximum effective range of 80-100 m. He also states that, "Arrows can kill at maximum distances of from 50 to 200 meters depending on their weight, point type, and the power of the bow." Obviously such generalizations subsume a substantial amount of variation, yet still have value for advancing a basic understanding. McEwen and Bergman (1986) compared the atlatl against simple self bows and angular composite bows replicated from ancient Egyptian examples. The atlatl dart was launched around 23 m/s (51.5 mph), the self bow 35 m/s (78 mph), and the two angular composite bows approximately 43 and 47 m/s (96 - 105 mph). Adam Kurpowicz (2006) estimated the velocity of a 110 pound draw-weight Turkish composite bow, argued to be the most efficient bow design achievable with natural materials, at 69-91 m/s (153 - 205 mph). The traditional archery community is an extremely valuable resource to any interested in the relationship of bow design and materials to mechanical efficiency, projectile velocity and even other factors such as the degree of hand shock. The *Bowyers' Bible* series has collected a wealth of such information, including the reconstruction of various historic and prehistoric bows from various regions all over the world. (For review of bow design principles, see Baker 2000) The atlatl has received a considerable amount of experimentation as well, Raymond (1986) records velocities of 23.3-25.3 m/s using weighted and unweighted atlatls, numbers which are comparable both to McEwen and Bergman's (1986) results as well as John Whittaker's (personal communication; Whittaker and Kamp 2007) though Whittaker and Kamp also cite some experiments with higher measured velocities.

Based on these examples, sling velocity falls within the same range as the angular composite bows (45 m/s average, McEwen and Bergman 1986), but significantly less than the more advanced composite bows of the Ottoman Empire (Kurpowicz 2006). Slings would outperform self bows (at least that used by McEwen and Bergman, self bows are highly variable, ranging from low draw weight hunting implements to the famous English longbow), atlatl-and-dart systems, and hand-launched javelins by significant margins. Especially considering the relatively low effects of drag on sling projectiles compared to fletched arrows and darts, this initial velocity advantage could lead to significant range differentials.

Childhood Archaeology.

The sling offers many advantages as a child's toy and training weapon over the bow-and-arrow or atlatl-and-dart. These latter systems are comparatively expensive to construct, requiring many hours of labor, while a sling may be manufactured in 1-3 hours if materials are available. Lost sling projectiles, most often simply being an unmodified pebble, are much less of an issue than lost darts or arrows, an incident which was surely frequent in early training or play. Children's weapons would need frequent replacement to account for their growth and also probably some loss or breakage, making this manufacturing advantage more acute. While training for adulthood has generally been recognized as an important part of childhood, children's contribution to group subsistence has only been studied more recently (see Bird and Bird 2000; Hewlett and Lamb 2005). To the extent that sling hunting necessarily targets small game, children's hunting would benefit from increased encounter rates and animals with shorter flight distances (the distance at which an animal will flee from a perceived danger) than in big-game hunting, creating a more forgiving learning environment with many opportunities to stalk and shoot at animals per outing. Aside from developing skills in stalking and animal behavior to use later in life, these activities could supplement the hunting and gathering efforts of adults in the community (Basso 1983). Additionally, constant pressure against small-game may have reduced damage to crops or stored food resources, though the effectiveness of this aspect of children's hunting has not been empirically or ethnographically demonstrated.

Suggestions for Further Sling Experimentation.

Though I have tried to present a coherent case for sling effectiveness here, it is obvious that this thesis can only be an introduction to a very complicated topic. I have previously explored the various ways experimental data can be utilized, here I want to suggest ways to improve and expand upon our experimental knowledge.

The most obvious weakness of this experiment has been that the efforts of only one user (myself) were measured. Future experimentation should attempt to locate skilled users, whether such skills are traditional within their native cultures (see Vega and Craig 2009, referring to the Quechua) or not (many users at www.slinging.org). Sporting groups may prove to be as helpful in furthering sling research as they have been in developing our knowledge of atlatls, unfortunately such organizations are rare. The only slinging organizations I am aware of exist on the Majorca islands in the Mediterranean. Though this is a limiting factor compared to the widespread atlatl and archery associations across the United States, they have published the scores from their competitions, which could be used to empirically evaluate the accuracy of modern users. It is important to document the skill of the user, despite the difficult problem of subjectivity, perhaps through surveys or by tracking length of competitive use through published scorecards.

It follows that experimentation should also test a range of slings and projectiles as well. Though this study used varying weights of projectiles, all were the same shape and were cast from the same sling. It appears that different pouch designs are more or less favorable to different projectile sizes and shapes, but this has not been empirically demonstrated. Intuitively, split pouch designs seem likely to be adapted to non-standardized ammunition, since the twin pouches can expand or contract to cradle smaller or larger projectiles. Once again, this claim can, and should, be empirically tested. Sling length is an obvious variable for analysis, especially given the evidence that different lengths of sling were selected for different ranges (Dohrenwend 2002; Finney 2005, 2006; Korfmann 1973; Skov 2011; York and York 2011) but has not yet been experimentally demonstrated.

Yet another source of variability is release technique. Though I explored four techniques, variations from each of them are possible and could prove more or less effective. In addition, I was not practiced enough to attempt slinging with some techniques, such as the figure-8 often used by members at www.slinging.org or the across-the-back cast described by York and York (2011). Combining these techniques with other variables we may find that different techniques are more productive with certain types of slings or projectiles.

Related to these variables is the study of the biomechanics of sling use. Though I have suggested that some techniques take better advantage of bodily motion than others, my general claims could be vastly improved by researchers with more knowledge of body mechanics and access to high-speed photography. This could also lead to refinement of technique, in the same way that film is used to improve the skills of modern athletes, speeding the acquisition of slinging skill.

Such approaches can also help evaluate the spin of projectiles and the techniques necessary to impart that spin. Spin should also be evaluated downrange, as rotation of the projectile is used by skilled slingers to either stabilize a projectile in flight (like a rifled bullet) or to generate lift (like a golfball). I was not able to evaluate the effect of spin-induced lift on spherical projectiles, but this could be an important avenue of research in evaluating the advantages of spherical or biconical ammunition. Flight characteristics may be measured by adapting sporting Doppler radar systems, which are currently used to track golf balls (Alan Baquet, PGA Golf Management Program Director at University of Nebraska, personal communication 2012). Doppler systems track velocity over the entire flight path, so could also be used to evaluate the real effects of drag on projectiles (not merely the theoretical, as presented in this paper)

Concluding Thoughts.

It is my hope that the research avenues presented here will receive extensive scholarly efforts in the near future and that the data presented in this paper can be of some use in those efforts. Obviously much more work is needed, both in applying knowledge of sling technology to archaeological problems and in further exploring the technology itself. For the latter reason, I would encourage wider experimentation with this technology as well as continued efforts with other weapon technologies. For archaeology to seek to understand the basic capabilities of the technologies in use within their cultures of study strikes me as an intuitively obvious undertaking, if a difficult one. At the same time, it is important to avoid crossing the line into technological determinism. Technology is a product of culture as well as a driver of cultural change, and in evaluating any technology we must always be wary of reducing cultures to the sum of their technologies. In applying the data presented here, I would caution researchers to be mindful of this pitfall but to also recognize the influence of technology on cultural change. I have discussed a number of research topics, and there are doubtless more that went unmentioned, that we can explore with the sort of empirical data I have presented here, so the real work is still ahead.

Appendix A: Sling Material Culture Variability, AMNH-derived

Description	Catalog #	Culture	Locale	Regions	Country	Material	Acquisition Year	Donor	Collector
Sling, War	16/2022	Nootka, Cayoquath	BC, Vancouver Island	West Coast	Canada	Plant Fiber	1897 (expedition)	Jacobsen, F.	
Sling, War	16/2023	Nootka, Cayoquath	BC, Vancouver Island	West Coast	Canada	Plant Fiber	1897 (expedition)	Jacobsen, F.	
Sling	16/9278	Kwakiutl, Kwag.UT	BC, Kwag.UT		Canada	Hide, Bark (cedar)	1903	Hunt, George	
Sling and stone (attached)	50/1858 AB	Gros Ventre	MT Blain or Phillips county, Ft. Belknap Indian Reservation	Plains	USA	Hide, Stone, pigment	1901 (gift)	Jesup, Morris K., Mrs.	Kroeber, A.L.
Sling	50/8275	Apache, Mescalero	NM	Basin, Plains, Southwest	USA	Hide, Cloth, String	1909 (expedition)	Goddard, Pliny E., Dr.	
Sling for shooting shot	50.1/1014	Winnebago			USA	Hide, Pigment	1910	Morgan, J. Pierpoint	Lender, Emil W.
Sling	50.1/2842	San Juan	NM, Rio Arriba County, San Juan Pueblo	Basin, Plains	USA	Hide	1910 (expedition)	Spinden, Herbert J., Dr.	
Sling	50.1/4638	Papago	AZ?	Basin, Southwest	USA?	Hide, Thread?	1911 (purchase)	Lumholtz, Carl, Dr.	
Sling	50.1/4648	Papago	AZ?	Basin, Southwest	USA?	Hide, Sinew?	1911 (purchase)	Lumholtz, Carl, Dr.	
Sling	50.2/276	Zuni	NM, McKinley County, Zuni	Plains, Southwest	USA	Hide, Sinew, Pigment?	1916 (expedition)	Spier, Leslie and Kroeber, Alfred L., Prof.	
Sling	60/362	Eskimo, Polar	North Greenland, Smith Sound		Greenland	Hide, Sinew	1895	Peary, R.E., Lt.	
Sling	60/3470	Eskimo, Baffinland	Cumberland Sound		Canada	Hide	1900	Mutch, James S., Capt.	

Appendix A: Sling Material Culture Variability, AMNH-derived, continued.

Description	Catalog #	Culture	Dimensions	Pouch Shape	Pouch Type	Cord Type	Retention cord end	Release cord end
Sling, War	16/2022	Nootka, Cayoquath	L:62 W:7 H:7cm	Indeterminate	Braided net	Braided	Loop?	Indeterminate
Sling, War	16/2023	Nootka, Cayoquath	L:42 W:8 H:4cm	Indeterminate	Braided net	Braided	Indeterminate	Indeterminate
Sling	16/9278	Kwakiutl, Kwag.UT	L:184 W:3 H:9cm	Diamond	Solid	Braided	Loop	Tassel
Sling and stone (attached)	50/1858 AB	Gros Ventre	A) L:104 W:5 B) D:4.5 H:1.3cm	Rectangular	Solid	Thong	Loop	terminated
Sling	50/8275	Apache, Mescalero	L:34 W:8 H:4.2cm	Diamond / Ovoid	Solid with short cuts at fold	Thong	Loop	terminated
Sling for shooting shot	50.1/1014	Winnebago	L:66.5 W:6.7 H:1.7cm	Ovoid	Solid	Thong	Loop	terminated
Sling	50.1/2842	San Juan	(folded) L:70 W:6 H:4cm	Diamond	Solid with punches in two rows down long axis	Thong	Loop	Indeterminate
Sling	50.1/4638	Papago	(bundled) L:10 W:8.5 H:4cm	Diamond	Solid	Thong	Indeterminate	Indeterminate
Sling	50.1/4648	Papago	L:71 W:7.5 H:3cm	Diamond / Ovoid	Solid	Thong	Loop	split toggle with knot
Sling	50.2/276	Zuni	(folded) L:73.2 W:9.8 H:2.2cm	concave sided diamond	Solid with short cuts at fold	thong	Loop	toggle
Sling	60/362	Eskimo, Polar	L:18.5 W:5.5 H:1.5cm	Diamond / Ovoid	Solid with holes cut at fold	single strand sinew?	Indeterminate	Indeterminate
Sling	60/3470	Eskimo, Baffinland	L:18 W:6.5 H:3.5cm	Diamond	Solid with holes cut at fold & additional hole in side of pouch	Thong	Indeterminate	Indeterminate

Appendix B: Cross-cultural variation in sling use, eHRAF-derived

	Alutiiq	Blackfoot	Cherokee	Chipewyans	Comanche	Copper Inuit	Havasupai	Hopi	Klamath*	Mescalero Apache
Warfare	Yes		Yes				Yes			Yes
Ritual Combat										
Games / Training								Combat game	?	
Hunting: large game						No				
Hunting: small game						No				Yes
Hunting: birds					In play	In play	In play			
Hunting: waterfowl						No				
Child's Toy		Yes		Yes	Yes	Yes	Yes		?	Yes
Crop Protection										
Herding Aid										
Use from boats										

*Klamath use slings "only in sport" (Spier 1930)

Appendix B: Cross-cultural variation in sling use, eHRAF-derived, continued

	Navajo	Nuu-chah-nulth	Nuxalk	O’odham*	Ojibwa*	Pomo	Quinault	Tlingit**	Ute	Western Apache
Warfare	Yes	Yes	Yes			Yes		?		
Ritual Combat			Yes							
Games / Training		Combat game	Proving for ritual combat						Yes	Combat game
Hunting: large game										
Hunting: small game	Yes	Yes				Yes		?	Yes	Yes
Hunting: birds	Yes	Yes				Yes			Yes	Yes
Hunting: waterfowl						Yes				
Child’s Toy	Yes	Yes		?	?		Yes	?	Yes	Yes
Crop Protection	Yes									
Herding Aid	Yes									
Use from boats			Yes			Yes				

*For the O’odham (Joseph et al. 1949) and Ojibwa (Rogers 1962), slingshots are mentioned as toys but it is unclear if these modern implements supplanted slings. **Tlingit ethnography (De Laguna 1960, Krause and Gunter 1956) established that the sling was known, but did not establish specific uses.

Appendix B: Cross-cultural variation in sling use, eHRAF-derived, continued

	Yokuts*	Yuki	Zuni**	Totals
Warfare		Yes	?	9-11 of 21
Ritual Combat				1 of 21
Games / Training				5-6 of 21
Hunting: large game				0 of 21
Hunting: small game	?	Yes	?	7-10 of 21
Hunting: birds	?	Yes	?	7-10 of 21
Hunting: waterfowl				1 of 21
Child's Toy	Yes		?	12-15 of 21
Crop Protection				1 of 21
Herding Aid				1 of 21
Use from boats				2 of 21

*Among the Yokuts, the sling was used "only by boys" (Kroeber 1953:531) **In Zuni mythology, a sling was used by a warrior, but not as a combat weapon (Cushing 1896:331). Another ethnography mentions use of slingshots as toys and for small game and bird hunting (Leighton and Adair 1963), but it is unclear whether the terminology is in error, the slingshot supplanted the sling in these uses post-contact, or if the sling was never used for these purposes.

Appendix C: Sling Material Culture Variation in North America, eHRAF-derived*

	Alutiiq	Blackfoot	Cherokee	Chipewyans	Comanche	Copper Inuit	Havasupai	Hopi	Klamath	Mescalero Apache
Material: Cords				“cord”			“thong”		Buckskin	
Material: Pouch				Uncured caribou skin			Skin		Buckskin	Rawhide
Retention Design				Loop for index finger			Loop for forefinger		Loop for a finger	Loop
Release Design										
Retention Cord Length				62 cm 71 cm						
Release Cord Length				59 cm 67 cm						
Pouch Dimensions				15.5x2.5cm 23x5.5cm					“wide piece”	
Pouch Shape				Diamond			Rectangular, corners cut obliquely		“wide piece”	Diamond, with center perforations
Projectile Material										Stone
Projectile Size										
Projectile Shape										

*Measurements have been converted to metric (rounded to nearest ½ cm) where standard measurements were originally given.

Appendix C: Sling Material Culture Variation in North America, eHRAF-derived, continued

	Navajo	Nuu-chah-nulth	Nuxalk	O'odham	Ojibwa	Pomo	Quinault	Tlingit	Ute
Material: Cords	Leather thong	"thongs" "cord"				Milkweed fiber leather	Wide thong or strip of cedar or willow bark		
Material: Pouch	Deerskin leather	"spruce-root twining" "cedar mat"				Tule Leather			Rawhide
Retention Design		Loop				Finger loop Finger loop			Finger loop
Release Design						Knot Knot			
Retention Cord Length	~30.5cm <91cm					About 91cm 61-91cm	"sling…about 4 feet (122cm) long"		61-91cm
Release Cord Length	~30.5cm <91cm					About 91cm 61-91cm			61-91cm
Pouch Dimensions		7.5 x 15cm				13-15x2.5cm			10-15cm max dimension
Pouch Shape	"wide piece" Diamond								Square or oval
Projectile Material	Stone	Stone	Stone			Clay Stone	Stone		Stone
Projectile Size		"hen's egg"				2.5-5cm 4-5cm			
Projectile Shape	Round					Balls or disks			

Appendix C: Sling Material Culture Variation in North America, eHRAF-derived, continued

	Western Apache	Yokuts	Yuki	Zuni
Material: Cords	“thong”		Buckskin or cord	
Material: Pouch	Thick hide		Elkhide or buckskin	
Retention Design	Loop for middle finger		Loop for middle finger	
Release Design	No knot or stick		Knot	
Retention Cord Length	61-76cm		61cm	
Release Cord Length	61-76cm		61cm	
Pouch Dimensions	7.5-10 x 15-18cm”		5x10cm	
Pouch Shape	Diamond, corners squared		Diamond, some with center hole	
Projectile Material	Stone	Clay	Clay or stone	Stone
Projectile Size				
Projectile Shape				

Appendix D: Velocity Trials Data

Session 1

Throw #	Style	Projectile Mass (g)	Initial Velocity (m/s)	Initial Velocity (mph)	Range without Drag (m)
1	sidearm	22.2	27.72	62	78.4
2	sidearm	20.4	40.69	91	168.8
3	sidearm	33.9	42.03	94	180.1
4	sidearm	35.2	45.61	102	212.1
5	sidearm	38.4	40.69	91	168.8
6	sidearm	39.6	36.67	82	137.1
7	sidearm	54.8	36.22	81	133.8
8	sidearm	55.2	38.46	86	150.8
9	sidearm	20.4	46.50	104	220.5
10	sidearm	35.2	43.82	98	195.8
11	sidearm	39.6	42.03	94	180.1
12	sidearm	55.2	39.80	89	161.5
13	overhand	22.2	48.29	108	237.8
14	overhand	20.4	45.61	102	212.1
15	overhand	33.9	49.63	111	251.2
16	overhand	35.2	44.27	99	199.8
17	overhand	38.4	39.80	89	161.5
18	overhand	39.6	39.35	88	157.9
19	overhand	54.8	41.14	92	172.6
20	overhand	55.2	40.69	91	168.8
21	overhand	20.4	48.74	109	242.2
22	overhand	35.2	43.82	98	195.8
23	overhand	39.6	36.67	82	137.1
24	overhand	55.2	39.35	88	157.9
25	underhand	22.2	33.98	76	117.8
26	underhand	22.2	36.67	82	137.1
27	underhand	33.9	33.54	75	114.7
28	underhand	35.2	30.41	68	94.3
29	underhand	38.4	31.30	70	99.9
30	underhand	39.6	35.33	79	127.2
31	underhand	54.8	31.30	70	99.9
32	underhand	55.2	30.85	69	97.1
33	underhand	22.2	36.22	81	133.8
34	underhand	35.2	31.30	70	99.9
35	underhand	39.6	34.88	78	124.0
36	underhand	55.2	32.20	72	105.7
37	Balearic	22.2	37.56	84	143.9
38	Balearic	22.2	42.48	95	184.0
39	Balearic	33.9	33.09	74	111.6
40	Balearic	35.2	40.24	90	165.2
41	Balearic	38.4	38.46	86	150.8

Throw #	Style	Projectile Mass (g)	Initial Velocity (m/s)	Initial Velocity (mph)	Range without Drag (m)
42	Balearic	39.6	40.69	91	168.8
43	Balearic	54.8	35.77	80	130.5
44	Balearic	55.2	35.33	79	127.2
45	Balearic	22.2	38.01	85	147.3
46	Balearic	35.2	37.56	84	143.9
47	Balearic	39.6	36.22	81	133.8
48	Balearic	55.2	36.67	82	137.1
49	overhand		0.00		0.0
51	overhand	33.9	44.27	99	199.8
52	overhand	33.9	45.16	101	208.0
53	overhand	33.9	42.03	94	180.2
54	overhand	38.4	42.03	94	180.2
55	overhand	38.4	42.93	96	187.9
56	Balearic	33.9	39.80	89	161.5
57	Balearic	33.9	39.80	89	161.5
58	Balearic	33.9	40.69	91	168.8
59	Balearic	33.9	34.88	78	124.0
60	Balearic	38.4	37.56	84	143.9
61	Balearic	38.4	39.35	88	157.9

Session 2

Throw #	Style	Projectile Mass (g)	Initial Velocity (m/s)	Initial Velocity (mph)	Range without Drag (m)
1	Hand	55	24.15	54	59.5
2	Hand	55	26.38	59	71.0
3	Hand	55	24.15	54	59.5
4	Balearic	55	37.56	84	143.9
5	Balearic	54.6	38.01	85	147.3
6	Balearic	28.1	38.46	86	150.8
7	Balearic	38.2	41.59	93	176.3
8	Balearic	35.1	37.56	84	143.9
9	Balearic	33.7	33.09	74	111.6
10	Balearic	28.1	35.77	80	130.5
11	Balearic	23.9	37.11	83	140.5
12	Balearic	55	33.09	74	111.6
13	Balearic	54.6	35.33	79	127.2
14	Balearic	33.7	35.33	79	127.2
15	Balearic	23.9	38.46	86	150.8
16	Underhand	55	32.20	72	105.7
17	Underhand	54.6	29.07	65	86.1
18	Underhand	28.1	29.07	65	86.1
19	Underhand	23.9	32.64	73	108.7
20	Underhand	35.1	29.07	65	86.1

Throw #	Style	Projectile Mass (g)	Initial Velocity (m/s)	Initial Velocity (mph)	Range without Drag (m)
21	Underhand	33.7	30.41	68	94.3
22	Underhand	28.1	33.09	74	111.6
23	Underhand	23.9	33.54	75	114.7
24	Underhand	55	28.62	64	83.5
25	Underhand	23.9	32.20	72	105.7
26	Underhand	33.7	26.83	60	73.4
27	Underhand	28.1	30.41	68	94.3
28	Overhand	55	40.24	90	165.2
29	Overhand	54.6	37.56	84	143.9
30	Overhand	39.5	39.80	89	161.5
31	Overhand	39.5	40.69	91	168.8
32	Overhand	35.1	43.37	97	191.8
33	Overhand	33.7	46.50	104	220.5
34	Overhand	28.1	42.03	94	180.2
35	Overhand	23.9	40.24	90	165.2
36	Overhand	55	38.46	86	150.8
37	Overhand	39.5	42.93	96	187.9
38	Overhand	35.1	42.48	95	184.0
39	Overhand	28.1	40.69	91	168.8
40	Sidearm	55	40.69	91	168.8
41	Sidearm	54.6	31.75	71	102.8
42	Sidearm	39.5	41.59	93	176.3
43	Sidearm	39.5	38.90	87	154.3
44	Sidearm	35.1	41.14	92	172.6
45	Sidearm	35.1	40.24	90	165.2
46	Sidearm	28.1	46.95	105	224.8
47	Sidearm	28.1	44.27	99	199.8
48	Sidearm	54.6	40.24	90	165.2
49	Sidearm	39.5	41.14	92	172.6
51	Sidearm	35.1	44.72	100	203.9
52	Sidearm	28.1	42.93	96	187.9
53	Hand	55	31.30	70	99.9
54	Hand	55	29.51	66	88.8
55	Hand	55	25.49	57	66.2
56	Hand	55	29.07	65	86.1
57	Overhand	39.5	42.48	95	184.0
58	Overhand	35.1	46.95	105	224.8
59	Overhand	28.1	44.27	99	199.8
60	Overhand	39.5	43.37	97	191.8
61	Overhand	35.1	43.82	98	195.8
62	Overhand	28.1	46.95	105	224.8
63	Overhand	39.5	43.82	98	195.8
64	Overhand	35.1	44.27	99	199.8
65	Overhand	28.1	43.82	98	195.8

Throw #	Style	Projectile Mass (g)	Initial Velocity (m/s)	Initial Velocity (mph)	Range without Drag (m)
66	Sidearm	39.5	41.14	92	172.6
67	Sidearm	35.1	48.29	108	237.8
68	Sidearm	28.1	46.50	104	220.5
69	Sidearm	39.5	43.82	98	195.8
70	Sidearm	35.1	46.06	103	216.3
71	Sidearm	28.1	44.72	100	203.9
72	Sidearm	39.5	44.27	99	199.8
73	Sidearm	35.1	49.19	110	246.7
74	Sidearm	28.1	46.06	103	216.3
75	Sidearm	28.1	50.53	113	260.3
76	Overhand	35.1	44.27	99	199.8
77	Overhand	28.1	49.63	111	251.2
78	Overhand	35.1	49.19	110	246.7
79	Overhand	28.1	44.72	100	203.9
80	Overhand	28.1	46.50	104	220.5

Appendix E: Flight Path Computations

Lead Biconical, 36.8 g *

T	V_o	Angle	$F_d/m/\Delta T$	$g/\Delta T$	V_x	V_y	D_x	D_y
0		45			30.33	30.33	0	1.8
0.33	42.9	45	0.217	3.267	30.18	26.91	10.11	11.91
0.66	40.435	41.72	0.192	3.267	30.04	23.52	20.12	19.75
1	38.152	38.06	0.171	3.267	29.91	20.15	30.09	26.47
1.33	36.064	33.97	0.153	3.267	29.78	16.8	40.02	32.07
1.66	34.19	29.43	0.138	3.267	29.66	13.47	49.91	36.56
2	32.575	24.43	0.125	3.267	29.55	10.15	59.76	39.94
2.33	31.245	18.96	0.115	3.267	29.44	6.846	69.57	42.22
2.66	30.226	8.31	0.108	3.267	29.33	3.563	79.35	43.41
3	29.55	6.93	0.103	3.267	29.23	0.284	89.09	43.50
3.33	29.231	0.56	0.101	3.267	29.13	-3.27	98.80	42.41
3.66	29.31	-6.4	0.101	3.267	29.03	-6.53	108.48	40.24
4	29.76	-12.68	0.104	3.267	28.93	-9.77	118.12	36.98
4.33	30.53	-18.66	0.11	3.267	28.83	-13	127.73	32.65
4.66	31.63	-24.27	0.118	3.267	28.72	-16.22	137.30	27.24
5	32.98	-29.46	0.128	3.267	28.61	-19.42	146.84	20.77
5.33	34.58	-34.17	0.141	3.267	28.49	-22.61	156.34	13.23
5.66	36.37	-38.44	0.156	3.267	28.37	-25.78	165.79	4.64
6	38.33	-42.26	0.173	3.267	28.24	-28.93	175.21	-5.01

Clay Biconical, 36.8 g *

T	V_o	Angle	$F_d/m/\Delta T$	$g/\Delta T$	V_x	V_y	D_x	D_y
0		45			30.33	30.33	0	1.8
0.33	42.9	45	0.9	3.267	29.69	26.42	9.90	10.61
0.66	39.75	41.66	0.772	3.267	29.11	22.64	19.60	18.15
1	36.88	37.87	0.665	3.267	28.59	18.96	29.13	24.47
1.33	34.31	33.55	0.575	3.267	28.11	15.38	38.50	29.60
1.66	32.04	28.68	0.502	3.267	27.67	11.89	47.72	33.56
2	30.12	23.25	0.443	3.267	27.26	8.45	56.81	36.38
2.33	28.54	17.22	0.398	3.267	26.88	5.07	65.77	38.07
2.66	27.35	10.68	0.366	3.267	26.52	1.74	74.61	38.65
3	26.58	3.75	0.345	3.267	26.18	-1.54	83.34	38.14
3.33	26.23	-3.37	0.336	3.267	25.84	-4.79	91.95	36.54
3.66	26.28	-10.5	0.338	3.267	25.51	-8	100.45	33.87
4	26.73	-17.41	0.349	3.267	25.18	-11.16	108.85	30.15
4.33	27.54	-23.9	0.371	3.267	24.84	-14.29	117.13	25.39
4.66	28.65	-29.91	0.401	3.267	24.49	-17.36	125.29	19.60
5	30.02	-35.33	0.441	3.267	24.13	-20.37	133.33	12.81
5.33	31.58	-40.17	0.488	3.267	23.76	-23.32	141.25	5.04
5.66	33.29	-44.46	0.542	3.267	23.37	-26.21	149.04	-3.70

Lead Sphere, 36.8 g *

T	V_o	Angle	$F_d/m/\Delta T$	$g/\Delta T$	V_x	V_y	D_x	D_y
0		45			30.33	30.33	0	1.8
0.33	42.9	45	0.4	3.267	30.05	26.78	10.02	10.73
0.66	40.25	41.71	0.47	3.267	29.7	23.2	19.92	18.46
1	37.69	37.99	0.62	3.267	29.21	19.55	29.65	24.98
1.33	35.15	33.79	0.72	3.267	28.61	15.88	39.19	30.27
1.66	32.72	29.03	0.62	3.267	28.07	12.31	48.55	34.37
2	30.65	23.68	0.58	3.267	27.54	8.81	57.73	37.31
2.33	28.91	17.74	0.54	3.267	27.03	5.38	66.74	39.10
2.66	27.56	11.26	0.5	3.267	26.54	2.02	75.58	39.78
3	26.62	4.35	0.46	3.267	26.08	-1.25	84.28	39.36
3.33	26.11	-2.74	0.44	3.267	25.64	-4.5	92.82	37.86
3.66	26.03	-9.95	0.44	3.267	25.21	-7.69	101.23	35.30
4	26.36	-16.96	0.45	3.267	24.78	-10.83	109.49	31.69
4.33	27.04	-23.61	0.48	3.267	24.34	-13.9	117.60	27.05
4.66	28.03	-26.75	0.48	3.267	23.91	-16.95	125.57	21.40
5	29.31	35.33	0.53	3.267	23.48	-19.91	133.40	14.77
5.33	30.79	40.3	0.58	3.267	23.04	-22.8	141.08	7.17
5.66	32.42	44.7	0.61	3.267	22.61	-25.64	148.61	-1.38

Clay Sphere, 36.8 g *

T	V_o	Angle	$F_d/m/\Delta T$	$g/\Delta T$	V_x	V_y	D_x	D_y
0		45			30.33	30.33	0	1.8
0.33	42.9	45	1.5	3.267	30.5	26.78	10.17	10.73
0.66	40.59	41.28	1.79	3.267	29.15	22.33	19.88	18.17
1	36.72	37.45	2.2	3.267	27.4	17.73	29.02	24.08
1.33	32.64	32.91	2.31	3.267	25.46	13.21	37.50	28.48
1.66	28.68	27.42	2.01	3.267	23.68	9.02	45.40	31.49
2	25.34	20.85	1.57	3.267	22.21	5.19	52.80	33.22
2.33	22.81	13.15	1.27	3.267	20.97	1.63	59.79	33.76
2.66	21.03	4.44	1.08	3.267	19.89	-3.14	66.42	32.72
3	20.14	-8.97	0.99	3.267	18.91	-6.25	72.72	30.63
3.33	19.92	-18.29	0.97	3.267	17.99	-9.21	78.72	27.56
3.66	20.21	-27.11	1	3.267	17.1	-12.02	84.42	23.56
4	20.9	-35.1	1.07	3.267	16.22	-14.67	89.83	18.67
4.33	21.87	-42.13	1.17	3.267	15.35	-17.15	94.94	12.95
4.66	23.02	-48.17	1.3	3.267	14.48	-19.45	99.77	6.47
5	24.25	-53.33	1.44	3.267	13.62	-21.56	104.31	-0.72

Clay Biconical, 55 g *

T	V_o	Angle	$F_d/m/\Delta T$	$g/\Delta T$	V_x	V_y	D_x	D_y
0		45		3.267	27.38	27.38	0	1.8
0.33	38.72	45	0.42	3.267	27.08	23.816	9.03	9.74
0.66	36.063	41.33	0.365	3.267	26.806	20.308	17.96	16.51
1	33.63	37.147	0.317	3.267	26.553	16.85	26.81	22.12
1.33	31.448	32.398	0.278	3.267	26.318	13.434	35.59	26.60
1.66	29.548	27.042	0.245	3.267	26.1	10.056	44.29	29.95
2	27.97	21.07	0.22	3.267	25.895	6.71	52.92	32.19
2.33	26.75	14.527	0.201	3.267	25.7	3.393	61.48	33.32
2.66	25.923	7.521	0.189	3.267	25.513	0.101	69.99	33.36
3	25.513	0.227	0.183	3.267	25.33	-3.165	78.43	32.30
3.33	25.527	7.122	0.183	3.267	25.148	-6.409	86.81	30.16
3.66	25.952	14.298	0.189	3.267	24.965	-9.629	95.14	26.96
4	26.758	21.09	0.201	3.267	24.777	-12.824	103.40	22.68
4.33	27.899	27.365	0.218	3.267	24.584	-15.991	111.59	17.35
4.66	29.327	33.043	0.241	3.267	24.382	-19.127	119.72	10.97
5	30.989	38.113	0.269	3.267	24.17	-22.228	127.77	3.57
5.33	32.837	42.603	0.303	3.267	23.947	-25.29	135.76	-4.87

* Working from left to right, the ending time of the interval is shown in “T”, the original velocity and angle of travel for the interval in “V_o” and “Angle”, respectively. “$F_d/m/\Delta T$” shows the change in velocity derived from drag, while “$g/\Delta T$” shows the change in velocity–always in a negative direction and only affecting the vertical component of motion–due to gravity. “V_x” and “V_y” shows the velocity of each component, respectively horizontal and vertical, after the effects of drag and gravity have been applied. “D_x” and “D_y” are the positions of projectile at the end of each interval, in the horizontal and vertical planes respectively. Note that position at T = 0 is 0 m for “D_x” but 1.8 m for “D_y”, which is approximately head-height. Using the ending velocities in the interval, one can solve the triangle to derive the “Vo” and “Angle” for the next interval, and the process is repeated until “D_y” < 0. The end result is a closely approximated flight path that also supplies the angle and velocity of the projectile at 1/3 second intervals. The results were then converted into a graphic by simply plotting the x and y positions. Overall range (horizontal displacement) was then estimated based on the x-intercept. The first four projectiles are the marginal mean projectiles launched at overhand velocity: a 36.82 g projectile travelling at an initial 42.9 m/s. The fifth projectile is a 55 g clay biconical projectile, which demonstrates the efficient flight characteristics of a heavier projectile, in spite of being launched at a lower velocity (38.7 m/s).

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