THE ORIGINS AND EVOLUTION OF PRE-INDUSTRIAL HUNTING WEAPONS: ONGOING CHALLENGES AND RECENT DEVELOPMENTS

by

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ABSTRACT

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Thesis directed by Professor Douglas Bamforth

Hunting remains an essential component of what archaeologists seek to understand about the past even if it was only one important aspect of ancient lives and livelihoods. While the way Westerners conceptualize old hunting tools and methods can result in biased interpretations of archaeological sites, it can also affect contemporary people who continue to hunt using traditional means. Understanding old hunting tools and methods outside of a technological deterministic framework is vital to the work of anthropologists. As I will demonstrate in later chapters, it is also a relevant topic for wildlife managers and conservationists, whose policies can negatively impact traditional hunters.

The work of the archaeological weapon investigator often calls for experiments to reconstruct and study old tools. Experiments can take the form of controlled laboratory tests or more realistic exploratory studies with replicas of artifacts and practiced users. Both approaches can be helpful or misleading, depending on how they are carried out and the contexts to which they are applied. Philosophers have for some time written about the pitfalls of assuming that laboratory controls are the only way to conduct real science. The questions archaeologists ask about the past are frequently questions about equifinality, the possibility that multiple past

processes could have produced a phenomenon of interest. Such questions are best approached through exploratory methods that are carried out with sufficient rigor.

My approach to ancient hunting tactics and weapons has largely been experimental in nature. In this document, I describe experiments to understand the ballistic natures of old hunting weapons. A series of exploratory experiments tracked the many ballistic characteristics that make Indigenous North American atlatl and dart systems lethal against medium and large prey. I also describe a controlled experiment designed to test the effects of material type and edge sharpness of stone and glass projectile point efficacy, but honestly, I found this experiment far less informative than the former. Following the descriptions of the experiments, a theoretical paper is meant to help experimental archaeologists think through the challenges and best practices of conducting their research. Finally, I describe a survey of Iowa deer hunters and a comparison between American and African San hunters to assess the relative impacts of new hunting technologies on hunter success. Surprisingly, skillful hunters with traditional weapons can experience a higher degree of success than users of modern weapons. However, the reality of hunting is highly complex and context dependent.

THIS THESIS IS DEDICATED TO MY FATHER, WHO INSTILLED IN ME A DEEP FASCINATION IN ANCIENT HUNTING CULTURES, TACTICS, AND TECHNOLOGIES.

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CHAPTER 1. A REVIEW OF ARCHAEOLOGICAL WEAPON RESEARCH

1.1 Introduction

In this chapter, I review the topic of hunting weaponry in ancient societies. The residues of hunting weapons found on archaeological sites, usually comprised of stone, bone, and antler projectile points (armatures), are used to infer the presence or absence of different types of weapons in the archaeological record with presumed implications for human behavior and human evolution. But this is a topic with many intricacies and challenges. Analysis of hunting residues requires archaeologists to undertake projectile experiments to create samples (analogs) with known histories for comparison with artifacts. Weapon experiments also help us understand how archaeological hunting weapons performed and assisted hunters in achieving success. Experiments with archaeological weapons are the topics of future chapters of this document, but first, future experiments carried out by myself and others will benefit from a thorough review of ancient hunting weaponry and the methods we use to study them.

The following review covers diverse topics related to ancient hunting weaponry, so you may find it helpful to skip ahead and review topics of interest. Following this introductory review, the subsequent chapters of this dissertation follow an article approach. Each chapter has been written as a stand-alone article on different topics of research. As a result, the material may seem slightly repetitive or disjointed, but the chapters all maintain a focus on ancient hunting weapons and tactics that in some cases remain in use to the modern day. You may find that these chapters have been published since the completion of this dissertation and can now be found as revised, peer-reviewed articles.

The origins of complex projectile weaponry are of interest to researchers working in diverse fields. But because of the difficulty of identifying weapon systems in the archaeological record, tracing the origins of specific types of weapons is a contentious topic. Organic components of weapons do not preserve in most open-air sites, so we are frequently tasked with interpreting weapons only from their stone armatures. This presents substantial challenges given that different modes of projection overlap in various aspects of use, performance, energy, and impact traces left on armatures. It may never be possible to distinguish projectile systems in most archaeological contexts with absolute certainty, though with the right background information, and using multiple lines of evidence, plausible arguments for the representation of one or another projectile technology on archaeological sites can be constructed.

Why is it important to know what weaponry early hunters were using? The ability to obtain nutrition from animal products was an important milestone in hominin evolution (Cordain et al. 2001). The development of ancient projectile weaponry is also assumed to have some bearing on the success and safety of hunters pursuing large game. This has further implications for the expansion of our species into broader ecological niches (Churchill 1993; Marean 2015; Marlowe 2005; Shea and Sisk 2010; Shott 1993). Advances in weaponry have been attributed to biological developments such as higher cognitive processes in modern humans (Lombard and Haidle 2012), social investment in rearing children, and prolonged time from adolescence to maturity (Kaplan et al. 2000). The development of complex projectile weaponry would seem to have a significant bearing on the evolution of our species. But this has a few associated problems.

As modern people we have something of an obsession with technology. Notions of technological progress permeate our search for ancient hunting technology and what it means for the dispersal of *Homo sapiens* and modern behaviors (Mcbrearty and Brooks 2000; Villa and Roebroeks 2014). However, in some contemporary societies hunters continue to use simple hunting weapons, such as spears, which require skill and planning to field effectively. In contrast, complex weapons—launching mechanisms that either provide an assist to the body or store energy outside the body and send projectiles at higher velocities (Shea and Sisk 2010)—are often more effective, but also harder to construct and maintain, and more likely to fail when most needed (Gaudzinski-Windheuser 2016). In certain hunting situations, such as hunting from horseback or with the aid of dogs, it can be more effective to deploy simpler weaponry (Hitchcock and Bleed 1997).

When taken out of the specific context of use, the distinction between simple and complex weapons seems to have limited application. Technology refers to the customary means by which a society manipulates the world around it (Bleed 1997). As technology becomes more complex, the application and development of skill transitions from *operation*, such as stalking close to prey, to *production* (Cundy 1989). Thus, a society that values operational skill will require a stronger impetus to embrace a new technology. When considering weapon advances in the context of pre-industrial warfare, elite warrior societies that allow upward social mobility through achievements in combat, can result in a conservatism towards traditional weapons and combat tactics. Macola (2016) demonstrates how this delayed the adoption of early firearms into Zulu society in colonial Africa despite the availability of those weapons through trade.

Bleed (1986) draws from theoretical principles used by engineers to distinguish between maintainable and reliable systems. *Maintainable* weapons are used regularly, are modular, can be used against a broad range of prey types, and are easily repaired. *Reliable* systems are well-designed and over-engineered. They are frequently made by specialists and are designed to be infallible on the rare occasion when they are needed. These two weapon types do not exist on two ends of a continuum. Whether hunters choose maintainable or reliable weaponry depends on the *efficiency* of the weapon types in a given situation. Efficiency is difficult to calculate given that many context-dependent variables are involved in the efficiency of a weapon. Bleed (1986:739) uses one component of efficiency—*availability*—to distinguish maintainable and reliable weapon types. Maintainable systems are available because they are used regularly, are repairable, and are broadly applicable. Reliable systems are available to work on demand for brief periods.

Also applicable to hunting weaponry is the concept of *risk*, or the probability of bearing the cost of failure (Bamforth and Bleed 1997). Like other technologies, hunting weapons are designed to minimize risk by reducing failure probabilities. This is done in a variety of ways depending on the circumstance, such as designing weapons to be maintainable or reliable. Complex weapons may increase risk of failure of components but reduce risk of failing to capture wary prey. The impetus to switch to a new technology might arise despite a high social value for operational skill when the costs associated with more complex production are lower than the cost of retaining older technology; for example, when most of the available prey is small, fleet and hard to hunt with slower projectiles, weapons such as blowguns or bows and arrows can provide an economic advantage that outweighs the higher costs of production and maintenance. Tool complexity is primarily associated with situations in which failure costs are high. This situation is typically found in association with hunting aquatic mammals, but other examples also occur. In recent times, risk come from a perhaps unexpected direction; social coercion. Traditional San hunters face significant risk from wildlife officers enforcing oppressive and misguided conservation policies (“Green Militarization,” see Duffy 2010), sometimes with lethal force (Hitchcock 2019; Hitchcock et al. 2020; Hitchcock and Bleed 1997). Despite that San hunting has been sustainable (Hitchcock et al. 1996), San hunters relabeled as poachers are forced into the lower rungs of an agro-industrial economy that possess a much greater threat to wildlife populations than small hunting societies (Duffy 2010; Fynn and Bonyongo 2011). For San attempting to maintain their traditional hunting practices, this situation favors simpler hunting spears that wildlife officers may not immediately view as hunting tools, as they are also used for protection from large predators. Chapter 6 provides a more thorough treatment of this issue.

Archaeologists have generally understood complex projectile weapons to have allowed our species to kill from greater distance, increasing both the likelihood of a successful hunt and safety for the hunter (Churchill and Rhodes 2009; Frison 2004). Complex projectile weaponry is therefore one of the recognized characteristics of the onset of modern behavior. However, this understanding would benefit from a more nuanced approach. Lances have been chosen over projectiles to increase operator safety in some situations, such as traveling on foot through areas that contain large predators (Hitchcock and Bleed 1997). Javelins have a greater range than previously assumed (Milks et al. 2019; Villa and Soriano 2010) and may place hunters at a comparable distance from large prey as atlatls and bows. Plains Indians who hunted bison on foot with bow and arrow still had to approach closely, even disguising themselves as bison and wolves (Anell 1964). They also drove bison into impoundments and over cliffs—a technique that could be dangerous, especially to the caller who dressed as a bison and lured the herd over the precipice (Grinnell 1972). A change in projectile weaponry probably would not have increased either safety or success in driving bison over a cliff, but it may have increased these variables in other kinds of encounters. Weapon systems need to be understood within the context of their application.

Many archaeologists think that by the Early Upper Paleolithic (40-50ka) the sudden appearance a combination of signals represents a “behavioral revolution” and the beginning of “modern behavior” in our species. Changes in symbolic expression, identity markers, social organization, and new hunting tools may indicate biological developments related to cognition, or simply local developments leading to what Bar-Yosef (2002:374) refers to as a “techno-cultural revolution” in a core area (the Levant). However, or wherever, modern behavior came about, most scholars see the disappearance of Neanderthals and other populations of Archaic Humans as a direct result. Mousterian hunters are thought to have been outcompeted by Upper Paleolithic hunters due to improvements in communication and information storage, weapon technology, or all of these factors (Bar-Yosef 2002; but see Villa and Roebroeks 2014). If *H. sapiens* appeared in Africa >100ka, this suggests the early modern humans in Africa remained “behaviorally primitive” for a long time. However, a more thorough search for the material signatures argued to indicate modern behavior reveals much earlier representations stretching back into the Middle Paleolithic with the appearance of *H. helmei* (250-300ka) (Mcbrearty and Brooks 2000). Rather than appearing suddenly, the complexity of the Upper Paleolithic taken to indicate behavioral modernity appeared early and intensified gradually. The invention, development, and performance of complex hunting weapons remains an essential component of this debate. Our ability to identify the appearance of complex weapons in the archaeological record, and to understand the implications of their appearance within specific contexts, is a vital component to understanding the processes that led to our evolution and spread around the globe.

1.2 A Summary of Preindustrial Hunting Weapons

One way to categorize the many forms of ancient hunting weaponry is to distinguish between weapons that kill through blunt trauma and those designed to pierce a target and cause internal hemorrhaging or introduce poison into the blood stream. Blunt trauma hunting weapons are predominately associated with small game with a few exceptions. Clubs may have been used in instances where prey was caught in a disadvantaged position, such as a trap or net. Thrown sticks that spin in flight were developed into straight flying boomerangs in many places around the world (Hess 1975). Large non-returning boomerangs have enough kinetic energy to disable medium sized prey and can be used in combat (Westaway et al. 2016). Similarly, slings allow smaller projectiles to be hurled with greater velocity than rocks thrown by hand and have an antiquity as weapons of war. In many respects, slings and hunting boomerangs mirror the transition from simple to complex piercing projectiles, but unfortunately, thrown rocks and sticks and slings made of leather, plant fiber, or animal hair are less likely to survive or be noticed in the archaeological record than the carefully shaped lithic tips of weapons designed to pierce and cut. To provide a little further confusion, javelins, atlatl darts, and arrows can be given blunt tips to kill small prey with blunt trauma, but such tips are usually constructed of wood, antler or bone—materials that rarely survive in the archaeological record. The archaeological record thus presents a bias towards lithic (and in some cases osseous) armatures designed to pierce and cut a path through a target. As a result, studies of the development of weapons have mostly focused on piercing weapons represented by knapped and ground stone armatures. The development of blunt trauma projectile weapons like boomerangs and slings requires more attention, but in this paper, I intend to review the discussion centered around piercing weapons.

Ancient piercing weapons (in this discussion I exclude crossbows and blowguns, the former are generally thought to be more recent inventions while the latter may have been important to early hunters but are less visible archaeologically) use linear shafts deployed in four different modes: thrust by hand (lances), thrown by hand (javelins), launched with the aid of a lever extension of the arm (atlatl and dart), or shot with spring energy stored outside the body (bow and arrow) (Figure 1.1). Importantly, these four modes can overlap in aspects of impact energy and construction. This is because each of these weapons can take a diversity of forms depending on material availability, application, and cultural and individual preference.

Figure 1.1. Showing three modes of deploying linear shaft piercing weapons ranging from "simple" on the left to "complex" on the right. Left) Maasai men with double-ended spears in use as javelins (photo in public domain); center) launching a dart with the aid of an atlatl; right) bow and arrow modeled after Catawba and Cherokee forms (photo by Gerald Pettigrew).

Some javelins used to hunt small prey are relatively light in weight, while some arrows are surprisingly large and heavy. Weapon systems can be designed in ways to allow for this range of diversity and still maintain functionality. For instance, an archer can fire an arrow with a point the size of a spear head (Chapter 4, see Ashby 2008). Increasing the power of the bow and the diameter of the arrow shaft will allow the arrow to function properly with a heavy tip. The same method can be used to balance a heavy tip on the end of an atlatl dart. Christenson (1986) points out that rather than paying attention to the range of diversity weapons can take and remain functional, we should study how weapons were actually made and used by hunters. However, the range of diversity I describe is drawn from examples in the ethnographic record of real hunters using equipment that works for them. I will come back to these points in the discussion of the various weapon systems in section 1.4.

What archaeologists have called the development from *simple* to *complex weaponry* is the development from handheld, or hand thrown, weapons to mechanical projecting modes that assist or store energy outside the body (Sisk and Shea 2011). Complex projecting modes often use more intricate, composite projectiles, although this can also be the case of “simple” projecting modes. The mainshafts of linear projectiles are usually constructed of wood or bamboo. Simple wooden spears are made from a single piece of wood with a sharpened and often fire hardened tip. In contrast, composite linear projectiles can be constructed of multiple shafting elements that allow long projectiles to be disassembled or made in natural settings, where long shafting materials are difficult to find. They may also have attachments such as osseous or lithic armatures that are more effective than sharpened wood tips, or fletchings that increase stability in flight (Hughes 1998; Osborn 1999). Given the stresses projectiles encounter when being launched and impacting targets, the assembly of composite projectiles requires effective glues and strong bindings (Figure 1.2). Foreshafts designed to detach from the mainshaft in the body of prey provides one example of a technological consideration in composite projectile construction. Such foreshafts have taken the form of toggling harpoon tips for hunting sea mammals and poison coated foreshafts designed to detach and distribute poison in prey animals (Figure 1.3). This level of technological organization clearly demonstrates various methods hunters have used to achieve success when pursuing certain prey species in certain settings. However, in other cases, ethnographic hunters have achieved high degrees of success with relatively simple weapons. Complex and composite projectiles may improve hunting success for some prey species and environments, but this is not always the case. I will return to this topic in Chapter 6.

Figure 1.2. Atlatl darts used in experiments described in Chapter 2. Top: a removable dart foreshaft that fits into a mainshaft with a shouldered socket. Penetration usually stops at the socket and the mainshaft detaches. Bottom: failure of a sinew socket binding on a heavy dart after impact to bison bone.

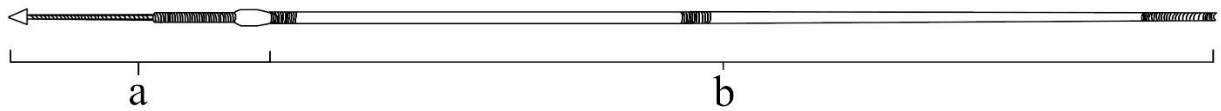


Figure 1.3. Diagram of a San hunting arrow, with poisoned foreshaft and bulbous weighted insert (a), which fits into a mainshaft designed to fall away for retrieval after striking prey (b) (after Archer et al. 2020; Wiessner 1983).

Understanding how hunting technology was organized, and how to identify it, requires first knowing how weapons work (Whittaker 2010a). Several challenges must be overcome in this process. First, as mentioned weapons can overlap in aspects of velocity and energy. Thrown replicas of Middle Paleolithic javelins can reach speeds of over 22 m/s (meters per second) on impact (Milks et al. 2019). Atlatl dart speeds can fall under 22 m/s in impact velocity and rarely exceed 35 m/s (Whittaker et al. 2017). Atlatl darts and javelins overlap more in velocity than do atlatl darts and arrows. An effective threshold between most arrows and darts is 37 m/s (Whittaker et al. 2017). However, the available data for arrow speeds are not complete. For example, no data exist on the speeds of arrows used by Papua New Guinea hunters (Ashby 2008), which are as heavy as many atlatl darts. Furthermore, the difference between the low speeds of arrows and high speeds of darts is not significant. These overlaps in energy, weight and speed problematize our ability to distinguish between projectile systems in the archaeological record. They also problematize our understanding of how and why new hunting technologies would be adopted. Javelins are effective projectiles when used by societies that value a high degree of operational skill, which may be why atlatls and bows did not replace javelins in some societies (Cundy 1989; Milks 2020; Tregear 1892).

A projectile designed to kill through internal hemorrhaging must strike vital organs or cut arteries and veins. Given this fact, accuracy of projectile weapons is an important measure of their effectiveness. Higher velocity can lead to improved accuracy in striking the desired location by giving prey less time to move after the projectile is released and before it reaches its mark. Higher velocity also leads to a flatter trajectory, requiring less vertical calculation by the shooter. However, more so than velocity, consistent accuracy requires a high level of skill, which makes variations in accuracy between weapon technologies more challenging to gauge than velocity (e.g. Whittaker et al. 2017). Few ethnographic records exist that provide a detailed account of accuracy outside of the recorder's own initial impressions (but see Cundy 1989), while it is challenging to judge how representative modern people who relearn old skills are of ancient or Indigenous use (Milks 2019).

Our inability to know if modern experimenters can develop comparable skill to ancient people constitutes one of the biggest theoretical hurdles to using modern experiments with replica weapons as analogs for interpreting past use. However, these weapons were designed and used by our species, and it is reasonable to think that modern humans can develop comparable levels of skill with adequate practice. This issue will come up again in section 1.5.1.2 regarding the *realistic* category of projectile experiments.

1.3 Projectile Development and Human Evolution

The earliest projectile weaponry for hunting and fighting must have been thrown rocks and sticks that killed or maimed through blunt force trauma (Oswalt 1973). Once hominins developed the ability to run long distances, memorize and interpret a complex array of tracks, and predict flight responses of prey when tracks were lost, larger animals the size of gemsbok and deer may have been chased to hyperthermia in hot weather and killed with simple weapons (Carrier et al. 1984; Liebenberg 1990, 2006; Nabokov 1981). Persistence hunting has been hypothesized as the earliest form of effective hunting for hominins who lacked complex projectile weapons. It may also have been an evolutionary driver of cognitive development and endurance running anatomy (Carrier et al. 1984; Liebenberg 2013; Lieberman et al. 2007).

Despite the common artistic depictions of cavemen throwing heavy rocks onto the heads of entrapped megafauna, this is more likely a product of old notions that ancient life was “savage, brutish and short” rather than a reality. Few good artistic depictions of ancient hunting scenes exist; most are founded on a lack of experience both in hunting and using preindustrial hunting weapons (Frison 2004). Effective hunting of larger prey from a distance required the invention of linear projectiles that pierced and immobilized prey or killed it outright. Early weapons appear to have been lances and javelins and hunting effectively with them probably took the form of complex drives and other methods to disadvantage larger prey, which required an understanding of prey behavior and communication between a cohesive group of hunters (Carlson and Bement 2018; Churchill 1993; Frison 2004; Olsen 1989). This has important implications for cognition and social organization among Archaic humans.

Levallois flakes from the Middle Paleolithic in Africa, approximately 500ka, have been identified as javelin armatures (but see Rots and Plisson 2014; Wilkins et al. 2012, 2015). Javelins constructed entirely of wood have been found in a coal mine in Germany next to the remains of horses, and dated between 400 and 300ka (Dennell 1997; Thieme 1997). Some authors have pointed to discrepancies between their size and that of ethnographic javelins to express reservations about the javelin identification (Oakley et al. 1977; Shea 2006). However, testing of close replicas confirms their effectiveness to a distance of roughly 15 m (Milks et al. 2019). Their careful balance, construction, and deposition among butchered horse remains strongly suggest hunting javelins (Gaudzinski-Windheuser 2016). The operation and archaeological representation of lances and javelins will be discussed further in section 1.4.1.1.

The next stage of development is complex projectile systems that fired projectiles lighter than javelins at higher velocity. Shea (2006) argues for this distinction on the basis that simple weapons (javelins and spears) were used by Archaic humans, while complex weapons (atlatls and bows) are exclusive to our species. Churchill and Rhodes (2009) suggests a better distinction might be between short versus long range weapons (see also Rots and Plisson 2014). However, the short range previously assumed for javelins (6 m; Churchill and Rhodes 2009) has recently been challenged through experiments (Milks et al. 2019) and historical documents of Roman soldiers throwing heavy javelins impressive distances (Villa and Lenoir 2009). The latter are also comparable to records of Tasmanian javelin use in hunting (Jones 1977). Apart from the problem of bias towards technological determinism, it must be recognized that from a mechanical standpoint using the term *complex* to refer to projecting modes that aid the body or store energy outside the body is somewhat problematic, since the human body is already an incredibly complex lever system—certainly more so than the bow. This has made studying the mechanics of javelin and atlatl throwing quite challenging (see Chapter 4) relative to bow mechanics (Baker 1992; Bergman et al. 1988). Nevertheless, these latter weapons entail more parts and are more challenging to construct and maintain.

Importantly, simple and complex projectile weapons can be used in tandem. San hunters in southern Africa use spears to finish off game shot with poison arrows, although ethnographic work in the Kalahari in the 1970s found that bow use was dropping off in favor of hunting exclusively with spears for a number of reasons (Hitchcock and Bleed 1997). It is necessary to recognize the shortfalls in our classificatory nomenclature. The presence of complex projectile weaponry alone does not signify modern behavior, but is part of a suite of compounding evidence that appeared early in time and gradually saw more intensive use (Mcbrearty and

Brooks 2000). Once it appears, hunters make a strategic decision whether to deploy it in any particular context. The terminology merely operates as a conceptual tool to distinguish weaponry by the level of effort and technical training required to construct and maintain it. It also must have some bearing on hunter success, but that appears partly dependent on the situation. Changes in weapons and other aspects of behavior through time do not always implicate more efficient resource acquisition or niche construction, and thus do not function consistently as operative criteria for modern behavior. As is so often the case, the strong boundaries we tend to draw around the patterns we recognize are more transparent than we would prefer.

A transition to smaller projectile tips 64-71ka in southern Africa has been argued to represent a transition to complex projectile systems (Lombard and Phillipson 2010). This transition coincides with the first major migrations of fully modern humans out of Africa (Brooks et al. 2006; Marean 2015). Brooks and colleagues (2006) see the development of complex projectile technology combined with movement of raw materials, development of symbolic expression, beadwork, and increased use of marine and lacustrine resources as forming part of increasingly complex social and economic systems that would have improved survivorship of both hunters and their kin. Brooks and colleagues, among others, see the development of complex projectile technology ~70ka in southern Africa as part of the increasing success of *H. sapiens* that helped precipitate their migration out of Africa. However, there is a lack of evidence to support radically different tool kits than archaic humans among the early populations of *H. sapiens* leaving Africa (Mcbrearty and Brooks 2000; Villa and Roebroeks 2014). Early developments of complex projectile weapons, such as the ~70ka backed microliths from southern Africa, apparently did not immediately take hold, since they are sandwiched between layers of MSA Levallois technology. From an ethnographic perspective, it is clearly possible for our species to favor javelins even when they have access to the bow (Hitchcock and Bleed 1997; Tregear 1892). Sisk and Shea (2011) suggest the best evidence of the transition to complex projectile technology occurred 100-50ka in Africa as part of niche broadening strategy of modern *Homo sapiens*. Their analysis is based on morphometric attributes that have recently been critiqued (see section 1.5.2.1). Other authors (Lazuén 2012; Villa and Roebroeks 2014) find reason to doubt that complex behavior actually began with our species. According to these authors, the recognition of complex behavior in the Upper Paleolithic from scant archaeological evidence is a product of modern Western biases (Mcbrearty and Brooks 2000). The early points from Blombos and other sites in southern Africa, for example, do not provide evidence of complex weapons, but a different form of javelin. Early members of our species migrating out of Africa were thus not using more sophisticated hunting weaponry than Neanderthals and other archaic humans (Villa and Lenoir 2009; Villa and Soriano 2010). If complex projectile technology did develop with our species, it is still unclear whether the initial transition begins with the invention of the bow, or with a more gradual transition from javelins to darts launched with the aid of atlatls (Brooks et al. 2006; Lombard and Phillipson 2010; Marean 2015).

Part of what has made our understanding of when and how these transitions occurred problematic has to do with an inherent bias in the coverage of archaeological work. Namely, little work has been done in sub-Saharan Africa, or southern or eastern Asia (Bar-Yosef 2002). The other part has to do with our ability to recognize the proposed evidence for complex behavior in the archaeological record, such as differences in weapon technology. Finally, we need an improved assessment of the implications of complex weapon development and what it means for hunter success. Essential to the identification of projectile weapons and understanding the social, biological, and ecological implications of its introduction, is first understanding how ancient projectile weapons work.

1.4 The Ballistic Properties of Preindustrial Piercing Projectiles

To understand the development of complex projectile weaponry it is first necessary to discuss the mechanics of projecting modes and the kinematics of projectiles. The launching, flight and penetration of javelins, atlatl darts, and arrows are studied using the branch of mechanics called ballistics. Ballistics of firearms is further subdivided into four categories (Kneubuehl 2011:65). For our purposes, we can ignore *intermediate ballistics*, which refers to the effects of combustion gases on a bullet as it leaves the barrel of a firearm. It is useful to consider javelins, atlatl darts, and arrows in terms of their *interior ballistics,* or the mechanisms involved in launching the projectile, their *exterior ballistics*, or the flight of the projectile through atmosphere, and their *terminal ballistics*, or impact and penetration of a solid target. First, I will introduce the interior ballistics of javelins, darts and arrows in the subsections devoted to each weapon. I will then discuss the exterior and terminal ballistics of preindustrial piercing projectiles.

1.4.1 Interior ballistics: weapons systems design, function, and variability

1.4.1.1 Lances and javelins

Thrusting spears, or lances, have a deep antiquity of use. Lances are effective when tactics are used to disadvantage prey (Churchill 1993), such as driving animals into natural enclosures, marshy areas or manmade traps, chasing them in deep snow on snowshoes, setting traps and snares along paths, and using hunting dogs or horses to run down game and hold it at bay. In other words, the use of lances by Archaic Humans does not necessarily implicate behavioral simplicity. Unlike projectile weapons, lances allow the operator continued application of force, making their lethality difficult to compare with that of projectiles (Milks et al. 2016). The recent analysis by Coppe and colleagues (2019) with a ballistics pendulum suggests that lances produce inordinately high kinetic energy relative to javelins, but this probably represents misuse of a ballistics pendulum (see section 1.5.1.1). Nevertheless, their analysis highlights an effective thrusting motion (what they call a gesture) with a lance. Depictions of this underhanded gesture are found on Greek vases. Milks and colleagues (2016) have shown that lances require some practice to master, and stronger, heavier operators will be more effective.

Neanderthals have traditionally been theorized as using lances based primarily on skeletal evidence (Churchill and Rhodes 2009; but see Rios-Garaizar 2016). This is presumably the reason for their high rate of healed broken bones. Consequently, Neanderthals have been compared to rodeo riders (Berger and Trinkaus 1995; but see Trinkaus 2012). However, getting close enough to kill large herd animals with javelins, atlatls, or even bows could also produce the conditions for dangerous big game hunting. A large survey of ethnographic spear use found more evidence of lance than javelin use (Churchill 1993). This may help explain the confusion around whether Neanderthal Levallois points and other MSA armatures belonged to javelins or lances or why skeletal evidence of extensive throwing does not exist on Neanderthal skeletons (Churchill and Rhodes 2009). Evidence of bilateral symmetry in Neanderthals—a stronger right than left humerus—has also been taken to support Neanderthal lance use. But a recent test of this hypothesis found it to be more likely a product of repetitive scraping tasks than lance use (Shaw et al. 2012a). These osteomorphological studies are problematized by small sample sizes. Ethnographic spear users seem to employ both lances and javelins, but more commonly the former; although ethnographic accounts of either are limited and lances are often used alongside other kinds of projectile weapons. Furthermore, the piercing projectile niche originally filled by javelins is now filled by other weapons in most hunting societies. The earliest known lance may be the complete specimen of yew found with elephant remains and Middle Paleolithic stone tools at Lehringen in Germany (Thieme et al. 1985). Unlike the Schöningen spears discussed below, experimental replicas and tests of the Lehringen spear appear to be lacking.

The use of javelins by Archaic members of our species is supported by finds of 300,000 year old wooden javelins alongside horse remains near Schöningen in Germany (Dennell 1997; Thieme 1997). The site has been interpreted as a marshy area lying in a natural cul-de-sac between three ridges when the artifacts were deposited. Archaic humans apparently cornered horses in the cul-de-sac where they could approach closely enough to dispatch the animals with javelins. The wooden javelins survived in the anaerobic conditions. If this interpretation is correct, this site represents the capabilities of Archaic humans to coordinate a group drive and understand how herd animals would react to various predation tactics.

Recent velocity data (Milks et al. 2019) demonstrates the power of replica Schöningen spears, which combined with ethnographic data on javelin use in hunting, recommends an effective hunting range at around 15 m. Perhaps more so than other weapons considered in this study, effective use of javelins requires substantial amounts of practice to achieve power and accuracy (Coppe et al. 2019; Milks et al. 2019). More complex piercing projectile weapons require more time to construct, but reduce the practice and strength necessary to achieve the desired outcome (Cundy 1989).

In contrast to a strict notion of linear technological progression, javelins and lances persist alongside other hunting weaponry as aids or stand-alone weapons. San hunters, for example, frequently use spears to finish off game wounded with poison arrows (Hitchcock and Bleed 1997). In the 1970s, San hunters of the northern Kalahari were very capable of hunting large ungulates with javelins from blinds at night and younger San hunters of the southeastern Kalahari were switching more from bows to spears used with the aid of horses and dogs (Hitchcock and Bleed 1997). The effective use of either lances or javelins requires skill, knowledge of prey animals and planning, bringing into question the assumptions about behavior and cognition associated with later weapon developments in comparison.

1.4.1.2 The atlatl and dart

The 64 to 71,000 BP points from southern Africa have been attributed to the introduction of the bow (Lombard and Phillipson 2010), although the atlatl, or spearthrower, is also possible (Brooks et al. 2006; Marean 2015), and specialized javelins have also been suggested (Villa and Soriano 2010). The development of the atlatl before the bow makes sense on the grounds of a developmental sequence from throwing by hand to throwing with the aid of a lever assist. Supporting this sequence are two facts. First, definitive evidence of the atlatl manifests as antler hooks in Europe around 17,500 BP (Cattelain 1989, 1997), whereas definitive bow and arrow technology does not appear in Europe until after 11,000 BP (Cattelain 1997; Meadows et al. 2018; Rust 1943). Second, the atlatl was never replaced in Australia, which was first colonized around 50,000 BP. This is the case despite that the bow was found on Cape York Peninsula (Davidson 1936) and on neighboring Papua New Guinea. However, a later arrival of the atlatl on Australia has been hypothesized based on associated stone tool transitions and the material culture of isolated populations, such as on Tasmania (Jones 1977). In the New World, most archaeologists seem to agree that the earliest immigrants around 15,000 BP were using the atlatl (Hutchings 2015). The bow did not arrive in the Americas until around 2,000-1,500 BP (Nassaney and Pyle 1999; Whittaker 2012). Even after the arrival of the bow, the atlatl continued to be used in such contexts as hunting sea mammals in the Arctic and ducks in Central Mexico

(Stirling 1960), as well as in warfare in the Mississippi delta (Swanton 1938), Mesoamerica (Nuttall 1891), South America (Prins 2010), and the western coast of North America (Jones 2010; Massey 1961). An atlatl even appears alongside a depiction of a bow on an engraved shell from the 15th century archaeological site of Spiro in Oklahoma (Fields 2005).

The usual assumption is that once the bow was introduced, it quickly replaced the atlatl as a superior weapon (e.g. Hildebrandt and King 2012). Although this does appear to be the case in some contexts, both archaeological and ethnographic evidence demonstrates that this is not a rule. In fact, it may not even have been the case in most contexts. In parts of North America (the Great Plains, the Southeast, and Baja California) atlatls and bows appear to have been used simultaneously for up to 1,000 years (Hoard and Banks 2006; Massey 1961; Nassaney and Pyle 1999). It has been suggested that human conflict, more than hunting, presents the conditions for the bow to readily replace the atlatl (Walde 2013). The adoption of the bow is even theorized to present the conditions for social complexity to arise by making social rules and hierarchies more enforceable (Blitz and Porth 2013). The continued use of the atlatl in a combat role in North America, Mesoamerica, and South America challenges these theories. The Tarairiu tribesmen in the highlands of Brazil who used only the atlatl for hunting and fighting were considered terrifying warriors to both European colonists and local Indigenous people who used the bow. They were employed by the Dutch as mercenaries against Portuguese colonial troops in the 17th century, who referred to them as the Dutch's "infernal allies" (Prins 2010). The bow gradually won out in many parts of the Americas, but the atlatl and dart was the principal piercing projectile weapon for 13,500 years and was not easily replaced. Atlatls have continued to be used for certain applications up to the present.

Atlatl comes from Nahuatl, the language of the Aztecs (Schwaller 2019), who used the weapon for duck hunting and extensively in warfare. Duck hunting with atlatls was still practiced in Michoacan until the mid-20th century (Stirling 1960). Spanish conquistadores in Mesoamerica quickly developed a respect for atlatl darts, which could penetrate their armor. An urban myth suggests that Aztec atlatl darts could pierce Spanish armor. This is true to a point. Most conquistadores were relatively poor and certainly could not afford the steel plate armor made for European elites that was designed to stop musket balls! The conquistadors adopted Mesoamerican quilted cotton armor (ichcahuipilli) after arriving in the Americas. It was even furnished by native weavers (Díaz del Castillo et al. 2012; Pohl and Hook 2001). Ichcahuipilli must have been familiar to the conquistadors since it filled the same functional niche as gambeson—medieval padded textile armor. Although the conquistadors are often depicted in codices wearing full suits of steel armor, most of these depictions were made centuries after the conquest and the native artists had probably witnessed such outfits in colonial religious pageants (Pohl and Hook 2001). Atlatl darts could not penetrate steel plate armor, but it seems they could pierce the ichcahuipilli as well as chain mail worn by most conquistadors (Swanton 1938).

Although atlatls are often referred to as spearthrowers, the weapon is quite distinct from a javelin. Most darts are lighter than javelins, have fletchings attached near the tail, and are more flexible. They are about as similar to javelins as most arrows are to darts. Use of the term “most” in the previous statements is necessary because size overlap does exist among all three of these projectile forms. The primary difference has to do with the mode of projection and associated aspects of velocity and controllability. This has some bearing on the ease with which the operator can learn to field the weapon effectively (Whittaker et al. 2017). Because archaeologists are interested in distinguishing these weapon technologies, it is fitting to use terminology to differentiate them. The terms *atlatl and dart* enter the literature with Nuttall's (1891) work, and seem fitting. Dart in its archaic form refers to a light spear that is usually fletched.

The atlatl operates by extending the throwing radius of the user's arm and providing him/her with more leverage and control on the dart (Cundy 1989; Whittaker 2010a). Usually, a hook on the end of the atlatl engages a small depression on the tail of the dart. The dart must flex in order to compensate for the arcing motion of the throw (Figure 1.1). Oscillation of the dart downrange takes many forms. Darts may oscillate as transverse waves traveling back and forth through the shaft as it rebounds from compression (Figure 1.4). Darts may also spin to find the side they naturally prefer to bend on as they oscillate. Spinning may stop or change direction as the dart flies down range. The thrower may also introduce a "crank-shaft" rotational effect, wherein the dart stays bent in one direction and rotates around a central axis without oscillating. More frequently, a combination of these phenomena occur, so that darts appear to wildly oscillate, rotate and spin as they fly downrange (Pettigrew et al. 2015). How a dart acts in flight depends on its composition and the throwing technique of the atlatlist. Viewing the flight of darts from behind

Figure 1.4. Showing a typical atlatl launching sequence and oscillation of a Basketmaker atlatl dart shortly after leaving the atlatl.

accentuates these effects, while slow motion video taken from the side makes them appear less pronounced. Nevertheless, oscillation can be fairly dramatic early in flight (15 cm at the tail). Displacement of the tip of a dart is less intense than at the tail (~5 cm: Pettigrew et al. 2015). This displacement will also vary for different darts and throwing techniques. Oscillation attenuates downrange, but within effective hunting ranges of ~15 m oscillation is still occurring in atlatl darts and can affect the angle at which the tip penetrates the target. This introduces an effect that is difficult to reproduce in projectile experiments that do not employ actual atlatls, or at minimum flexible projectiles that mimic darts.

There is a lot of variation in atlatl weaponry, affecting such things as how much energy a dart can carry and what one can hunt with it. Much of the variation in the design of atlatls can be traced to cultural and individual preferences for style and specifically how the body is oriented to perform the actions of holding and throwing. This plays out particularly in regard to how the atlatl is gripped. For this reason, various types of atlatl can be effective cultural markers (Pettigrew 2018). However, other variations can be traced to functionality in particular contexts. Variations in parameters can be determined by the characteristics of available materials to make atlatls and darts from and how they are intended to be used: e.g. for harpooning fish, hunting big game, or small game (Christenson 1986; Oswalt 1973).

The simplest method of increasing the power of the dart is to increase its mass (Hutchings and Brüchert 1997; Pettigrew 2015). Frison’s (1989) experiments on elephant carcasses demonstrated that Pleistocene hunters using heavy darts (350-400 g) could effectively hunt megafauna from 17 m or more. As with other projectile weaponry, lighter darts that can be launched with higher velocity are better suited to smaller and swifter prey. But throwing light darts with enough velocity to achieve the energy needed to hunt large animals is much more challenging than simply increasing the mass of the dart. It is also more difficult for the atlatlist to transfer energy into a low mass dart. I have found that my darts of 100-120 g travel slightly faster than darts of 80 g (Pettigrew 2015). This may vary depending on the design of the atlatl and the technique and body of the operator. Clearly throwing with a lot of force is easier with heavier darts (see also Toyoshima and Miyashita 1973). But as with javelins and arrows, the mass of darts needs to be balanced with the intended target and with the design of the launching apparatus.

Velocity data for darts launched by a large sample of throwers using a variety of equipment shows that darts typically travel between 50-70 mph (Whittaker et al. 2017). Some throwers in the sample were young strong throwers who have been practicing for many years, and could occasionally reach speeds between 70-80 mph, but at the expense of accuracy. Velocity above these recordings have been achieved, as have distances beyond the typical range of 70 m, but these figures have been achieved using distance throwing equipment; essentially very long atlatls and very short and light darts. Distance throwing equipment that can reach distances greater than 250 m has been developed by modern enthusiasts (Whittaker 2010a:214) as well as by native Australians for use in long range skirmishes ("Goose" spear and spearthrower: Cundy 1989). Because long distance darts are light weight, although they travel at higher velocity they do not impact with increased energy (Whittaker et al. 2017), and these systems are inaccurate at close range. Therefore, atlatls and darts designed for distance throwing are not viable hunting tools.

Even with effective hunting equipment, accuracy is much more challenging to achieve and to measure, and in many ways more important for effective hunting than high velocity. Accuracy can be broken down into components related to interior and exterior ballistics. The former is far more difficult to measure with atlatls, since it has to do with the body mechanics of the thrower, how naturalized he/she is to the weapon and her/his ability to focus on a given target at a given distance. Once the operator has developed the muscle-memory to use the weapon, concentration is the most important key to accuracy. This is apparently why Ishi, the last of the Yahi in California, performed better at hunting with the bow than shooting at flat paper targets (Kroeber 1961; Pope 1918). Probably for the same reasons as Ishi, I find it easier to focus on a small, 3-dimensional target than on the center of a large, 2-dimensional target. The tendency is to focus on the whole target at once. Variation in the shooter's ability to concentrate on different types of targets means that using modern accuracy competitions with large 2-dimensional targets as analogs for the accuracy of hunters could be problematic.

Ethnographic accounts may provide a better measure of the capabilities of atlatlists to hit their mark than modern competitions. During Darwin's travels on the Beagle in 1836, native Australians could transfix a brimmed hat at 30 yards, and an explorer to the Arctic in 1899 was impressed by the accuracy and force of seal harpoons from 30-50 yards (Whittaker 2010a). At short ranges, small targets can be hit. Ancient hunters in the southwestern US fitted darts with bone blunts for hunting small game (Pepper 1902). Of course, there are no accounts of how frequently Basketmaker hunters could hit rabbits with darts, but the weapon must have been effective enough to warrant their use. Indigenous Australians preferred to throw at targets not more than 20-30 yards distant. Compared to the bow, atlatls can be accurate within effective ranges and on targets of moderate difficulty, but accuracy seems to decline more rapidly on targets of increasing difficulty (Cundy 1989). A conservative range for effective hunting with the atlatl is 15-30 m.

1.4.1.3 The bow and arrow

Substantial information on the operative parameters of various bow and arrow designs has been published (Baker 1992; Bergman et al. 1988; Hickman et al. 1947; Klopsteg 1943; McEwen et al. 1991; Pope 1923) and various authors have written about bow and arrow efficacy in hunting (Ashby 2005a; Bear 1980; Pope 1947). Bows take many forms. Like atlatls, local forms are in part adaptations to the materials in the area, the environment, and the application, although cultural and individual preferences also play a role in bow design. Western notions of technological advancement have even permeated the traditional bow scene. At least the most effective design is no longer reckoned to be the English longbow (Pope 1923), but rather a modified Turkish form with wide limbs and recurved tips (Baker 1992). These design considerations can influence how we understand ancient bow wielding cultures, but traditional hunting bows are often the result of many generations of development and can be highly effective even if they do not reflect the parameters of a modern optimized design ideal.

Effective simple wood bows send arrows at around 50 m/s. Simple D-shaped bows made by the author and reproduced after hunting bows made by southeastern Native American tribes (Cherokee, Catawba and Yuchi) (Allely and Hamm 1999:80–92) (Figure 1.1) meet these arrow speeds and prove to be effective hunting bows.

Saying that bows are more accurate than atlatls does not quite capture the situation, since accuracy is largely determined by the capabilities of the user and his/her ability to concentrate on a given target. However, unlike the atlatl, which is an extension of the human body, the bow fires more consistently by storing energy in its limbs. It is fair to say that consistency in accuracy is more easily achieved with less practice (Whittaker 2013). Since arrows travel faster, prey also has less chance to dodge the projectile. And bows require less movement to operate, so they can be fired from more confined positions and are less likely to give away the position of the hunter. However, the greater complexity of the bow requires longer construction time and more parts that can fail. Bow limbs and strings are under tensions not experienced by other projectile systems, which means they are more fragile and can wear out more quickly. Bow strings need to be both strong and thin to avoid breakage or stretching, while being as aerodynamic as possible. These elements require training, skill, and the right materials to produce.

Unlike javelins and atlatls, which rely on the complex biomechanics of the human body, the general principles of bow and arrow operation are technically less complex. Archaeologists, like many others, often simplify the power of various bows and arrows to the weight of the bow at full draw. However, several factors lead to the velocity of the arrow. These factors include the weight of the arrow, the design of the bow limbs and the subsequent leverage they have on the arrow through the full length of the draw, the properties of compression and elasticity of the materials from which the limbs are made, and the elasticity of the bowstring. A better simplification of bow performance than poundage at full-draw is what is known as the force-draw curve.

As the archer draws the bow, the weight of draw at any given length of draw can be graphed. The variable weight of the draw along the archer's draw length is the *force draw curve* (Baker 1992; Klopsteg 1943). Some bows are relatively easy to draw for most of the draw length, then suddenly become harder towards the end of the draw. This is an effect known as *stacking*. Among modern bowyers stacking is often considered a characteristic of a poorly designed bow. In contrast, a Turkish flight bow, with its stiff recurved tips and composite limbs, is challenging to draw at the beginning of the draw length, and then slackens off near the end. These two bows have very different force draw curves, although they may have the same final draw weight at a given draw length. The Turkish bow is an incredible design feat (Baker 1992; Bergman et al. 1988; Karpowicz 2008; McEwen et al. 1991) and would send an arrow of comparable weight at significantly higher velocity than the bow with a lot of stack. Therefore, the final draw weight of a bow is an easy way to discuss the potential relative performance of various bows but turns out to be potentially misleading when misused.

Early bows were simple straight staves of wood that describe a D-shape when strung and drawn. A bow made from a single piece of wood is called a self-bow. English longbows are essentially D-shaped self-bows, although they have horn string knocks at the tips and thus could be technically considered composite. Simple D-bows can be made very powerful and like other forms of projectile weaponry, simple wooden self-bows have not been completely replaced by advances in bow design. In part, simple self-bows are easier to construct, and they can be made highly effective. Relative to composite bows that are constructed of multiple materials, simple self-bows bows are also more robust. This is because before the advent of modern glues, composite bows were put together with hide glue made of animal protein, which is water soluble. This makes preindustrial composite bows fragile in wet conditions (the Ottomans solved this through extensive use of paints and sealants, Karpowicz 2008). When possible, some cultures on the Great Plains of North America avoided using composite bows for this reason (La Flesche 1926). In Bleed’s (1986) scheme from reliable to maintainable, simple wood bows are more maintainable than complex composite bows.

Making a bow shorter increases the tension on its limbs, leading to breakage, or the bow taking a lot of set (becoming permanently bent, which reduces its power). Preindustrial composite bows are generally composed of wood cores with horn bellies and sinew backing. The *belly* of the bow, the side facing the archer as the bow is held, compresses when drawn, while the *back* of the bow stretches. For this reason, horn, a material with high compression, is placed on the belly, and sinew, which has high elasticity, is placed on the back. Most woods have decent qualities of compression but poor elasticity. However, some woods excel at both. The need for a composite bow can be circumvented by making longer bows or using higher quality woods to make short bows. Short bows from the Great Plains that are constructed of Osage Orange (*Maclura pomifera)*, a high quality bow wood with good properties of both compression and elasticity, are not sinew backed (Allely and Hamm 2002).

What ultimately leads to the effect of stacking in a bow is not the type of wood or how far it is drawn relative to its length, but the angle between the string and the limb (Baker 1992). In effect, the string acts as two levers and the angle between the end of the limb and the string affects the leverage the archer has on the limbs. Therefore, keeping this angle smaller throughout the draw length makes drawing the limb easier and produces the effect of a smoother draw with less stacking. This can be accomplished by increasing the overall length of the bow or recurving its tips. Reflex or recurvature refers to permanent bending applied to elements of the bow in a direction away from the archer as the bow is held. Similarly, a more acute angle between the end of the limb provides the limb more leverage on the string and the arrow when the archer releases. Long bows and bows with recurved tips existed in the Americas at the time of contact.

Deflex refers to permanent bending applied to the bow towards the archer, or in the direction of flex as the bow is drawn. Bends are usually applied to wood and other elements using heat (e.g. La Flesche 1926). Moisture or oil may be added to keep elements from scorching. The application of sinew soaked in hide glue to the back of the bow will often result in recurvature as the sinew dries and shrinks. As just mentioned, reflex leads to a smoother draw with less stacking. It can also produce a more powerful bow since the elements will be under more tension when strung and drawn. However, many native bowyers in North America made bows with deflexed, rather than recurved tips. This is the case of the Plains tribes and cultures in the desert Southwest, among others (Allely and Hamm 2002; Bohr 2014). Many of these bows have a side profile referred to as "gull wing," meaning they are reflexed in the center and deflexed at the mid-limbs or tips. Deflexing the mid-limbs or tips may have a couple of functions. First, it produces a bow of shorter length that is easier to string and under less tension when strung, making it more durable. Second, stacking at a given draw length in these bows acts as a mechanism to prevent overdraw that would damage the wood, causing it to break or take unnecessary set. Like most other technologies, bow designs must balance efficiency and power with durability and usability. Plains people produced bows of this type that were clearly effective, given their use in bison hunting (see Bohr 2014).

The last thing to consider regarding bows is the archer's paradox (Klopsteg 1943). Like javelins and spears, arrows need to be somewhat flexible to perform correctly. The arrow needs to bend around the handle of the bow. This is accomplished by having an arrow of the correct spine that first bends away from the bow handle as it is being launched, then bends inward as it leaves the string. This allows the tail of the arrow to miss the handle of the bow. The arrow continues to oscillate for a brief period down range. When spined properly, arrows will fly straight away from the archer. This is essential for both accuracy and effective penetration. Downrange oscillation will attenuate, like atlatl darts. But like darts, at short range oscillation may affect the angle at which the tip of the arrow penetrates the target. Albeit much less pronounced than in atlatl darts, arrow oscillation could lead to inconsistencies in close range controlled experiments that utilize consistently drawn bows and seek to control for angle of impact or obtain close measurements of penetration.

1.4.2 Exterior ballistics of preindustrial piercing projectiles

Once projectiles have left the firing mechanism they are in the realm of exterior ballistics and can be modeled using the branch of classical mechanics called kinematics, or the study of bodies in motion. The exterior ballistics of projectiles can be tracked within an XYZ ballistic coordinate system, where Y charts the drop in a projectile over a given distance (X), which may also deviate to the right or left (Z). Lighter projectiles that travel at higher velocity drop less than heavier and slower projectiles, all else being equal. This drop is what makes slower projectiles potentially less accurate. Flatter shooting projectiles are generally considered easier to aim, because the operator still has to calculate for Z, but can focus less on compensating for drop (Hughes 1998; Whittaker et al. 2017). However, understanding the accuracy of preindustrial projectiles is challenging, as discussed in the previous sections on atlatls and bows. To fully understand the effects of accuracy we need to understand not only the projecting mode and the exterior ballistics of the projectile, but the operator's ability to focus on a given target.

A projectile has weight; this is the mass of the projectile relative to a gravitational constant. Since weight refers to the *mass* (m) of a projectile being accelerated in a certain direction (downward) by a body of higher mass (the Earth), weight is a *force*. *Velocity* (v) refers to distance in a given direction covered per unit time and is thus a *vector* quantity; it has both magnitude and direction. Velocity is the most important kinematic parameter in projectile ballistics (Kneubuehl 2011). Frequently, velocity is used to refer to *speed*, which is a scalar quantity referring only to the magnitude of velocity. Velocity entails a direction of magnitude, but the term is often used without reference to direction and thus technically describes speed.

Any object with mass also has some resistance to changes in its state of movement, or *inertia*. Objects of high mass also have high inertia. In preindustrial projectile ballistics, inertia is an important component of the target that the projectile strikes, as alluded to in section 1.5.1.2. This is a primary reason why effective projectiles are often specifically crafted toward the goal of hunting specific sizes of prey. Projectiles are often adapted with variables of speed and mass to match the intended target (Christenson 1986; Hughes 1998). Finally, the penetration of a projectile is a product of its velocity, its mass, and the many aspects of its shape and texture. I discuss this in the following section on terminal ballistics and further in Chapter 2.

The last criterion of effective linear projectiles is stability in flight. This can be achieved by ensuring that the center of pressure is behind the center of gravity (Christenson 1986; Cotterell and Kamminga 1990; Cundy 1989; Hughes 1998). The center of pressure is the point on the projectile where air resistance operates. In many cases, the center of pressure and the center of gravity (the balance point of the projectile) are close to the same location. This is true when linear objects that are consistent in such aspects as diameter and texture along their entire length are flying in line with their long axis. When they angle upwards relative to their forward trajectory, the center of pressure moves in front of the center of gravity, and the opposite is the case if they angle downwards. By either ensuring that the center of gravity is well forward of center, usually accomplished with a weighted tip, or by attaching something to create a strategic amount of drag to the tail (fletchings) and thus moving the center of pressure back, stability in flight can be achieved. This is an essential characteristic of linear projectiles, both for accuracy, and to ensure that the projectile impacts the target in line with its long axis. This ensures minimal drag on the trailing shaft as occurs in skewed impact.

1.4.3 Terminal ballistics of preindustrial piercing weapons

The capability of a projectile to penetrate and damage a target is expressed in two ways; *momentum* and *kinetic energy*, which are functions of velocity and mass. Momentum (P=v*m) is a vector quantity in which the direction is the same as the projectile's velocity. Momentum expresses a projectile's ability to resist change in direction under the influence of a given force. Therefore, change in momentum during impact is reflective of impact forces. Given this description, momentum seems like a good candidate to represent a projectile's ability to penetrate a target denser than air. Kinetic energy ($KE=½m*v^2$) represents the overall *work* a projectile can do on the target. It is more responsive to the projectile's velocity than to its mass. If wounding occurs to an organic target, it is a result of the transformation of energy into work (damage) (Kneubuehl 2011). Studies of firearm ballistics use both KE and P, but with different goals of analysis (Anderson et al. 2016).

Whether to use KE or P to describe the effectiveness of preindustrial projectiles has been a matter of debate (Ashby 2005a; Tomka 2013). The effectiveness of a projectile designed to cut a path through vital organs and cause hemorrhaging is measured based on its ability to penetrate. However, the potential effectiveness of a projectile is a product of many factors and cannot be simplified to either energy or momentum. The challenge of employing either KE or P in studies that analyze multiple projectile types is problematized by variations in the morphology of the projectiles, as well as the nature of the target, all of which affect penetration. Such factors include the surface texture of the projectile, the nature of the hafting area, the thickness and taper of the trailing shaft relative to the size and shape of the armature, the size, shape and cross-section of the armature, the efficiency of the armature's cutting edges, and the strain-rate sensitivity of the target, or its propensity to fracture faster with higher velocity impacts. Obviously, the factors that govern a projectile's potential effectiveness are complex. This will be treated more thoroughly in the next chapter.

Kinetic energy is generally suggested to be a better indicator of a projectile's ability to penetrate a dense target (Anderson et al. 2016; but see Ashby 2005a). This is because penetration cuts and tears apart material, creating new surface areas. The depth of penetration of a projectile is directly tied to the amount of new surface it has created. This cutting and tearing action requires energy to accomplish (Anderson et al. 2016). In fact, the penetration of a fast-moving projectile into a dense medium alters the state of that medium during the brief moments of penetration, which changes the forces of resistance and the surface flow around the projectile. Higher velocity results in deeper penetration with less effect on the surrounding material. The effect is repeated with high velocity bullets, which cause cavitation as they slow near the end of the wound channel (Kneubuehl 2011). Bullets designed to break apart or deform are made to shed a greater amount of energy and cause increased damage to soft targets, whereas those made to hold together are designed to penetrate tough targets, such as armored targets. Cavitation is not the intended effect of piercing preindustrial projectiles designed to cut a wound channel, although bruising of vital areas from shed energy may increase lethality. According to Anderson and colleagues (2016) the area of effect will increase when penetration to a given depth occurs by a slower piercing projectile of higher mass.

Anderson and colleague's study, however, used low velocity arrows against ballistics gelatin, which has been demonstrated to be not a scalable simulant to biologic tissue for low-velocity piercing and cutting projectiles (including javelins, darts and arrows Karger et al. 1998). According to their recommendation, similar studies need to be made with higher velocity projectiles, targets of varying consistency, and variation in armature morphologies to better understand projectiles that are intended to pierce and cut. When projectiles encounter different target materials, like biological tissue, momentum may play a more important role in modeling effectiveness, but this requires further testing to find out (see Chapter 2).

1.4.3.1 Lithic armature design and hafting

The performance of piercing projectiles in penetrate living targets is dependent on a complex range of factors. Among the most important are the mass and velocity of the shaft, and the tip cross-sectional area, shape, and sharpness of the hafted armature (Cotterell and Kamminga 1990; Hughes 1998). We must also consider the drag coefficient of the target medium. When the objective is to kill through hemorrhaging, penetration with an efficient cutting head into the thoracic cavity is the best approach. The cutting armature should simultaneously open a wide enough wound to reduce drag on the trailing shaft and produce a wound surface area proportional to the size of prey animal (Friis-Hansen 1990). Chapter 2 covers this topic in detail.

Some piercing weapons were armed with tips designed only to pierce rather than to cut. Osseous and wooden armatures fall into this category when microliths were not glued along their sides to form a cutting edge. Many are cylindrical or somewhat lanceolate in cross section. These “sagaie” points occur at Old World Pleistocene sites (e.g. Pétillon et al. 2011) as well as in Pleistocene assemblages in North America (e.g. Wilke et al. 1991). Old World sagaie points have been found with microlith edges, but this feature has yet to be found on new world examples. Guthrie’s (1983) experiment suggested that a lanceolate shaped sagaie tip increased penetration. He reasons that this was because a cylindrical point lashed to a mainshaft of the same diameter creates a “hilt”—a point of drag—at the lashing. A wider point is needed to cut a hole for the lashing. Guthrie found that the most efficient design of antler sagaie point, which combined durability with penetration, was a lanceolate shaped form about 1 cm average diameter. Guthrie's arsenal did not include sagaie points with microlith edges.

Ashby (2005a, 2005b, 2007, 2009) has recommended criteria for efficient designs in modern steel hunting broadheads. A broadhead should taper gradually in thickness toward the arrow shaft, have a straight cutting edge that is not serrated but is extremely sharp, and two blades that are beveled on opposite sides. Beveling of the blades causes a broadhead to rotate as it penetrates, which torques and splits bone and thus dramatically reduces friction on the trailing shaft. How exactly these criteria apply to stone projectile points is not clear. Beveling on stone dart points does cause the point to rotate through a dense target that exerts pressure on the bevels. But beveled stone points have not produced the dramatic splits in bone that Ashby records of thinner and more durable steel broadheads (Pettigrew et al. 2015). Furthermore, serrations may assist a projectile in getting through skin, which requires more force to penetrate than the interior of the body (O'Callaghan et al. 1999). However, serrations also bind up with deeper penetration, or when they encounter fibrous materials (Hughes 1998). Animal hair and sinew may clog serrated edges and reduce penetration (Ashby 2006). Serrated points may be associated with higher energy projectiles (Hughes 1998), but it is not clear why this should be the case. It is possible that serrated edges perform better in certain cutting tasks depending on the worked material. Thus, selection of serrations may depend on the composition of the intended target as well as the projecting mode. Variation in the specific morphology of serrated edges also impacts how they function in a given material (Abler 1992). Ashby (2009) claims that a smooth, extremely sharp edge is more lethal than a serrated edge, since the former produce less trauma when cutting blood vessels, and trauma induces cells to release proteins that cause blood to coagulate. Serrated points require more research into wound trauma and projectile experiments to understand the circumstances in which they are selected.

Archaeologists who study the performance of ancient hunting weapons needed the ability to model the effects of various armature designs in order to predict what characteristics should be selected for in projectile weaponry in a given context (Anderson 2010; Christenson 1986). When a projectile system surpasses the energy requirements to hunt certain prey, highly efficient armatures are not necessary, and armature design may take many forms. But when weapons systems are tested to their limits, such as in hunting very large animals (e.g. Frison 1989), the necessity of effective armatures should be more pronounced (Ellis 1997). This is the probable reason for such design elements as basal thinning in Clovis points, which has been hypothesized to reduce the width of the haft (Christenson 1986; Frison 1978; Guthrie 1983; Hughes 1998).

Frison's (1989) experiments employed heavy atlatl darts (>400 g) and he was able to manage lethal wounds on elephants. Critically, African elephants have thinner skin than Asian elephants and mammoths, and the latter had an additional layer of thick hair (Banks 2000; Eren, Meltzer, et al. 2021). Frison's equipment was not what one might consider well-optimized. The hafting was bulky and the transition from the dart's foreshaft to the mainshaft was not smooth, which caused some of his darts to stop at the foreshaft juncture.

Bulky hafting and pronounced transitions in composite shafting, such as from the foreshaft to mainshaft, have been demonstrated to reduce and even completely halt penetration (Callahan 1994; Frison 1989; Guthrie 1983; Huckell 1982; Pettigrew 2015). Shoulders strategically placed between the foreshaft and mainshaft on ethnographic projectiles (e.g. Figure 1.2) is a strategy that reduces penetrate past the transition, and is generally associated with the use of poisoned foreshafts to increase the odds that the mainshaft falls away while the foreshaft stays in the wound (Jones 2007; Knecht 1997). Some interpretations of hafting methods have completely overlooked the inefficiency of bulky hafts by recreating hypothetical hafts, such as with Clovis points and bone rods, that are extraordinarily bulky (Lahren and Bonnichsen 1974). Rather, certain elements of terminal Pleistocene projectile points, such as fluting on Clovis and Folsom points, suggest that some of Ashby's criteria could be present, but more experimental work is required to fully understand the characteristics of optimized stone projectile armatures.

1.4.3.2 The problem of projectile poison

A large number of hunting cultures around the world use poisoned projectiles for both large and small game (Donald Macre and Neil Towers 1984; de la Harpe et al. 1983; Hill and Hawkes 1983; Jacobsen et al. 1990; Jones 2007; Kao et al. 1989; Knecht 1997; Lee 2005; Osborn 2004). Projectiles that are poison coated do not need to carry substantial amounts of energy to pierce deeply, nor do they need large cutting armatures that cause substantial hemorrhaging (Ellis 1997). However, Hadza hunters use poison on arrows with large cutting heads shot from powerful bows, with the primary goal to kill prey through poisoning (Bartram 1997) in environmental conditions similar to the San, whose poisoned arrows are shot from relatively small bows. Most poisons do not cause animals to drop on the spot, so poisoned projectiles may also be designed to kill through hemorrhaging when the opportunity arises. The impetus to design projectiles that can do both should be less in areas where powerful poisons are available (Ellis 1997), such as South America where highly toxic plant alkaloids are made into curare (Lee 2005).

It has been suggested that projectile poison could have deep antiquity in the Americas (Jones 2007; Osborn 2016). As of yet, no attempts have been made to look for poison residues on Paleo-Indian hunting gear. Poisons for warfare often take a different form than hunting poison. For example, warriors in the southwestern US would taunt a rattlesnake into biting a fresh deer liver several times. The liver would then be buried for multiple days, and later dug up to be mixed with ground up venomous spiders before being smeared onto arrows. There are varying accounts of how effective such poison was (Jones 2007). Certainly, poisons that attack the body with serious infection are unlikely to be used for killing prey one intends to eat.

Poisons for hunting are usually derived from plants that contain toxic alkaloids (Osborn 2004:149). Exceptions include San Bushman poison, which is derived from beetle pupae (Woollard et al. 1984) and dart-poison frogs in Central America (Myers and Daly 1983). If Poisons were in use by terminal Pleistocene hunters in the Americas, it would seem to indicate a fast development of familiarity with the resources in their new environment. However, there may have been poisonous plants that were already familiar to them. Monkshood (*Aconitum sp*) is a family of over 250 flowering plants that occurs in both the old and new worlds. Monkshood enjoys subalpine meadows in the continental US, and occurs in Alaska, so it may have been present on Pleistocene landscapes such as Beringia and Siberia (Osborn 2016). It also enjoys a lengthy history as a hunting poison. The poison is extracted by boiling roots, stems, leaves and flowers. If it was used, poison problematizes our understanding of how or why projectiles would need to be optimized for hunting large animals.

1.5 Approaches to studying preindustrial piercing weapons

Projectile experiments have been going on a long while. Ancient hunters to some extent must have tested the capabilities of their weapons. This section focuses primarily on projectile studies of archaeological projectiles, which began in earnest in the latter half of the 20th century. But it is worth mentioning a few historic examples. Examples from the medieval and colonial eras are mentioned by Pope (1923). Medieval archers shot arrows into seasoned wooden targets to test penetration. During De Soto's expedition through the Southeast, a captured Apalachee man won his freedom by testing his arrows against a coat of mail set over basketry. His arrows were able to pierce two shirts of mail, which prompted the Spaniards to rethink their choice of protective gear. Modern Cherokee archers play a game of cornstalk shooting, in which a man-sized target of densely bound cornstalks is shot at from a distance. The goal is both to hit the target and have the arrow penetrate deeply. This may be a survival of old war games to train southeastern archers (Herrin 2000).

Projectile studies of the late 19^{th} and early 20^{th} centuries placed weapon advancements within a cultural evolutionary framework. In one of the earliest pieces of literature on the subject, Cushing (1895) theorized a sequential development of weapons from simple to more complex based on related components. Cushing thought that flexible atlatls propelled darts through spring action, which led to the development of a purely hypothetical "arrow sling" and finally to the bow and arrow. This is problematic because neither flexible atlatls nor their darts rebound before the dart has left the atlatl. Therefore, none of the energy stored in compression contributes to the dart's velocity (Whittaker 2016; Whittaker and Maginniss 2006). Cushing could not have known this before the invention of high-speed cameras. The atlatl and bow operate in entirely different ways: the atlatl as a lever and the bow through elasticity and compression in its limbs. Nevertheless, Cushing is among the first to focus on weaponry and the circumstances and implications of its development. Cushing may also be the first to replicate and test preserved atlatls and darts from the southwestern US, although he unfortunately did not describe these efforts.

Advances in weaponry and other technologies were not the focus of archaeologists in the early half of the 20^{th} century, and the topic remained largely neglected (Bleed 1997; Oswalt

1973). With the work of Oswalt (1973) and others, weapon technology came back into focus, and even more so within an evolutionary framework. Among the most frequently cited papers on ancient projectiles is Hughes' (1998) study of evolutionary changes in projectile weaponry. Using a Darwinian evolutionary paradigm, projectile weapons and other tools are included in the human phenotype. This approach allows analysts to study weaponry by the increased level of fitness it provides its users (Hughes 1998:347). Darwinian evolution can be an effective metaphor for thinking about transitions in projectile technology. However, humans are complicated creatures. We may work to enhance our somatic success, but this does not always improve reproductive fitness (Bamforth 2002b). It should also be recognized that, to an extent, both human predators and their prey can adapt to changing circumstances. Prey may change its behavior in response to new predatory behavior associated with new weapon systems. New weapon systems may not provide a clear advantage in every context. This is well demonstrated by a number of examples of survival of outdated weapon technologies, and failure of cultures to adopt new ones (Oswalt 1973), even when they have access to them (Macola 2016). I will return to this topic in the final section of this paper.

More recent studies of archaeological hunting weapons have been made primarily to identify the presence of a particular projecting mode in the archaeological record, and to assess the implications of weapon introductions on human ecology, social organization, and evolution. Studies of weaponry have drawn from ethnographic accounts of hunting weapon use among non-Western cultures and from modern experiments.

1.5.1 Preindustrial Piercing Weapon Experiments

Experiments to understand ancient weaponry fall under the categories of experimental archaeology (Coles 1974, 1979; Ferguson 2010) and reverse engineering. Like most of archaeology, ancient projectile weapons must be understood through modern and ethnographic analogs (Ascher 1961; Stahl 1993; Wylie 1985, 2002). While it is easy to understand what ethnographic records of weapon use are, modern analogs can take at least three forms: 1) Analysts attempt to gain informal experience making and using close copies of weapons to better interpret artifacts and associated behaviors. 2) Experiments of the *controlled* type seek to isolate causal mechanism of the variables of interest to enhance their visibility. In projectile studies these take the form of a consistent launching apparatus such as a calibrated crossbow that control for aspects such as velocity and impact angle, as well as consistent target media. 3) *Realistic* experiments on the other hand seek to mimic as closely as possible the original, and highly variable, conditions of use. These generally entail human experimenters using replica weapons often against animal carcasses dispatched immediately prior to the experiment. Realistic experiments simultaneously meet the first objective as well, gaining direct experience making and using old tools. Chapter 4 covers this topic in detail.

Dividing projectile experiments into realistic and controlled categories provides a way of framing the theoretical trends that have led to the structuring of projectile experiments. However, some level of control, such as a consistent shooting distance or limitations on variation in experimental projectiles, is necessary to make realistic experiments interpretable. Realistic experiments are obviously not entirely "real." Furthermore, the difference between realism and control should be thought of as a spectrum; some experiments lie closer to the middle by melding the two approaches, such as by using a synthetic target medium and realistic mode of projection, or vice versa. In fact, any attempt to neatly categorize archaeological experiments is problematic, since projectile experiments are carried out with different goals and a variety of methods have been used to achieve them. I attempt to circumvent the confusion by including in the controlled category any experiment that uses a consistent firing apparatus with the goal of achieving ballistic consistency. Bows are consistent mechanisms, especially modern compound bows with cam systems, although human operators still introduce subtle inconsistencies in the way they draw and release the arrow. Realistic experiments, therefore, include real humans launching arrows, darts and spears into various targets, including composite organic and synthetic targets. This topic is treated further in chapter 4.

1.5.1.1 Controlled experiments

Controlled approaches to the study of archaeological projectiles began in the 1980s. These experiments used calibrated crossbows, which can achieve consistency in velocity, accuracy, and angle of impact. Carrère and Lepetz (1988a) may be the first to have constructed a calibrated crossbow for projectile studies. Knecht (1991) also constructed a crossbow to study breakage patterns on replicas of Upper Paleolithic osseous projectile points. Subsequently, the crossbow used by Shea and colleagues (2001) was based on these earlier experiments. Several experiments have since followed that have employed crossbows, although there is a great range of variability. Calibrated “crossbows” often use mounted handheld bows, including wood or fiberglass “traditional” bows, or compound bows, that are mounted either vertically or horizontally and provided with a mechanical string release. Other forms of controlled launching apparatus include air cannons (Iovita et al. 2014), a large mounted sling shot (Pargeter 2007), and gravity (Anderson 2010).

Controlled experiments have been conducted with a variety of objectives. They have been undertaken to produce fracture patterns on osseous and lithic armatures to replicate those found on artifacts at particular sites. Some have been undertaken to test the effectiveness of various hafting parameters, and to model penetrating efficiency of projectile points and hafting design. Others have focused on our ability to distinguish between projectile systems. The last objective has by far been the most challenging to achieve (Hutchings 2016).

Hutchings (2011, 2015) has made the most thorough attempt to distinguish projectile systems. He performed detailed studies of microscopic fracture patterns on atlatl dart armatures that were launched in controlled experiments to replicate the velocity and energy produced in his previous realistic experiments (Hutchings and Brüchert 1997). This was done to study the velocity of fracture propagation in stone points launched by various projectile systems (discussed more in section 1.5.2.4). But there may be problems with Hutchings' velocity data. Hutchings and Brüchert (1997) launched atlatl darts at night with a light attached to the tail of the dart, and used two cameras to measure the undulating streak of light. Their method is not entirely straight forward, and myself and colleagues had trouble reproducing it (Whittaker et al. 2017). The dramatic range of variation in their velocity data (28-64 m/s) may be a product of discrepancies between the distance of the projectile and of the scale from the camera. The scale used to calibrate a video for velocity calculations needs to be as close to the projectile as possible to achieve accuracy in measurements. Preferably the scale is actually marked on the projectile shaft itself, and the projectile shaft crosses at a right angle to the lens of the camera. This has been a problem with several experiments that have used visual measuring techniques to calculate velocity (see Whittaker et al. 2017). Consequently, the velocity used for atlatl dart proxies in Hutchings controlled experiments, 36-37.5 m/s (Hutchings 1998:89), are above the highest recordings for a large sample of well-trained atlatlists using a variety of equipment and measured using multiple techniques and instruments (Whittaker et al. 2017).

This helps to illustrate a point: controlled experiments must be based on parameters of known weapon function, which must be derived from ethnographic accounts or well-conducted realistic experiments.

In addition to reducing inconsistencies and isolating variables, controlled experiments circumvent some of the necessity of learning to make and use replicated technologies. Building the requisite skill to perform well under pressure during realistic experiments takes time that many experimenters may not have. However, some degree of skill and familiarity with weapons is still necessary to plan and carry out effective controlled experiments. Even if experimenters are not crafting replica armatures, they often need to build the firing platform and functional projectiles. Finally, experimenters need some understanding of how the ancient weaponry they're mimicking operates. Importantly, gaining experience in making and using weapons in a realistic fashion has potential to inform interpretation in unpredictable ways.

As is the case of realistic experiments, controlled experiments have taken a wide range of approaches. The inconsistencies between experiments are potentially problematic when attempting to draw comparisons between their results. It may even be challenging to compare their results with archaeological residues when the parameters of controlled firing apparatuses do not match ancient weaponry. Waguespack and colleagues (2009) utilized a compound bow with 60 pounds final draw weight against a target one meter away. This was intended to mimic the draw weights of Native American traditional bows; however, final draw weight is not the only parameter that leads to the final velocity of the arrow, as discussed in section 1.4.1.3. Modern compound bows fire arrows at much higher velocity than traditional bows.

Waguespack and colleagues (2009) found that stone tipped arrows only penetrate 10% better than sharpened wood tips, perhaps because the stone tipped arrows were slightly heavier.

They did not check the velocity of these arrows. Given these surprising results, it isn't clear to them what advantage stone tips provide. Possibly there was an element of costly signaling to the production of knapped stone tipped projectiles. Salem and Churchill (2016) address this by showing that stone tips cause far more damage in ballistics gel. Stone tips and other cutting armatures cut a wide wound that leads to substantial blood loss (Ashby 2006; Friis-Hansen 1990; Frison 1978). Waguespack and colleagues' experiment tested wood and stone tipped arrows fired from a compound bow into ballistics gelatin covered with leather at close range, not the terminal ballistics of arrows fired from appropriate bows at appropriate hunting distances into real bodies. Tanned leather has very different qualities than living skin, and the arrows encountered no bone in the target. Most importantly, ballistics gelatin is not a scalable medium to prey bodies for low-velocity projectiles that pierce and cut (Karger et al. 1998). Karger and colleagues found that arrows with field points (lacking cutting blades) penetrated deeper into ballistics gelatin than into fresh pig carcasses, while the opposite was the case for arrows with broadheads and other cutting tips. These penetrated much deeper into the pig carcasses. This suggests that penetration of the sharpened wood tips in Waguespack and colleagues (2009) experiment is probably artificially high, and penetration of the stone tips is artificially low, relative to animal targets.

Guthrie (1983) had very different results with wood tipped spears shot with a compound bow into a fresh moose carcass. The skin of the animal often rejected wooden tips, whereas stone tipped spears penetrated well. But the parameters of Guthrie's experiment and the design of his projectiles was different. Gelatin and consistent firing apparatuses provide consistency within experiments, not necessarily between them, and the results need to be compared with those of realistic tests to understand how the effects might play out in a real hunting situation.

It is not fair to focus criticism too much on the test of Waguespack and colleagues (2009). Several archaeologists have used ballistics gelatin to test the penetration of ancient projectiles (see Appendix C). The goals and design of such experiments need to be founded on actual experience in making and using ancient weaponry, as well as what constitutes effective hunting tools and strategies.

Mimicking thrusting spears (lances) presents an additional problem to those using a controlled approach (see Milks et al. 2016). Initially, controlled experimenters were lacking information on what kinds of force values to assign to lances. This was remedied by using values from experiments in one-handed stabbing (O'Callaghan et al. 1999; Shea et al. 2001). Coppe and colleagues (2019) recently attempted to better fill the data void with a study that deployed bows, atlatls, javelins, and lances against a ballistics pendulum. Their values of kinetic energy are comparable with previous studies, and are useful, with the exception that lances produced an incredible range of kinetic energy from 26 to 3198 joules. Their experiment supposedly did not contain a pushing motion since the pendulum was set at the end of the lancer's "gesture." However, this is not how lances operate. By the very nature of its operation, a lance requires use of a thrusting motion in which force continues to be applied after contact with the target, at least for a brief moment. Crossbows and other shooting devices struggle to accurately mimic this (Milks et al. 2016). A ballistics pendulum is not designed to provide a comparison between this type of applied force and projectiles.

In their comparison of breakage on Upper Paleolithic points from Japan, Sano and Oba (2015) used a crossbow to mimic projectiles, but decided to rely on a realistic spear thrust by a human operator to produce breakage from lance use. Iovita and colleagues (2016) used a weighted swinging contraption to reproduce lance thrusts in a controlled way. Such a contraption seems to be an improvement on previous designs but is still not capable of mimicking the continued and dynamic application of force and direction of a real lance thrust. As the problems in the recent paper by Coppe and colleagues (2019) demonstrates, how to make lance use comparable to projectiles is still not fully understood. Mimicking lance thrusts in a controlled fashion presents an ongoing challenge.

Some controlled experiments have successfully produced breakage patterns on replica lithic and osseous projectiles that compare with those found in archaeological sites (Knecht 1993, 1991; Rots and Plisson 2014; Sano and Oba 2015). Even with composite organic, or synthetic targets, and controlled modes of projection that do not accurately mimic ancient ones, diagnostic impact fractures (DIFs) may be similar to archaeological finds. The reason for this may be that DIFs are often consistent across firing platforms, with the exception of burin length (Clarkson 2016). The main problem with our current body of data for distinguishing projectiles, however, has to do with equifinality (Hutchings 2016). It is challenging to reproduce the range of conditions that may have led to breakage patterns on ancient projectiles, and few experimenters have tried (but see Fischer et al. 1984; Hutchings 2016; Pargeter 2011; Sano 2009). By their very nature, controlled experiments reduce the range of variability in causal mechanisms of breakage and wear on ancient stone tools.

Controlled experiments remain an applicable avenue of research into ancient weapons when designed and implemented effectively, but more such experiments need to be based on more accurate criteria, such as atlatl dart velocity and force in lance gestures. This would allow observations to be further refined. Furthermore, controlled experiments work best when they are used in conjunction with realistic experiments (Iovita et al. 2016; Pettigrew et al. 2015), including not only realistic projectile use, but other kinds of uses, and post depositional effects such as trampling. It should be clear that the controlled approach must draw from either experiments that test modern replicas deployed by practiced users (the realistic approach), or with ethnographic records of indigenous use. The strength of a controlled approach is also its weakness; isolating variables of interest enhances our ability to observe them, but does nothing to solve the issue of equfinality, which is the primary roadblock in our ability to distinguish projectile systems from their armatures alone.

1.5.1.2 Realistic experiments

Realistic experiments attempt to mimic the complex conditions of past use. They also form part of the background data that allow parameters of controlled experiments to be set. Isolating the causal mechanisms leading to effects such as impact fracturing and penetration depth remain challenging. In part, this is because realistic experiments have lacked adequate observational methods to record the complexities of projectile flight and impact, although methods are improving in more recent experiments. It is also a result of using realistic targets—often complete animal carcasses—which are highly variable in composition. In the past, the construction of hunting weaponry was founded on generations of real hunting experience, but this is entirely out of the question for modern projectile experiments, which means that building large enough samples for statistical observations is challenging.

Not all realistic experiments have been undertaken using fresh, complete animal carcasses as targets, and some controlled experiments, as defined here, have. However, if these approaches exist on a spectrum, then the realistic end of the spectrum includes human operators of replica projectile systems shooting into fresh and complete animal carcasses from appropriate distances. At the other end of the spectrum would be experiments using consistent firing mechanisms and synthetic, homogenous targets. Clearly many experiments fall somewhere in between. Nevertheless, I have placed the following discussion of carcass experiments in the realistic category because in my perspective, they fall more on the realistic side of experimental designs.

Dead carcasses are imperfect analogs to living bodies. However, using live animals is out of the question from an ethical standpoint, although this has been done in at least one experiment (Flenniken 1985). Frison (1989) also fired an atlatl dart into a live but injured elephant, which killed it. But this was unplanned since the cullers with high powered rifles had moved on to follow the herd. The most realistic approach would be to hunt with replica weapons, but many ancient weapons are illegal to hunt with in most states in the US and from an ethical standpoint hunters need to start with an understanding of what weaponry is generally capable of. Additionally, hunting usually (ideally) allows only single shots into living bodies, which provides a very small sample size. Nevertheless, actual hunts would be a highly informative approach as an addition to current projectile studies (Loi and Brizzi 2011).

Ashby (2005a, 2005b, 2006, 2007) has performed tests into carcasses with hunting bows and arrows immediately following a successful hunt of an animal and feels that fresh carcasses provide an adequate alternative to living animals. When carried out properly, fresh carcasses can also be consumed after the experiment (Pettigrew 2015). However, carcasses present several challenges. Partly, this is due to the composition of a dead versus a live body. The contraction of muscle fibers in live animals may create a type of obstacle that projectiles do not experience when penetrating a lifeless body. Furthermore, the lungs of a carcass are not filled with air, which may alter tension in the body cavity. Finally, carcasses do not run or fall over with projectile shafts sticking out of them, which could cause additional breakage patterns and trauma (Pétillon 2005).

The carcass experiments undertaken thus far have all demonstrated that damage to points is relatively infrequent (e.g. Schoville et al. 2017; Shea et al. 2001). This would never have been clear without performing carcass experiments, but it also means that to replicate diagnostic impact fractures (DIFs) many experimenters have turned toward targets of hard materials, usually exposed bone from butchered carcasses. As Shea and colleagues (2001) note, building an adequate sample of broken points would have required far more sheep than they had access to.

A final issue with the use of carcasses is how to prop them up in a way that mimics a life-like stance. Most past carcass experiments, including controlled carcass experiments, have used a carcass that was suspended from a frame by ropes and straps. This method proved problematic in a recent carcass experiment I undertook on a goat (see Chapter 2). Arrows penetrated well, but the slower and heavier atlatl darts often bounced off. In the high-speed video, this was clearly because the carcass was swinging and absorbing much of the impact. A lifeless suspended carcass clearly does not have the same inertia or resistance as live animals that are anchored to the ground with gravity and are supporting their own weight. Arrows performed better, since smaller projectiles with higher velocity work better against targets with lower inertia (Anderson et al. 2016). Even when suspended carcasses are lowered so their feet are on the ground, as we attempted with the goat, and as other experimenters have attempted, they still do not mimic the inertia of a live animal standing on its own four feet. This may call into question the results of many past carcass experiments that have used suspended carcasses, especially those that have sought to explore aspects of penetration and performance, but damage on stone and bone could also be affected by artificially low target inertia.

Realistic projectile experiments have not only been carried out on carcasses. Several have been performed on composite synthetic, or composite organic (or composite synthetic and organic) targets. The choice of what target to use has been even more diverse than the projecting mode tested. For archaeologists, target choice, more so than other parameters of an experiment, is responsive to convenience and availability. Animal carcasses may be both challenging to obtain and variably responsive to time and temperature after death. Local regulations may also prohibit the use of fresh and complete animal carcasses (Smith et al. 2020) For this reason, Iovita and colleagues (2016) find composite synthetic targets used with controlled projectile apparatuses more appropriate for narrowing down the causes of impact damage. However, such experiments must be validated by more realistic weapon use. Controlled projectile apparatuses do not accurately mimic the behaviors of some projectiles, such as flexible atlatl darts. Darts spin, rotate, and flex dramatically, often impacting the target at a slightly skewed angle, and continue to flex after impact (Pettigrew 2015; Pettigrew et al. 2015). Crossbows also cannot create the spin imparted to a javelin when it is thrown (Iovita et al. 2016).

A principal challenge for realistic experimenters is attaining the requisite skill and fitness in using the weaponry (Milks 2019). As already stated, this also hampers controlled experiments. However, the possibility that weapons experimenters do not provide adequate analogs for ancient users is a common argument against their applicability. In a study of atlatl and dart velocity, myself and colleagues attempted to overcome this by measuring velocities from a large sample of atlatlists using their personal equipment. Some of them had been training from a young age and some had hunted effectively. What was additionally instructive was to measure velocity from some atlatlists who had only recently learned to use the weapon and had yet to develop accuracy. One such thrower achieved the high velocity that was recorded of strong throwers who had practiced from a young age, convincing us that accuracy rather than power is far more challenging to learn with an atlatl (Whittaker et al. 2017). We may also compare these results with the extant information regarding indigenous atlatl use (Cundy 1989; Nelson 1899), and see that they are comparable. Several tests of indigenous users show that 70 m is an approximate maximum distance for launching atlatl darts designed for hunting, which is also a typical maximum distance for myself and other modern users. We can never say with absolute certainty that modern use is comparable to past use, but these results seem to strongly suggest they are.

The observations of Whittaker and colleagues (2017) are encouraging regarding the applicability of realistic experiments. This is especially true when the goals of experiments are to measure such aspects as penetration and breakage, and these are achieved more through the force of throwing than accuracy. Still, weapons experimenters need to be capable of hitting the target from a realistic hunting range with adequate velocity and good (straight) trajectory. Lack of proper training in javelins and atlatls can mean that carrying out a projectile experiment effectively is challenging to impossible, although the lack of representative skill may not be immediately apparent. In other words, experimenters can fail to develop adequate skill, carry out an experiment anyway, and present highly misleading results regarding ancient weapon performance. Aside from acquiring and deploying effective observational tools to isolate causal mechanisms, this is the biggest hurdle for realistic weapons experiments. In short, experimenters using a realistic approach need to practice regularly. There will always remain questions of how much practice and skill is required to mimic prehistoric hunters, and how experiments performed by participants of differing skill can be compared (Whittaker 2013). Milks (2019) provides a good review of this topic.

My previous work was intended to tackle the abilities of realistic experimenters to observe the effects of projectile impact by crafting an experimental design that could record the flight and impact of the projectile, as well as its velocity on impact. This was done using a high-speed camera to observe the impact, and a second high speed camera to measure velocity from the side as the projectile impacted. The velocity from video was cross-compared with radar gun measurements of the same shots, and scales were attached to the projectile shafts themselves to ensure higher accuracy in calibrating the videos (Pettigrew 2015). This experiment produced a database of projectiles with detailed shot and impact histories. The results demonstrate that the data from one realistic experiment deploying effective observational tools can be used to answer a range of questions. To make the database more useful, more experiments need to be undertaken following similar procedures. This would allow more powerful statistical analysis to be undertaken on such features as the efficiency of projectile point design. Few of the previous realistic projectile experiments have been focused on design efficiency of projectile tips (but see Frison 1989; Huckell 1982; Pokines and Krupa 1997; Pokines 1998). Of these, none have made a concerted effort to understand the terminal ballistic properties of armature morphology when attached to projectiles of various mass and velocity. Since the aforementioned experiment (Pettigrew 2015), I have undertaken more realistic experiments using a similar protocol. The results are presented in Chapter 2.

A drawback of using realistic experiments on complex targets (carcasses) is our inability to carefully observe effects on projectile armatures when they encounter various materials inside the carcass. This is one area where controlled approaches that utilize high speed cameras, transparent ballistics gelatin, and exposed hard targets have an advantage, but only when the objective is to check wear patterns formed under synthetic conditions (Sano and Oba 2015). However, one benefit of using high-speed cameras and markings on long projectile shafts is that deceleration through the carcass can be tracked. This provides a detailed examination of armature efficiency over a realistic penetration event. This can be paired with careful observations of projectile impacts and wound channels traced to particular shots, allowing damage to armatures, skeletal lesions, and terminal ballistic variables such as kinetic energy to be effectively traced in realistic experiments (Pettigrew 2015; Schoville et al. 2017). This provides an enhanced degree of realism regarding the formation of projectile and skeletal damage than is achieved in controlled experiments in target simulants. In fact, carefully recorded realistic projectile experiments on carcasses can capture a range of goals in singular events, allowing hypotheses to be developed and tested simply by analyzing the resultant data. This is a hallmark of realistic “exploratory” experiments, the popularity of which is increasing in a variety of scientific fields (Franklin 2005; Steinle 1997). The ability to cross-compare multiple such experiments will enhance our ability to generate more powerful statistical observations of ancient weapon performance and the residues they leave behind.

To summarize, although controlled methods can be used to isolate the causal mechanisms that produce particular archaeological phenomena, they lack real-world context, and thus are less likely to present the researcher with new and unexpected information. They are also less likely to produce the range of features that might be present on archaeological hunting armatures. In other words, equifinality remains hard to address. At the same time, uncontrolled experiments come with their own problems. They struggle to isolate causal mechanisms and thus the mechanisms that produce a particular phenomenon may be less observable. Improved methods that utilize effective observational equipment and methods to carefully track affects in wound channels may help resolve this issue. The most effective results will come when realistic and controlled experiments are compared. This topic will consume Chapters 2-4 of this dissertation.

1.5.2 Methods used to distinguish hunting weapons on open air sites

Lithic armatures are usually all that remains of preindustrial hunting weapons on open-air sites and many ancient weapons did not employ such armatures. Distinguishing weapon systems from points alone has been a major challenge. Archaeologists have explored diverse methods to make the distinction between lances, javelins, atlatl darts, and arrows. Part of the issue lies in the degree of size and energy overlap that exists between the weaponry (Whittaker et al. 2017). Despite this, some clear patterns emerge within weapon systems in terms of their design and how they're used. It may never be possible to distinguish between systems with absolute certainty. However, to increase the degree of certainty will require more structured experimental approaches (Hutchings 2016).

1.5.2.1 Morphometrics

Of the approaches to identify projectile weaponry that will be discussed, morphometric approaches have been around the longest. A number of researchers have used morphometric attributes of projectile points to distinguish general categories of projectile systems (Ames et al. 2010; Bradbury 1998; Christenson 1986; Corliss 1972, 1980; Fenenga 1953; Hildebrandt and King 2012; Hughes 1998; Okumura and Araujo 2015; Patterson 1985; Shea 2006; Shott 1997; Sisk and Shea 2009, 2011; Thomas 1978, 1986). Initially, researchers attempted to use the weight of projectile tips alone to distinguish projecting modes, but by the 1940s archaeologists understood that weight alone is not a good discriminator of whether a point belongs on an arrow or a dart, since these projectiles can, to a point, be designed to accommodate a variety of tip weights and still maintain effective ballistics (Browne 1940; Christenson 1986; Fenenga 1953). Clearly, options exist to make functional projectiles within a broad range of tip weights (Christenson 1986; Ellis 1997).

Corliss (1972) measured neck widths of a large sample of points to determine if a bimodal pattern existed that would distinguish darts from arrows. Thomas (1978) added additional size attributes; length, maximum width, and thickness, and performed a discriminant-analysis. He collected a sample of arrow sizes from ethnographic collections and atlatl dart sizes primarily from archaeological finds. Unlike Corliss' study, Thomas looked for points that were clearly hafted to dart or arrow shafts. As a result, his archaeological sample of darts came predominately from the southwestern US where drier conditions enhance preservation. Thomas' metrics samples were broadened by Shott (1997), however, confidence intervals in blind tests did not increase dramatically. In Thomas' study 70 percent of dart points were successfully classified, whereas in Shott's study 76.9 percent were.

To calculate a projectile's ability to penetrate, Hughes (1998) introduced tip cross-sectional area (TCSA), which was subsequently used by Shea (2006) to distinguish weapon systems represented by African Middle Paleolithic stone points. Sisk and Shea (2009, 2011) later introduced tip cross-sectional perimeter (TCSP) as an improved metric for calculating penetration and thus point design efficiency. TCSA/P has since been used by a number of researchers for judging whether a point belonged to an arrow, an atlatl dart or a javelin (see Clarkson 2016).

My own tests on a hog carcass (Pettigrew 2015) found that the sample of TCSA/P measurements are too constrained, being based as they are on a limited sample of hafted archaeological darts and arrows and experimental javelins. Shea's (2006) sample of TCSA/P measurements for the various weapons systems came from Thomas (1978) and Shott's (1997) studies, and his measurements for spears were his own experimental spear point data. Hafted dart points in Thomas and Shott's studies come primarily out of Basketmaker deposits in the US

Southwest, where atlatl gear is of relatively small size. Darts of this size in the hog experiment often performed poorly, given that their kinetic energy was below the recommendation to hunt an animal of that size (Pettigrew 2015; Tomka 2013). According to Tomka (2013), the kinetic energy of replica Basketmaker darts from White Dog Cave in Arizona would be effective only on small game (<20.5 kg), suggesting that it is unlikely they would have been used to hunt animals larger than desert bighorn sheep, which are commonly depicted as pursued by hunters with atlatls and darts in Basketmaker rock art. However, Basketmaker darts were fitted with detachable foreshafts and there is usually a shoulder at the mainshaft juncture (Figure 1.2). It may be that the trend toward smaller and lighter corner notched projectile points in many parts of North America in the Late Archaic indicates a switch to hunting with powerful hunting poisons. However, as the next chapter will demonstrate, the data compiled by Tomka (2013) from recommendations for modern bowhunters may not adequately reflect the capacities of ancient projectile weapons to produce lethal wounds on larger prey.

When compared with penetration, TCSA/P measurements in the hog experiment failed to produce statistically significant results. Darts that were within the recommended range of kinetic energy to hunt an animal of that size, when fitted with points with TCSA/P values well into Shea's (2006) spear category, continued to fly and penetrate well. Clarkson (2016) also found TCSA/P to correlate poorly for shots with a calibrated crossbow into ballistics gelatin. However, given the controlled nature of both the target and shooting apparatus, penetration should have been far more consistent than it was. It is not clear what effect the bulky hafting method played in the results. Perhaps most importantly, Newman and Moore (2013) document dart points from Australia that fall well above Shea's dart category and even surpass the spear category. This is another instance where improved observations of realistic experiments on animal carcasses need to be paired with controlled experiments to better understand the effects of TCSA/P on projectile performance.

Ames and colleagues (2010) used a combination of TCSA/P recently to reclassify a number of point types from the Columbia Plateau from dart points to arrow points. Some of the points in their study occurred as early as 8500 BP. This is surprising, since most researchers agree that the bow did not initially appear in North America until around 2000 BP. This apparently spurred Hildebrandt and King (2012) to use what they call the dart-arrow index to resolve the situation. Hildebrandt and King (2002) deployed a simple approach, adding neck-width to maximum thickness to calculate the dart-arrow index, and compared this with a series of dates on a large sample of Great Basin projectile points to test its validity. This index has the advantage that fragmentary points where length is missing can still be classified if the necessary basal area is intact. This basal area is also minimally altered when broken or worn projectile points are rejuvenated, unlike other metrics such as tip weight and TCSA/P (Hildebrandt and King 2012:791). For a sample of over 1,000 Great Basin projectile points, the dart-arrow index successfully classifies them based on the classic chronology of bow and arrow introduction around 2,000 BP, with a bimodal distribution around a threshold of 11.8 mm of neck width. Stylistic attributes between points used by Great Basin cultures also do not affect this index.

Unfortunately, there is reason to doubt the broad applicability of the dart-arrow index, despite its apparent utility in the Great Basin. When the index is applied to the *N*=118 ethnographic arrows from Thomas' (1978) study, the result is an index value of 14.3 mm, on the dart side of the Great Basin index. Hildebrandt and King (2012) reason this, and other discrepancies in ethnographic collections, to be due to loss of traditional bow technology with colonial disruptions. The general trend is that points they have analyzed from ethnographic collections are often larger and more crude than archaeological arrow points.

This is an interesting point, but we cannot know from these discrepancies alone that larger, cruder arrow points do not fulfill their intended function. In other places in the world, very large arrow points are used by serious hunters. The most extreme examples are the heavy iron points on Papua New Guinea (PNG) arrows (Ashby 2008). These are used for hunting deer, crocodiles, pigs and small game. Rusa deer are stalked on open grasslands and frequently taken at >25 yards with the heavy, unfletched arrows and powerful palm-wood bows. Colonial interactions did change Papua New Guinea bow and arrow technology. Pre-WWII arrows were tipped with barbed wooden points and were much lighter. With the acquisition of iron rebar, PNG bowyers switched to heavy, forged steel points, and shaft dimensions were changed to match the spine of the arrows to the heavy points. This was not for selling arrows to tourist, but continuation of subsistence hunting practices. Post-WWII arrows are as much as 2.5 times heavier than pre-WWII arrows, and weigh up to 256 g. The heaviest arrows used in PNG are fitted with barbs and used to shoot crocodiles from close distance. Arrows fitted with cutting heads for hunting terrestrial game are in the 120 g range, which is still the size of many atlatl darts (Pettigrew 2015). The PNG arrow data adds to the data from Australian dart points used by Newman and Moore (2013) to critique morphometric indices.

Clearly morphometrics alone cannot be used to distinguish darts from arrows. Modern PNG arrows are as large and heavy as many atlatl darts but apparently effective for hunting. Their iron tips are similar to spear points used by San hunters. Atlatl darts can also be small and fairly light. There is a size overlap in projectile points that can and apparently do work on all three technologies for actual hunting. Hildebrandt and King (2012) claim their method works to demonstrate the introduction of the bow around 2000 BP. However, Erlandson and colleagues (2014) used the dart-arrow index to measure small, barbed points from Santa Rosa Island off the coast of California, which date to the terminal Pleistocene, 11,700 BP. They found that these points fell on the arrow side of Hildebrandt and King's (2012) 11.8 mm threshold. But rather than belonging to arrows, based on associated faunal remains they suggest these were used on atlatl propelled harpoons for hunting marine mammals, aquatic birds and catching fish.

1.5.2.2 Diagnostic Impact Fractures (DIFs)

Macroscopic impact damage on stone armatures is a productive way to identify armatures from other tools and can be performed by archaeologists in the field without the need for complex instruments. Unlike morphometrics, understanding how projectile points break when they impact various targets (for a good review see Dockall 1997) can only be approached experimentally, and this has been the focus of many projectile experiments (Appendix C). The first, and still among the most important, is Fischer and colleagues (1984) thorough series of realistic tests to document impact fractures. They shot arrows into carcasses, bones, vegetation, and performed "trampling" tests, dropping hammer stones and walking on stone tools, to attempt to account for equifinality in point breakage. They identified cone fractures and various types of bending fractures on projectile points.

Bending fractures result from slightly skewed impact or buckling of the armature under load, resulting in a snap across the width roughly parallel to the longitudinal axis of the point (Figure 1.5:c). *Spin-offs* occur on bending fractures when, having struck a hard target and snapped at a right angle across the blade, the projectile continues to drive the fractured surface into its own tip and the target, which produces flaking down the face of the point from the freshly broken surface (Figure 1.5:a). When spin-offs are small (Figure 1.5:c), this can result from impact as well as when points break from lateral pressure to the long axis, such as being stepped on. But when spin-offs are substantial to the degree that they produce a large flute down the length of the point, or large flakes running down the face and terminating in hinges as shown in Figure 1.5:a, this is most likely diagnostic of projectile impact. The most diagnostic impact fractures from Fischer and colleagues' (1984) experiment were bending fractures with substantial spin-offs occurring on both faces. This type of catastrophic damage is unlikely to occur from trampling events or flintknapping mistakes.

Fluting can also occur with *longitudinal* fractures; cone or bending initiating fractures from the tip resulting in flaking down one face (Figure 1.5:e). Sometimes flutes resulting from this type of break can be quite large, running nearly the entire length of the point. *Tip crushing* may also occur, resulting in a series of small step fractures initiating from the tip (Figure 1.5:d). When projectiles encounter hard targets along the margins of the armature, such as glancing off the edge of a rib during penetration into the thoracic cavity of a bison, this can produce abrasion that dulls the edge, as well as flaking along the face of the point initiating from the edge (Figure 1.5:d). This type of impact fracture can be challenging to distinguish from flintknapping or trampling events. Lastly, *lateral* or *burin-like* fractures produce fracture planes that run perpendicular to the width of the tool and generally propagate along one edge (Figure 1.5:b), producing a burin-like feature near the point of initiation. Lateral fractures may initiate from either the tip from direct contact with a hard target, or from the base when the armature is driven back into the notches of the shaft. These are generally considered diagnostic of impact.

These various types of impact fractures can occur singly or together on impacted armatures. Frequently in the carcass experiments to be described in the next chapter, corner and side notched dart and arrow points experienced bending fractures both at the tips and across the

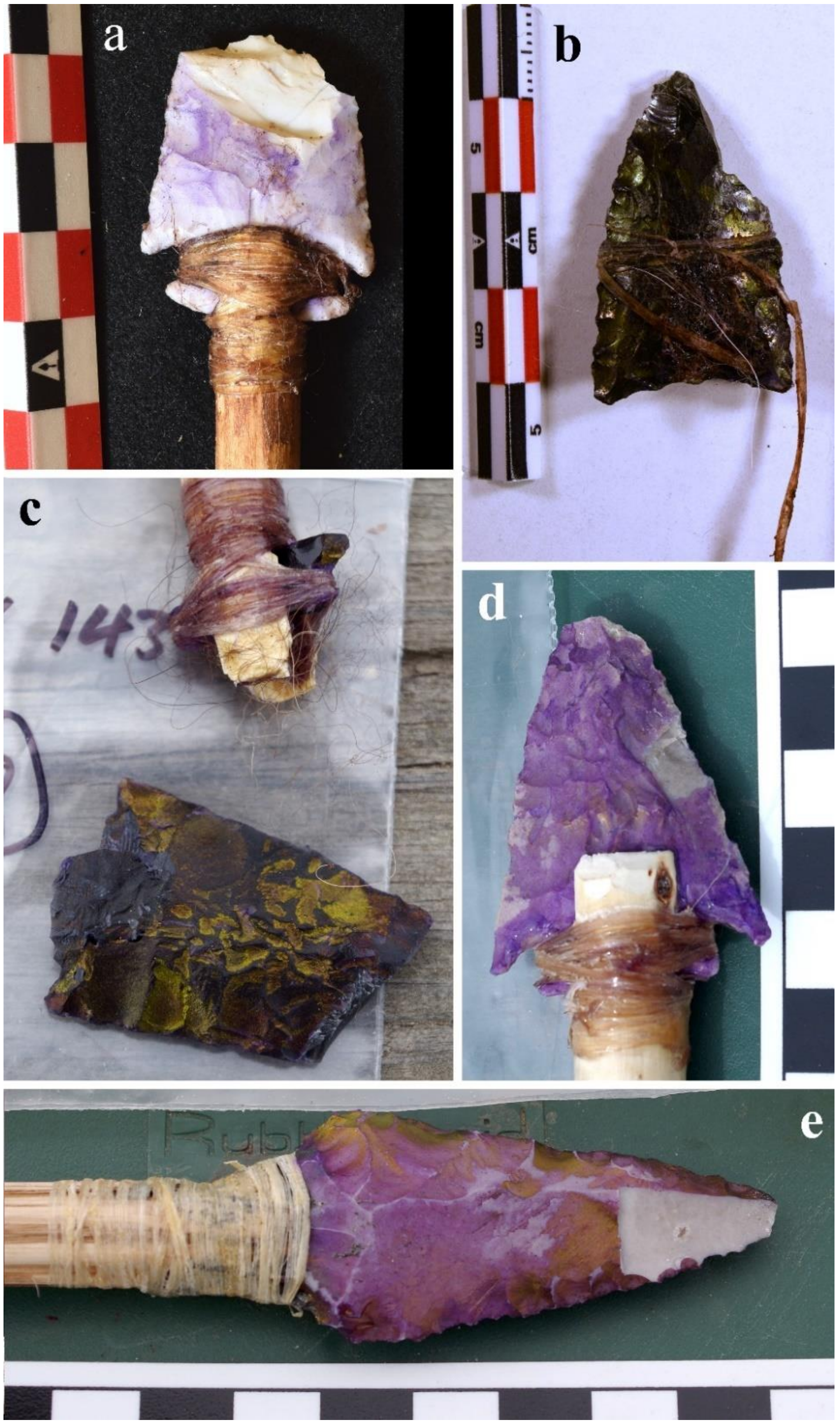


Figure 1.5. Typical examples of impact damage on experimental dart points that impacted bison bone (a, c-e) and an obsidian arrow point that impacted a goat scapula (b): a) bending fracture with substantial spin-off initiating from the right corner, b) lateral or burin-like fracture, c) bending fracture across the neck of a corner notched point along with bending fracture of the tip and mild spin-off, d) crushing of the tip as well as facial flaking and abrasion along one edge, e) longitudinal fracturing of the tip resulting in a small flute.

neck of the base between the notches Figure 1.5:c. This type of impact breakage could easily result in obliterated distal sections of points, midsections being left in the field, and basal sections being brought back to camp with the projectile shaft for retooling. Frequently in the experiments, notched points, or lanceolate points with concave bases experienced lateral fractures from the base that removed corners of the base as well as fracturing of the tip. Sometimes when this type of fracture occurs to the base of armatures that are hafted with a lot of sinew and mastic, the break may not be noticeable until the point is removed from the haft. Simultaneous fracturing to both the base and tip is common when armatures impact hard targets. Lateral fractures generally occur from impact but bending fractures to both bases and tips without substantial spin-off can occur from trampling events.

DIFs have a place in helping to distinguish projectile weaponry, but according to Hutchings (2016), more rigor is necessary for experiments to give definitive examples of the types of fractures that are truly diagnostic of projectile impact. Spin offs and other DIFs have been documented in low frequencies in knapping, retouch and trampling experiments (Fischer et al. 1984; Pargeter 2011; Sano 2009), thus many so called DIFs are not necessarily diagnostic markers of impact. DIFs, however, appear to be more frequent in projectile experiments, as well as at hunting sites, but it remains challenging to distinguish variation in DIFs between different modes of projection (Hutchings 2016). Many factors are involved in projectile impact. The frequency and specifics of recorded DIFs will depend on the material from which the points are made, the presence of hard materials in the landscape that a projectile might hit in the case of a miss, the size of the animal being hunted, and the velocity and mass of the projectile. Larger animals have heavier bones that provide larger and more resistive targets, and they also require projectiles with more kinetic energy to hunt effectively, both of which result in more substantial

DIFs. Although hunting small animals in rocky terrain may also produce substantial DIFs, since striking rocks often has catastrophic results.

The size of impact fractures is also a function of the the material of the point (Clarkson 2016; Iovita et al. 2016). Clarkson (2016) found that burin-like fractures (not recorded by Fischer and colleagues) are the least common type of DIF but the most diagnostic of impact, and can tell something about the nature of the projectile. Clarkson finds burin-like fractures to be most responsive to the mode of projection and resultant velocity and energy of impact. They occur with high energy impacts and are more frequent on soft materials like obsidian (Figure 1.5:b). When comparing across impacted points made on the same material, particularly large burin scars may indicate complex projecting systems. But what size to look for on a given material will require more experiments to find out. Both of these experiments (Clarkson 2016; Iovita et al. 2016) used controlled firing apparatuses to control for, among other things, angle of impact, and this has a result on the way fractures are formed (Iovita et al. 2016). Relative to stone, fewer experiments have been conducted with osseous armatures (see Appendix C). However, DIFs can also be identified on osseous armatures (for a review see Pétillon et al. 2016) and may be less responsive to breakage from post-depositional processes, and especially from manufacturing mistakes.

Clearly impact fractures will continue to play an important role in identifying projectile weaponry from stone and osseous armatures, but the critiques of Hutchings (2016) are derived from important and necessary observations. Namely, equifinality needs to be addressed, and methods of documenting raw material and observations of impacts to various materials need to be improved. To increase rigor in future experiments to identify DIFs, while addressing the equifinality of impact damage, it is not necessarily prudent to increase controls that remove variability. Realistic experiments with skillfully knapped, hafted, and delivered armatures that capture the many details of impact with effective observational tools can be highly beneficial in diagnosing impact damage on stone armatures.

1.5.2.3 Microwear

Like impact fractures, microwear on stone and osseous projectiles must be studied using a sample of experimental analogs. Microscopic wear on projectile points takes the form of polish and striae when projectiles impact hard objects (Albarello 1986; Crombé et al. 2001; Dockall 1997; Fischer et al. 1984; Geneste and Hugues 1990; Moss and Newcomer 1982). Unlike knife use, striae often occur at high points on the interior faces of stone points and should parallel the long axis of the points. These striations frequently can be found on the trailing edge of breaks, since striae are formed by micro particles coming off the broken section of the point itself. These abrasive microscopic particles are drug along fresh layers of silicate residues that adhere to the surface of the point and form polished areas on the microtopography.

Silicates from projectile impact or cutting tool use may also accumulate in a spot and form microcrystalline structures. As with striae, crystallization on the trailing edge of a microwear event have been used to infer direction of impact or tool use. However, striae and crystallization at the trailing edge of polish does not always follow the longitudinal axis of the point, as demonstrated in our hog experiment (Kay and Pettigrew, in press). Microwear often looked similar to knife use, perhaps due to the flexure of large dart shafts after impact, which moved the point around in the wound cavity in a “knife-like” way. Missed shots that resulted in impacts to ground, grass, rocks and wood also produced microwear that apparently exploded across the microtopography of the point at angles not in line with the direction of impact. Furthermore, there is yet to be any solid evidence that microscopic impact damage varies between projecting modes. One way it could vary is between shafts that penetrate completely through or most of the way into bodies (arrows), versus those that stop penetrating with a large section of the shaft projecting from the body (javelins and darts). The latter effect could produce more knife-like microwear when the shaft continues to vibrate after impact and bounce as the animal runs, whereas the former may produce striations that are primarily in line with the long axis.

Relative to microwear at impact areas, microwear of haft areas has been given little attention (Rots 2016). Hafting elements cover haft areas and prevent them from receiving the residues of impacted materials, while hafting elements can lay down their own residues, such as plant fiber from vegetable fiber hafting elements (twine) and mastics (Lombard et al. 2004; Rots 2016). This helps demonstrate that tools were hafted and gives some indication of how, but this alone does not demonstrate projectile use. Surprisingly, these residues may last in soil for thousands of years (Lombard et al. 2004). Hafting elements also form their own microwear polish, usually around the margins of the point base. Microwear from hafting is a neglected field of study that has potential to add to the approaches useful for identifying projectile points (Rots 2016).

1.5.2.4 Wallner lines and fracture wings

The final method to consider was introduced to projectile studies by Hutchings (2011, 2015; Sahle et al. 2013) from a method previously used to infer flintknapping methods. Wallner lines and fracture wings are products of microscopic ripple marks that intersect across a fracture surface. These are the products of longitudinal and distortional waves that travel across the fracture front, encountering local irregularities and forming ripples. Measuring the intersections provides an indication of the velocity of a loading event. Critically, this method can only be used on obsidian and potentially on very fine-grained crystalline materials. Hutchings' tests were performed with obsidian.

Hutchings (2011) found that loading rates of fractures separate javelins and lances from arrows and atlatl darts. Flinknapping and spear use creates fractures that indicate quasi-static or rapid loading, but only atlatl darts and arrows produce dynamic loading events. However, as discussed in section 1.5.1.1, in modeling dart impacts, Hutchings also relied on experimental dart velocities that were too high (Whittaker et al. 2017). Iovita and colleagues (2016) further tested this with a controlled experiment that launched replica Levallois points made in soda lime glass against synthetic polyurethane bones set in ballistics gelatin. They used an air gun to propel projectiles at different velocities and a weighted swinging contraption for controlled lance thrusts. Their fracture velocity confirmed that of Hutchings', however, they were not able to reach the high speeds of Hutching's dart values with their air gun. The result was that they did not record any fractures in the dynamic range, which according to Hutchings should characterize darts and arrows. Their maximum achieved velocity of 30 m/s is actually in the upper range of velocities achieved by a large sample of modern atlatlists (Whittaker et al. 2017), suggesting that their sample is more appropriate than Hutchings'. Like other methods to distinguish projectile weapons, the velocities of fracture propagation requires more evidence from carefully documented projectile experiments. On its own this method cannot produce definitive evidence of projectile systems where overlap occurs in velocities between weapon systems.

1.6 Discussion

Many scholars adhere to a narrative that follows a strict linear progression from simple to complex weapon development. In part, this is probably a remnant to the outdated Man the Hunter paradigm (see Iovita et al. 2016). Early hominids were once thought of as frequently battling large beasts, where increasingly sophisticated weapons were among the traits that allowed them to overcome a ferocious landscape and emerge as top predators. In reality, simple thrusting spears have remained among the most effective weapons for warding off large predators (Hitchcock and Bleed 1997).

In the Americas, some scholars think that the atlatl was quickly replaced following the introduction of the bow, as native hunters saw the latter as a clearly superior weapon (e.g. Hildebrandt and King 2012). In part, this derives from assumptions about the bow's superior range and rate of fire, although the latter has never been shown empirically to be true. History and archaeology provide compelling evidence that in fact the bow did not swiftly replace the atlatl in every or even most circumstances. Conquistadors encountered the atlatl in warfare in Mesoamerica as well as at the mouth of the Mississippi. In the 17th century in Brazil, the Dutch recruited frightening Tarairiu warriors who used only atlatls for projectile weapons as guerrillas against the Portuguese (Prins 2010).

In various locations in North America, including the Great Plains (Hoard and Banks 2006) and eastern woodland (Nassaney and Pyle 1999) the two weapon systems seem to have been in use simultaneously for hundreds of years. A depiction of an atlatl alongside bows and arrows can be found on an engraved shell from the 15th century AD site of Spiro in Oklahoma (Fields 2005) and preserved wooden atlatls found in water logged deposits in Florida also suggest the survival of the atlatl after the bow (Whittaker 2011). The bow may have been immediately seen as superior and adopted by some groups, but that was not universally the case.

This is true in other parts of the world as well. The bow and arrow was used in Papua New Guinea alongside the atlatl. The bow was also used on Torres Strait islands, and Captain Cook saw it in use on an island close to mainland Australia near Cape York (Davidson 1936).

Spears were traded to Torres Strait islands from the mainland, but the bow was not used on mainland Australia. Like the atlatl, javelins and lances also survived after the introduction of the bow. In Tasmania and various parts of mainland Australia javelins were still in use but the atlatl was missing. The bow and arrow was known in Polynesia, but saw little use, since javelins were preferred for both hunting and warfare (Tregear 1892). Why this would be the case may have something to do with social value for developing certain skills (Cundy 1989:18).

The case of San hunting in southern Africa demonstrates the utility of traditional technology for hunting until a series of changes makes hunting more challenging. These changes include edgier prey from increased rifle hunting, equestrian and motorized transport, and the spread of large-scale agriculture (Hitchcock and Bleed 1997). Most hunters might switch to rifles but this is not economically feasible, since traditional hunters are among the poorest members of the introduced market economy (Hitchcock 2019; Hitchcock et al. 2020). A switch from bows to spears is more feasible for complex reasons in the Kalahari. Younger hunters find equestrian spear hunting more attractive and spears are also effective when hunting with dogs. Importantly, game laws in southern Africa have led to persecution of traditional hunters, but hunters are less likely to be prosecuted when hunting at night or when carrying spears. However, hunting from blinds at night can be highly effective in some locations in southern Africa and is more likely to lead to retrievable prey in areas with a lot of large predators and scavengers.

The introduction of the bow has been argued to be a product of interpersonal conflict. This may be the reason for the transition to arrow points in the northern Great Plains (Walde 2013). It has even been suggested that the introduction of the bow in the Americas made social justice more enforceable within communities and precipitated the development of social hierarchies in complex societies (Blitz and Porth 2013). In many cases, it would probably be advantageous to have a bow in a fight, but the use of the atlatl for large scale warfare in many parts of the Americas, the javelin for warfare in Polynesia, and the complete disregard for such weapons among societies like the Zulus and Spartans, demonstrates the difficulty of broadly applying this theory as well.

Smaller prey should be easier to hunt with smaller and faster projectiles. Arrows fire more consistently so they are easier to aim and reach their target more quickly. Smaller, faster projectiles are also better suited to targets with smaller inertia (Anderson et al. 2016). Bows are therefore better suited to swift and small prey. Although atlatls were used for small game, as demonstrated by wood, bone and antler blunts for Basketmaker darts (Pepper 1902), larger, heavier atlatl darts and spears may be better suited to large animals in open environments when group tactics are used (Tomka 2013).

In any instance where new weapon technology is introduced, whether it is adopted or not depends on a variety of factors. These factors may have to do with complex social norms, the type of hunting methods undertaken, the type of prey, and resource availability. There must be a limit to which prey becomes less edgy to the extent that simpler weaponry can be successfully employed. Hunters and wildlife biologists have recognized the pronounced degree to which deer change their behavior a week into rifle season (Little et al. 2016; Rodgers et al. 2021). Changes in human hunting methods must impact the behavior of our prey (see Chapter 6).

Archaeologists have dedicated substantial effort to identifying the introduction of complex projectile weaponry in the archaeological record. Complex weapons are included in the material signatures of the onset of “modern behavior” in *H. sapiens*. But several problems have arisen in our ability to distinguish the mode of projection from stone projectile armatures alone. These problems are due primarily to the overlap in size and energy between javelins, atlatl darts, and arrows. The search for a fool-proof method will likely continue without resolution. At best, any method to identify the mode of projection will be a statistical argument based on likelihood. This search is also driven by Western biases of technological progress that have variable application to reality. Both archaeological and ethnographic evidence demonstrate that the introduction of new weaponry is often a gradual process. In some cases, new weaponry is not adopted for a significant period of time. Little has been done to consider prey response to human predatory behavior relative to specific weapon technologies and resulting changes in hunter success rates. Understanding hunting weaponry is an essential step toward understanding human behavior and ecology in hunting societies. Archaeologists who theorize about behavioral complexity should look more closely at the forces that drive the uptake of new technology in any given situation, before uncritically including complex weaponry in a conceptual framework of modernity.

CHAPTER 2. ARCHAIC ATLATL HUNTING EFFICACY AND VALIDITY IN ARCHAEOLOGICAL WEAPON EXPERIMENTS

2.1 Introduction

Weapons are among the most frequently studied residues of ancient material culture, in part because stone armatures are among the few traces of ancient hunting and foraging societies that withstand the elements. Weapon improvements are listed among the material signatures of the Upper Paleolithic "behavioral revolution" (Churchill and Rhodes 2009; Sisk and Shea 2011). Despite potential problems with the latter (Milks 2020; Villa and Roebroeks 2014), it is clear that weapons were important to ancient human livelihoods, in terms of both defense and resource acquisition. But despite decades of research (e.g. Christenson 1986; Cotterell and Kamminga 1990; Friis-Hansen 1990; Hughes 1998) some aspects of effective hunting projectiles are not well-characterized or are mis-characterized. Experimental archaeology offers an accessible and necessary way to test the efficacy of ancient hunting weaponry as represented by archaeological finds.

This project set out to test the terminal ballistics (mechanics of target impact and penetration) of replica atlatls and darts from the southwestern US, such as the complete examples from White Dog Cave (hereafter WDC) in Arizona (Figure 2.1) (Guernsey and Kidder 1921; Pettigrew and Garnett 2015). These weapons are fairly small and light when compared with atlatl darts in other parts of the world (e.g. Palter 1977). When analyzed against recommendations for modern bowhunting kinetic energy and momentum (Table 2.1) (Tomka 2013) Basketmaker darts like those from WDC do not meet the requirements for hunting large game such as American bison (*Bison bison*) (Pettigrew 2015; Whittaker et al. 2017). But preserved atlatl artifacts like the Basketmaker

Figure 2.1. A replica of the White Dog Cave (WDC) atlatl and dart system photographed near its place of origin: Marsh Pass, AZ. Photograph by Justin Garnett.

type are found throughout the intermountain west and across the Great Plains in Missouri and Arkansas (Pettigrew 2018). A transition to smaller, corner notched points across even wider space during the Late Archaic (e.g. Christenson 1986), even occurring at bison kill sites, is likely indicative of the popularity of this particular iteration of the atlatl and dart weapon system (Pettigrew 2018). Consequently, the archaeological record challenges our assumptions (Chapman and Wylie 2016), providing cause to question the applicability of modern hunting arrow kinetic energy and momentum to ancient hunting, and necessitates a realistic comparison of the hunting efficacy of archaeological dart and arrow terminal ballistics. This is the first objective of this study.

The terminal ballistics of javelins, darts and arrows is situated in the complex interplay of mass, velocity, shaft flexibility, hafting and shafting transitions, size and sharpness of the armature, and the composition of the target. An accurate assessment of the hunting efficacy of Basketmaker atlatls and darts requires situating those weapons in a realistic framework of ancient hunting weapon terminal ballistics. This article describes realistic experiments designed to *explore* this broader framework. The ability to address multiple hypotheses and derive new insights is an inherent aspect of such an approach, while statistical power from repetition is more limited. The results show that Basketmaker darts can kill big game when heavy bone is not encountered. But the results are not confined to this topic.

Table 2.1. Average mass and velocity of primary experimental projectiles compared against recommended values for bowhunting, with additional values for Frison’s (1989) heavy experimental elephant darts. Velocity is estimated for the latter. WDC and CDC are replica Basketmaker darts. See Supplementary Materials Table 1 for further details of mainshafts.

	Recommended arrow KE and P by game size (Tomka 2013)							
	Small Game <20.5 kg KE=<34 J P=<1.1 kg-m/s				*Medium Game* 33-136 kg KE=34-56 J P=1.1-1.7 kg-m/s	Large Game 73-300 kg KE=56-88 J P=1.7-2.6 kg-m/s		*Very Large Game* 227-998 kg KE=>88 J P=>2.6 kg-m/s
Experimental Projectiles	Cane arrows	WDC (#1)	CDC (#8)	Light cane (#4)	Medium cane (#5)	Heavy cane (#7)	Heavy ash (#3)	Clovis dart (Frison 1989)
Mass (g)	26	88	98	104	130	200	213	465
V (m/s)	40	24	24.2	24.2	23.2	24.5	25.3	20
KE (J)	21	25	29	30	35	60	68	93
P (kg-m/s)	1.0	2.1	2.4	2.5	3.0	4.9	5.4	9.3

In most situations archaeologists have only stone armatures from which to draw insights about ancient hunters. Recent research tends to emphasize cross-sectional metrics of armatures to distinguish between weapon technologies and study their efficacy (Borrell and Štefanisko 2016; Eren, Meltzer, et al. 2021; Eren, Story, et al. 2020; Lombard 2020, 2021; Mika et al. 2020a; Sahle et al. 2013; Shea 2006, 2009; Shea and Sisk 2010; Sisk and Shea 2009, 2011; Sitton et al. 2020; Villa and Lenoir 2006; Villa and Soriano 2010; Wilkins et al. 2012). This study will demonstrate that these measures do not perform well as isolated indicators of efficacy for variable darts and arrows that penetrate variable prey. This is due to the often-unrecognized variability that occurs *within* weapon technologies. Kinetic energy, armature sharpness, and ratios of armature cross section to shaft size (Friis-Hansen 1990), are the most significant variables in these data affecting the penetrating efficacy of darts and arrows.

The second objective of this paper is to present a case study for one type of ancient weapon experiment, the exploratory realistic approach, with improved observational methods to increase validity (control over experimental variables and relevance to real-world application). Ancient weapon experiments fall along a spectrum from internal to external validity corresponding to a spectrum from control to realism (Eren et al. 2016). Controlled approaches generate artificially reduced (laboratory) contexts that isolate phenomena of interest to ensure causal mechanisms are not affected by extraneous variables. As a result, they have greater internal validity: the experiment is stable and reproducible. But controlled contexts are further removed from the complex variability of the "real world", so there is no guarantee the observed phenomena would not manifest differently outside the experiment.

Realistic approaches solve this by reproducing contexts that are closer to those the researcher is interested in. Consequently, realistic approaches meet the requirements for external validity: the variables being measured are more likely representative of variables occurring in the real world. This is especially pertinent in experimental archaeology, where past tools were not made and used in laboratory contexts (Bamforth 2010; Keeley 1980). But realistic approaches have trouble isolating causal relations: the cause of a phenomenon is challenging to associate with a particular variable when many variables are kept in play. Validity of both types is generally achieved when we compare realistic and controlled experiments (Lycett and Eren 2013; Pettigrew et al. 2015).

Controlled weapons experiments are defined here as using artificial firing mechanisms that deliver test weapons with consistent force into consistent target media, such as ballistics gelatin. In contrast, realistic experiments deploy real human users of replica or reproduction weapons and realistic target media. In practice, though, weapons experiments do not fit precisely into these categories. Their design is dependent on the goals of the experiment, hindering comparability between experiments. As with validity, the differences between control and realism should be thought of as a spectrum. Some level of control and loss of realism is found even in the ideal realistic experiment, such as in the use of a consistent shooting distance or a recently deceased animal carcass, the latter showing some physiological changes from live prey. And while controlled approaches are more abstracted from the processes that produce the archaeological record, they do not always succeed in fully isolating phenomena or achieving reproducibility (Cartwright 1999; Mets 2012; Müürsepp 2012; Prigogine 1997).

Increasingly, scientists in some fields are turning towards non-repeatable exploratory methods that use "wide" (also known as "high-throughput") instruments, allowing the simultaneous measurement of many variables occurring in complex contexts (Franklin 2005; Müürsepp 2012). Such experiments are more flexible, more open to unexpected outcomes, and less constrained by narrow instrumentation that is designed to address a single theory-driven question (Steinle 1997).

High-throughput instruments have revolutionized fields such as biology, being central in sequencing the human genome. For experimental archaeology, we can think of the ability to simultaneously test multiple hypotheses, study additional variables, and address the issue of equifinality: the possibility that multiple past behaviors led to the phenomena of interest. Frequently, controlled experiments are applied to fundamental questions regarding the *essential* *natures* of weapon systems, and how to distinguish between weapon technologies. In section 2.4 I provide some examples of how this has led to problematic results for archaeological weapons studies. I should stress that my goal is not to critique all controlled experiments. Controlled approaches remain important methods to efficiently test specific components of a tool or its application and to validate findings from realistic experiments. But I argue that the general forms and functions of variable tools and the variable contexts of their application are better approached first using exploratory methods.

Readers resistant to these ideas will want to argue that exploratory experiments can tell us very little about ancient hunting weapons due to the variability kept in play. The literature promoting exploratory studies, and other non-reductivist strategies to explore causation, suggests that with improved observational tools and computational methods the many variables in realistic contexts can be isolated in post-processing, although this is not without challenges in designing experiments to capture variables and learning effective statistical procedures (Cartwright 1999; Franklin 2005; Spirtes et al. 1993; Steinle 1997). In the following I test the feasibility of such an approach for ancient weapon research. Fortunately, we archaeologists do not require anything so complex or expensive for our "wide instrumentation" as in other fields.

2.2 Methods

In 2008 with aid from staff of the Arkansas Archaeological Survey, I carried out a realistic experiment using atlatls and darts on a cow carcass that died of natural causes for my honors thesis. In 2015 myself and three colleagues conducted a similar experiment on a fresh ~100 kg hog carcass for my Master's thesis, but with vastly improved methods (Pettigrew 2015). Since then, I have carried out two projectile experiments on goat carcasses (hereafter goat1 [38 kg] and goat2 [40 kg]) in winter of 2019-2020, and one on a 23-year-old ~450 kg female bison carcass in summer of 2020. These latter four animals were put down humanely by the ranchers immediately prior to the experiments. Each experiment improved on the previous ones but also brought new and unexpected challenges

2.2.1 Experimental Design

To arrive at a proper comparison of penetration across darts and arrows, it was necessary to capture their velocities on impact. I also recognized that it was necessary to track darts as they rotate, spin and oscillate through air and flex on impact (Pettigrew et al. 2015). If this could be done, it would be possible to track the orientation of the projectile point during penetration and tie it to damaged bone. All these goals can be accomplished using slow motion video and markings on shafts. Careful observation allows the near reconstruction of an impact event, where ballistic information, use-wear, hunting lesions and various aspects of performance are captured simultaneously.

Given this flexibility, I decided to test both darts and arrows with multiple armature types and hafting arrangements. Imposing controls by holding variables constant, such as armature and hafting design, could produce misleading results. This is in line with the *outcome driven* approach for testing hunting arrows described by Ashby (2005a). When we study ancient weaponry, we are ultimately trying to understand the tendencies and capacities of weapons to perform within variable contexts (Ashby 2005a; Cartwright 1999; Rosenberg 2012). However, a result of drawing an experiment out in this fashion is reduction of statistical power, since not only are carcasses variable, but the instances of each weapon type being fired are reduced. The results are immediately more useful for qualitative, rather than quantitative analysis, but with future repetition of this or comparable protocols the latter can also be achieved.

2.2.1.1 Experimental arsenal

The projectile weapons were either modeled after artifact types (reproductions) or were true replicas of individual artifacts (Whittaker 1996). Most preserved prehistoric atlatls and darts in North America come from the arid Southwest, although artifacts found under Ozark bluffs were also replicated. These artifacts and attempts to replicate them have been described in detail elsewhere (http://basketmakeratlatl.com/) (Guernsey and Kidder 1921; LaRue 2010; Pettigrew 2015, 2018; Pettigrew and Garnett 2015) so I will not dwell on them. Further details can be found in the supplementary materials attached to this article.

The experimental arsenal included three bows based closely on southeastern (Catawba and Cherokee) forms. Sixteen projectile mainshafts included nine darts and seven arrows constructed of river cane (*Arundinaria gigantea*), coyote willow (*Salix exigua*), and green ash (*Fraxinus pennsylvanica*). Foreshafts were attached into sockets in the mainshafts supported by a whipping. The experiments deployed 129 knapped armatures, mostly donated by flintknappers (see Acknowledgements), that were dipped in methyl violet dye to facilitate observing damage from impact (Kay 1996). All armatures were thoroughly weighed and measured. Detailed photographs were taken before and after dying and again after hafting. Most archaeological notched armatures belonging to the small Late Archaic weapons kit were hafted solely with hide glue and sinew (Cosgrove 1947; Frison 1965) and some from the Ozarks with bark bindings (Pettigrew 2018), while I assume stemmed or lanceolate points were usually hafted with additional glue or mastic. The experimental armatures were hafted following these procedures. Darts were launched with multiple atlatls. Those used with Basketmaker darts were replicas of Basketmaker atlatls from the Southwest. Others were personal types that were familiar to the experimenters.

2.2.1.2 Photogrammetry and fluid dynamics

For goat2 and the bison, hafted armatures were photographed for photogrammetry, allowing detailed measurements of armature cross sectional area and perimeter, as well as modeling drag using computational fluid dynamics (CFD). Photogrammetry models were meshed in Agisoft Metashape, and cleaned, scaled, solidified, and aligned to axes in Meshmixer. To allow the necessary length of the computational domain behind the modeled body for simulating flow, the armatures were cut off directly behind the hafts and straight tubes 5 times the length of the hafted armature were attached in Meshmixer to mimic the trailing shaft. The models with consistent "false shafts" were imported into SimScale, where simulations deployed a Newtonian laminar flow with density and viscosity values from porcine muscle (ρ=1060kg/m^3, μ=1.26Pa·s) (Kneubuehl 2011; Urban et al. 2009). As will be seen, the CFD analysis does not provide a significant component of the ballistic results and need not be considered in further detail in the body of this paper. For a fuller description of the photogrammetry and CFD methods see the supplementary materials.

2.2.1.3 Experimenters as analogs for past users

Six experimenters launched darts at carcasses (four at the hog, two at goat 1, three at goat2 and five at the bison). As recommended by Milks (2019) details such as stature, age, and years of experience are provided in the supplementary materials. Additional experimenters helped with filming, record keeping, and butchering (Figure 2.2; see Acknowledgments). Having multiple shooters helps reduce fatigue, which causes results to suffer. Atlatlists are also trained on different variations of the weapon. Some of the experimenters (Dust and Gover) could launch heavy darts with accuracy and force, while others (Whittaker, Garnett, Hashman and myself) were practiced in lighter weaponry.

It goes without saying that sufficient strength and skill is necessary in realistic studies of weapon performance (Milks 2019). The atlatlists in these experiments have extensive training and could direct shots straight at the target with comparable velocity to a larger sample of competitors using a variety of atlatl and dart equipment (Whittaker et al. 2017). A common complaint of realistic experiments is that modern people cannot regain the skill of ancient users. I agree with others (Longman et al. 2020; Milks 2019, 2020) that with sufficient practice, modern people can learn to use tools designed by and for our species, providing adequate (if imperfect) analogs for past use.

Figure 2.2. The general layout of a carcass experiment. At least 3 participants are needed: 1) shooter and flight camera operator, 2) photographer and recorder, and 3) velocity camera operator who also assists with measuring penetration and placing shot markers. More hands speed up the process and ensure better record keeping. Photograph by John Whittaker.

Skill and fitness are challenging variables to measure (see Milks 2019). To arrive at a more rigorous understanding of skill with the atlatl, it is necessary to test large numbers of atlatlists using a variety of equipment and compare their performance with records of Indigenous use. In terms of velocity we compare favorably with ethnographic records (Cundy 1989; Whittaker et al. 2017). Even atlatlists in Whittaker and colleagues' (2017) records who were relatively new to the weapon could throw darts with comparable velocity to more experienced users. Accuracy is much harder to master than powerful throws. Undoubtedly, ancient people who relied on the weapon for their survival were more accurate than most modern atlatlists, although data from Australia provide some grounds to question this (Cundy 1989). For the carcass experiments, accuracy was necessary to direct shots at the target, but misses into natural substrates still produce useful samples (Pétillon et al. 2011).

2.2.1.4 Carcasses (and other targets) as analogs for living prey

Experimenters are also faced with the ethics of using animal carcasses. All animals (except the cow that died of natural cause) were put down humanely by the ranchers immediately prior to the experiment. This negated the need for approval through an Institutional Animal Care and Use Committee. The experiments took place when the carcasses were fresh and they were butchered afterwards with stone tools. Butchering was filmed and the skeletons were cleaned for analysis. Even after experiments lasting over five hours and in warm weather, the meat was perfectly salvageable in every case. Surprisingly little meat was lost around wound cavities. In hunting contexts, hemorrhaging occurs around wounds and can ruin significant portions of meat, but this does not occur after the heart has stopped.

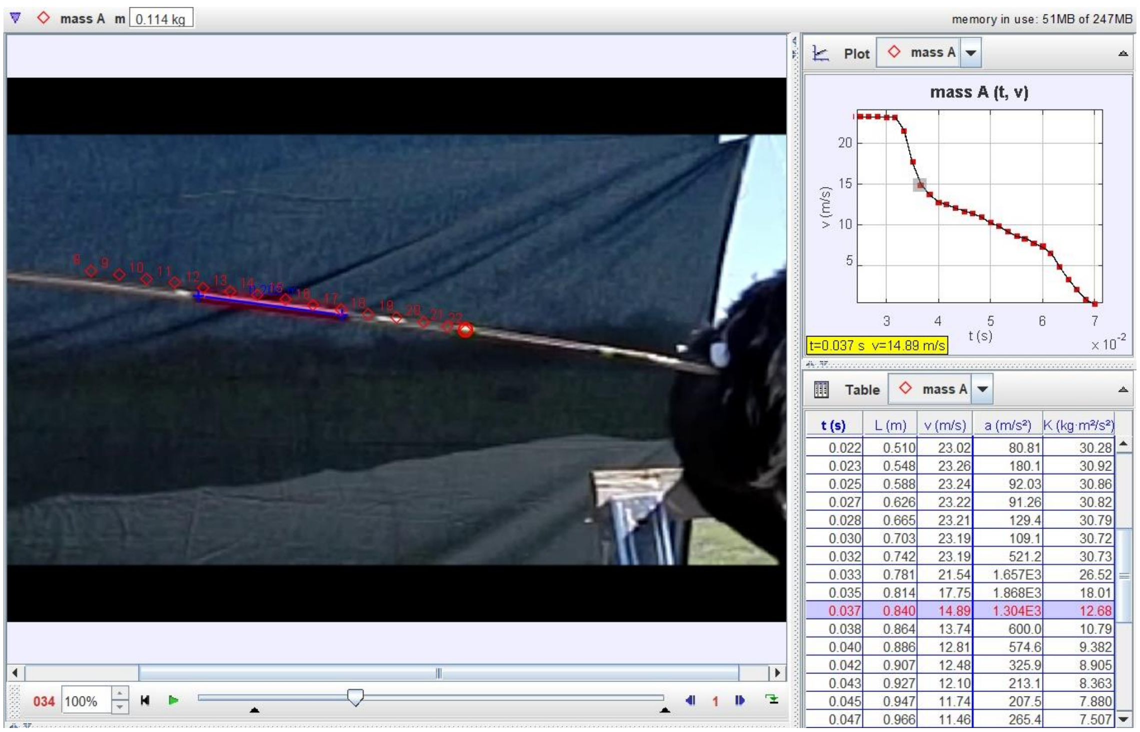
It is essential that carcasses are fresh for proper testing of weapon performance (Ashby 2005a; Kneubuehl 2011:157). Fresh carcasses are imperfect analogs for living animals, but while gelatin is used internationally as a medium to mimic firearm terminal ballistics in soft tissues (Kneubuehl 2011), several studies have shown that it is an inadequate analog for darts and arrows penetrating bodies (Ashby 2005a; Gaillard et al. 2016; Karger et al. 1998; Key et al. 2018). The most thorough of these is the experiment carried out by Karger and colleagues (1998), which demonstrated that neither 10% ballistics gelatin nor ballistics soap provide scalable simulants to biological skin and underlying tissue when arrows and crossbow bolts with cutting armatures are the objects of study. These projectiles always penetrated deeper through tissue than through simulants, while the opposite was the case for duller but smaller non-cutting tips with less surface area (e.g. target field points). Potter's clay has been used extensively in recent tests at Kent State University as a target simulant for flesh (Bebber and Eren 2018; Eren, Story, et al. 2020; Key et al. 2018; Mika et al. 2020b; Mullen et al. 2021; Sitton et al. 2020), however, an experiment performed at Kent State demonstrated disparate fracture mechanics between meat and clay when utility blades were pressed straight down into the materials. Arrows fitted with a ground stone armature and a steel field point were also shot into meat and clay, demonstrating deeper penetration of the field point in clay but comparable penetration in meat and clay for the stone point (Key et al. 2018). But the effects of sharper armature edges remains unclear from this experiment. Research in knife stab wound forensics has demonstrated that clay does not capture the capabilities of sharper knife tips to meet significantly less resistance when penetrating skin and underlying tissue of cadavers. In fact, completely blunt tips could experience less resistance than sharper ones when penetrating clay (Ankersen et al. 1998). The use of clay for studying the efficacy of variable piercing and cutting armature morphologies to penetrate bodies is therefore questionable.

For tools that cut, such as knives, darts, and arrows, fresh animal carcasses are generall accepted as providing far better analogs to living bodies than artificial mediums like gelatin or skin simulants (Fenton et al. 2020; Karger et al. 1998). The data from this study and another experiment (Wood and Fitzhugh 2018) did not reveal noticeable changes in penetration into carcasses over 3 or 4 hours after death, but there has been concern that physiological changes could cause "erroneous" results for hunting arrow penetration after only a few minutes (Ashby 2005a). Research in firearm terminal ballistics have extensively used both live (unconscious) and recently deceased animal carcasses, although such experiments are less common in recent years due to ethical concerns and the difficulty of comparing human and animal flesh (Humphrey and Kumaratilake 2016). For ethical reasons, medical research that requires the fracturing of skin is performed on in vitro samples. Skin cells in in vitro samples remain living for up to 24 hours after death, or 48 hours if the cadaver is placed in cold storage within 6 hours of death (Fenton et al. 2020). Specifically how differences between living and recently deceased animals affect the penetration of low-velocity cutting projectiles requires further research, but this will be challenging without a medical background and given ethical concerns.

For logistical reasons I found it best to use domesticated animals where the timing of death and the location of the experiment can be carefully controlled. This required ranchers who were willing to allow an experiment on their land. An important concern is how to support the carcass. The hog and goat2 were laid on a board across sawhorses with ropes holding their legs (see Pettigrew 2015). This created a solid target at a good height for the shooters, but for goat2 the belly area was noticeably compressed. Goat1 was suspended between two poles, but this had the surprising effect of causing several darts to bounce off as the carcass flexed and swung on impact. Many prior experiments have used suspended carcasses but the inertia and rigidity of the carcass is a concern. The bison was laying on all fours with a board propping up the back to keep it upright, which presented a more realistic target than the other two modes. Shots in the past sometimes occurred on bison that were laying down, having been driven into arroyos or over cliffs.

2.2.2 Carcass experiment protocol

The experimental protocol uses two high speed video cameras, a “flight camera” placed slightly in front and to the side of the shooter looking towards the carcass and a “velocity camera” set near the carcass perpendicular to the trajectory of the projectile (Figure 2.2). A backdrop opposite the velocity camera assists tracking the projectile using the Tracker video analysis program (Figure 2.3) (https://physlets.org/tracker//).



t (s)	L (m)	v (m/s)	a (m/s²)	K (kg·m²/s²)
0.022	0.510	23.02	80.81	30.28
0.023	0.548	23.26	180.1	30.92
0.025	0.588	23.24	92.03	30.86
0.027	0.626	23.22	91.26	30.82
0.028	0.665	23.21	129.4	30.79
0.030	0.703	23.19	109.1	30.72
0.032	0.742	23.19	521.2	30.73
0.033	0.781	21.54	1.657E3	26.52
0.035	0.814	17.75	1.868E3	18.01
0.037	0.840	14.89	1.304E3	12.68
0.038	0.864	13.74	600.0	10.79
0.040	0.886	12.81	574.6	9.382
0.042	0.907	12.48	325.9	8.905
0.043	0.927	12.10	213.1	8.363
0.045	0.947	11.74	207.5	7.880
0.047	0.966	11.46	265.4	7.507

Figure 2.3. A screen clipping of Tracker during analysis of a dart penetrating goat2. Tabulated velocity is averaged from several values prior to penetration. Initial acceleration for this shot is averaged from the two values provided at times 0.033 and 0.035. Beginning deceleration at 0.032 is less rapid, because the measure began prior to the point encountering skin.

For the hog test, a Casio EX-F1 was used as the flight camera and a Casio EX-ZR1000 as the velocity camera. For subsequent experiments the EX-F1 was transitioned to the role of velocity camera and a Chronos 1.4 became the flight camera. The EX-F1 is capable of filming at 600 frames/sec and 432x192 pixel resolution, which provides better video for velocity analysis than the EX-ZR1000 at 240 frames/sec. Darts are easily tracked with a solid backdrop and clear markings on the shafts, while arrows are scaled to the length of the shaft and the nock or tip is tracked across the backdrop. The Chronos is a powerful camera that is more than adequate for projectile experiments as either a velocity or flight camera, although the EX-F1 is more compact and easier to operate, which can speed up an experiment and reduce operator error.

High-speed cameras are finicky instruments that function best in good lighting. Clouds and shadows can necessitate slower shutter speed and reduce clarity, so it is best to choose a position for the carcass and throwing lane where sunlight will illuminate the projectile. More powerful cameras such as the Chronos still provide good video in less-than-ideal lighting.

To facilitate tracking the projectile with both cameras, the shafts are marked with various colors of reflective and electrical tape. The distal ends of the tape lie under the socket whipping to reduce friction during penetration. At the socket end, a band of red tape provides an index matched with a red mark on the foreshaft, which together with thorough photographs of the foreshafts taken prior to the experiment and good flight video allows the orientation of the armature to be tracked as it penetrates. Multicolored fletchings also facilitate tracking armature orientation, which can change during penetration. White or reflective tape bordered by black at the socket provide points to track for velocity. Additional markings near the center of the shafts provide a scale for the calibration of the velocity video and extra points to track during penetration.

Experiments that use a scale set along the planned flight path of the projectile can introduce substantial error when the projectile deviates from the path (Whittaker et al. 2017). For this reason, the scale is placed on the projectile itself. This can introduce error if the scale is measured when the projectile is at a skewed angle relative to the velocity camera. A small offset does not significantly affect the results, which is apparent when making subtle alterations to the scale in Tracker. But this needs to be accounted for as much as possible. This can be done by assessing the orientation of the projectile shaft using the flight camera and timing the measurement in Tracker. In a few instances when the projectile shaft was never perpendicular to the velocity camera the results suffered. Multiple points to track at 20 cm intervals along the shaft and clear video frames provide multiple opportunities for setting the scale before or as the projectile penetrates. Some error is expected in video analysis, but this is true of other devices as well (Eren, Romans, et al. 2020; Whittaker et al. 2017).

Overall, high-speed video is a powerful tool for tracking projectile velocity. Unlike radar or a chronograph, velocity can be calculated right up to the point when the armature encounters the target. Some error is expected with any instrument. Chronographs may not function properly in changing light or give consistent readings (Eren, Bebber, et al. 2021; Eren, Romans, et al. 2020) and radar guns do not always capture the projectile's flight (Whittaker et al. 2017). In comparison to these instruments, the error in high-speed video analysis is often more apparent and can be controlled for by adjusting the setup. Deceleration can also be calculated over the penetration event.

The range from shooter to carcass in these experiments was 10-12 m, which fits well with ethnographic accounts of atlatl and bow hunting distances (Cattelain 1997; Cundy 1989). During the experiment, each shot is recorded on a shot record sheet (Pettigrew 2015:Appendix B) and photographs are taken of the shot placement before retracting the projectile. The shot number is written on a shot marker composed of a bamboo skewer with a masking tape flag that is trimmed and inserted into the wound. If any visible damage occurs to the armature, it is photographed before being used again, or it is retired. Many armatures were fired multiple times and retired when significant damage occurred or because they became loose in the haft. Photographs are taken of the placement of each shot, although analyzing the flight videos sequentially and marking shot placement on a screen capture from the video is the best way to carefully track the position of each shot and tie shots to damaged bone.

The large amount of data produced by the experiments was incorporated into a Microsoft Access database and analyzed in JMP statistical analysis software. The shot data used in the statistical analysis can be found in the supplementary materials.

2.2.3 Dart and Arrow Terminal Ballistics

Before we can discuss dart and arrow terminal ballistics it is necessary to introduce some terms and conditions. Effective projectiles have sufficient velocity (**v**) and mass (**m**), which are used to calculate kinetic energy (**KE**=$1/2m*v^2$) and momentum (**P**=m*v). Ancient weapon researchers question whether **P** or **KE** better predicts arrow, dart and spear penetration (Ashby 2005a; Tomka 2013; Whittaker et al. 2017). In classical mechanics *energy* is synonymous with *work* (**W**), both measured in Joules (J). Penetration into solid media results in the creation of new surface areas within the material (Atkins 2009), which takes **W** to accomplish (Anderson et al. 2016; Kneubuehl 2011). However, when a projectile encounters a target, it *decelerates* (**a**=$\Delta v/\Delta t$), due to *forces* (**F**=m*a) of resistance (F_r) and drag (F_d). Resistance in fluid media is often simplified as increasing exponentially with **v** ($F_r \propto v^2$), so faster and lighter projectiles will

Nomenclature	
a	Acceleration (m/s^2) (also deceleration, $-m/s^2$)
AR	Area ratio
$\mathbf{C_d}$	Drag coefficient
CM	Center of mass
F	Force (N)
KE	Kinetic Energy (J)
m	Mass (kg)
MaxPen	Total penetration into and through the target (mm)
P	Momentum ($kg\text{-}m/s^2$)
PR	Perimeter ratio
SR	Shaft ratio
TCSA	Tip cross-sectional area
$TCSA_h$	Tip cross-sectional area, thickness at the haft
$TCSA_{hPV}$	Tip cross-sectional area measured in ParaView
TCSP	Tip cross-sectional perimeter
$TCSP_h$	Tip cross-sectional perimeter thickness at the haft
$TCSP_{hPV}$	Tip cross-sectional perimeter measured in ParaView
v	Velocity (m/s)
W	Work (J)
WSA	Wound surface area

decelerate more rapidly. This seems to indicate that penetration is more aligned with **P** (Ashby 2005a), but fluid models are not necessarily the best way to understand how sharp, cutting projectiles penetrate solid targets. When placed under *stress* (**F**/area) solid materials may give way and fracture (Anderson 2018; Atkins 2009). Sharper objects increase stress by applying **F** over a smaller area. Fracturing of the target is also dependent on such factors as the target's hardness, elasticity, strength, density and viscosity (Carlucci and Jacobson 2018). Ductile materials like skin stretch before fracturing, whereas brittle materials like bone fracture dramatically with crack propagation. Second, in the case of projectiles that penetrate entirely through a target, less **W** may be done when impact velocity is high. This is due to the speed of fracturing (rupture lines) in the target (Anderson et al. 2016; Kneubuehl 2011:85). Solid materials exhibit different degrees of strain-rate-sensitivity, or speed of fracturing at higher velocity impacts. In other words, faster projectiles can cause faster fracturing in many targets, thereby reducing the amount of **KE** and **P** spent during penetration (Hetherington 1996). That this applies to bodies is demonstrated by experiments in knife stab wound forensics, where faster stabbing reduces the force of resistance penetrating skin and underlying tissue (Ankersen et al. 1998; Knight 1975).

There is no theoretical problem with using either **KE** or **P** to model penetration, but penetration is a result of the complex interplay of the target material and characteristics of the projectile (Hetherington 1996). As a result, firearm terminal ballisticians typically test the threshold velocity at which a certain projectile will penetrate through a certain target 50% of the time, while mathematical models of penetration vary depending on the specifics of the projectile and target (Carlucci and Jacobson 2018:380). In other words, the threshold velocity is highly context dependent, as are the equations used to model penetration. Most impact equations seem to use functions of **KE**, but the relationship between energy and tissue damage caused by munitions is not necessarily linear (Carlucci and Jacobson 2018:600). Effectively modeling penetration into highly complex organic targets is challenging to say the least (but see Kneubuehl 2011:159–161). In wound ballistics of firearms, the composition of various tissues in the body determines how the projectile behaves during penetration and its ability to incapacitate. It is also important to consider target material relative to the parameters of cutting armatures. The composition of the material being worked on by a tool is an essential component of cutting tool mechanics (Reilly et al. 2004).

Obviously, the degree to which velocity and mass contribute to penetration is dependent on many factors of the target and projectile, but this is not to say that penetration cannot be modeled through simple terms. Although explanatory power is reduced, simple models are preferred in terminal ballistics for their reduced error and increased range of application. Complex models of penetration do not always yield better results (Carlucci and Jacobson 2018:379).

Part of the role of the armature is to cut a hole wide enough to reduce friction on the trailing shaft (Friis-Hansen 1990; Guthrie 1983; Hughes 1998). This can be measured by taking the *perimeter ratio*: the tip's cross-sectional perimeter and the shaft's circumference (PR=TCSP:SC). When PR>1 the armature cuts a sufficiently large hole for the shaft. But larger armatures increase drag. This is measured by taking the *area ratio*: the ratio between tip and shaft cross-sectional areas (AR=TCSA:SCSA). The AR should be as small as possible to reduce drag, but TCSP should be large enough to achieve a sufficient wound surface area (WSA=TCSP*wound length) relative to the size of prey (Friis-Hansen 1990). Importantly, Friis-Hansen's equations measure thickness at the haft ($TCSP_h$ and $TCSA_h$) rather than on the armature itself.

$$TCSA = \frac{Width * Thickness}{2}$$

$$TCSP = 4 * \sqrt{\left(\frac{Width}{2}\right)^2 + \left(\frac{Thickness}{2}\right)^2}$$

In firearm terminal ballistics, penetration depth into living targets is sometimes simplified as proportional to the bullet's *sectional density* (SD=m:TCSA) and its **KE** ($MaxPen \propto SD*v^2$). Relative to bullets, arrows and darts have high SD and should be excellent penetrators (Kneubuehl 2011:65, 94). Features such as the distal shape of the bullet also affect penetration, but such features are not generally incorporated into simplified equations. The penetration of modern munitions into bodies can be modeled using fluid dynamics, where muscle and other tissues in the body act on the projectile in a manner similar to a viscous fluid (Kneubuehl 2011). At the relatively low velocities of darts and arrows such models lose explanatory power as the overall structural dynamics of the target act on the projectile (Carlucci and Jacobson 2018). However, these models require consideration because they have been incorporated into studies of ancient projectiles (e.g. Cotterell and Kamminga 1990; Hughes 1998). A simplified equation for drag (F_d) in a fluid considers the projectile's TCSA, its drag coefficient ($\mathbf{C_d}$), its **v**, and the density of the medium (**ρ**):

$$C_d = \frac{2F}{\rho v^2 TCSA}$$

$$F_d = 0.5C_d * \rho * \text{TCSA} * v^2$$

2.3 Results

The carcass experiments resulted in a large body of data that is still being analyzed. In this paper we will consider the results specifically as they pertain to the terminal ballistics of atlatl darts relative to arrows.

Many experiments have been carried out to interpret the efficacy of various armature designs, but hunting weapons are variable tools that are refined in a number of ways depending on the circumstances of use and the goals of the hunters (Bleed 1986; Knecht 1997). There is a window to allowable variation in efficient design in which stylistic or preferential (stochastic) variation can occur (Hughes 1998). In projectiles that incapacitate prey by damaging internal organs or causing hemorrhaging, this window should narrow as the limitations of projectile systems are tested against larger prey, although this assumption is problematized by hunting poison (Ellis 1997).

Efficient projectiles must be comfortable to the users so they can be launched with speed and accuracy. Skill and effective design results in power, accuracy and the ability to launch projectiles with straight trajectory. However, darts flex in flight and as they penetrate, inherently reducing their efficacy. This is mitigated to a degree with careful engineering. The river cane darts armed with long hardwood foreshafts that seat securely in the socket are sturdy and well-balanced, and performed well in all experiments. Displacement from oscillation shortly after the dart has left the atlatl is approximately 15 cm at the tail and 5 cm at the tip for these darts (Pettigrew et al. 2015). Replica Basketmaker darts are also characterized by low oscillation and straight flight. Our heaviest ash dart averaging 212 g with foreshafts, did penetrate deeply on some occasions, but it was more flexible at the distal (tip) end and more prone to skewed impacts, eventually causing the socket to warp from impacting bison bone. Higher energy projectiles also require stronger engineering, as their energy not only acts on the target but back on armatures, hafting, and shaft junctures (Frison 1989). Designing effective weaponry for an intended application requires making compromises, such as sacrificing ease of use, production and maintenance for increased energy (Whittaker et al. 2017).

One assumes that comparisons across the carcasses would be in error due to variations in skin, muscle, hair and other factors. A comparison of MaxPen and **KE** across the carcasses is provided in Table 2.2 (goat1 is excluded for reasons that will be discussed). This comparison includes the projectiles that are best represented across these experiments: the Basketmaker and medium cane darts. Despite obvious differences in body composition, the goat and bison provide a relatively good comparison, while the hog had denser muscle and skin and penetration was altogether shallower. This may be in part due to the elderly status of the bison, which can affect skin composition (Jussila et al. 2005). Bison skin can be 2+ cm thick, but cows generally have thinner skin than bulls, and their skin is thinnest in spring and summer when they were frequently hunted to make tipi covers (Brink 2008). By the time of the experiment (May) the bison was shedding her winter coat. Skin thickness was not measured during butchering and this should be considered in future tests. Penetration depth is also a function of the size of the animal. A deeper body cavity means a projectile can penetrate farther through less resistant organs before encountering more resistive tissues and bone on the other side. Although pigs are commonly used in firearm terminal ballistics, they are known to have dense, tough skin (Bartell and Mustoe 1989; Kneubuehl 2011:155).

In the following discussion, four groups of data are isolated for statistical analysis due to their qualities of impact and penetration: 33 and 41 shots with darts and arrows are discussed in section 2.3.1, and 51 shots with darts and 28 shots with darts and arrows are discussed in section 2.3.5. These data and the filters used to isolate them can be found in the Supplementary Materials attached to this article.

Table 2.2. A comparison of total penetration depth (MaxPen) and KE of shots with Basketmaker (#1 & 8), and Medium Cane (#5) darts. The hog was denser, so penetration was consistently shallower, while the goat and bison offer a relatively good comparison.

		Bison	**Goat2**	**Hog**
MaxPen	**Mean**	328	322	175
	Min	217	210	110
	Max	434	410	272
	Std Err	26	26	13
KE	**Mean**	30	27	33
	Min	25	25	19
	Max	35	31	49
	Std Err	1.16	0.78	3.04
	N	9	7	14

2.3.1 Variables of effective pre-industrial piercing projectiles

Figure 2.4 depicts 33 shots with darts and arrows that impacted the thorax or belly areas of the goats and bison with straight trajectory, were not significantly hindered by bone, and did not penetrate more than half the length of the projectile completely through the carcass. Shots on the hog are excluded from this comparison for reasons just discussed. **KE** provides a better overall fit with penetration than **P** for these shots, but when only darts are considered, **P** always provides a slightly better fit with penetration (R^2=0.58, P-value=<.0001) than **KE** (R^2=0.567, P-value=<.0001). Shots with arrows into ballistics gelatin provide further comparison, where penetration depth and the length of tears in gel correlate significantly with **KE** but not with **P** (Anderson et al. 2016). Gelatin acts differently during cutting and penetrating events than bodies, however, and Anderson and colleagues tested a limited range of arrow velocity and mass. In the carcass experiments **P** distinguishes the penetrating abilities of projectiles of similar velocity but dissimilar mass more readily.

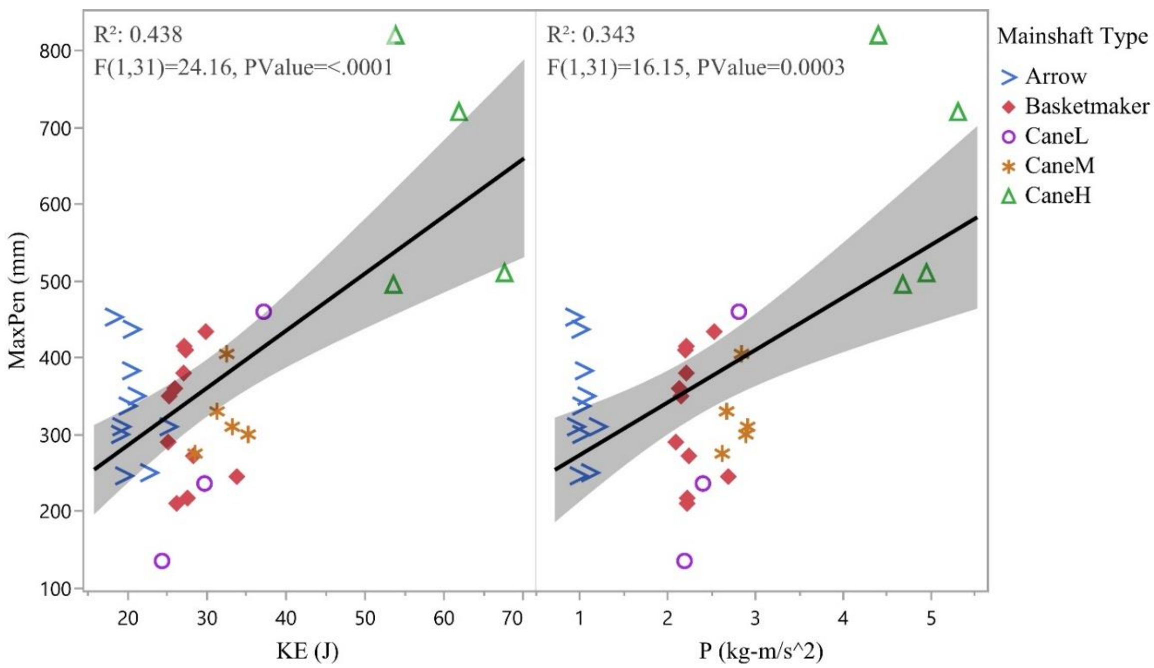


Figure 2.4. Linear regression of total penetration (MaxPen) plotted against kinetic energy ($KE=0.5m*v^2$) and momentum ($P=m*v$) of 33 atlatl dart and arrow shots into the goat and bison carcasses.

We can also see that the data in Figure 2.4 are problematized by other factors of the targets and projectiles not included in the simple regression. The shots group by type: arrows, light and medium darts, and heavy darts. A larger sample of heavy darts with higher **KE** and **P** is desirable, otherwise we run the risk of encountering Simpson's Paradox or other statistical problems. But good shots with these darts tended to penetrate more than half the shaft length through goat2 and only a few shots to the bison did not hit bone. These particular shots are carefully chosen for the qualities of the impact: straight impacts to the center of the body without encountering bone. Additionally, within each group the shots in Figure 2.4 present a range of penetration depths, presumably dependent on aspects of the armatures, carcasses, and other variables. The arrows were much smaller than the darts and should meet less force of resistance, which explains their slightly deeper penetration than darts with comparable **KE** and **P**. In the following I will discuss these additional variables affecting penetration before returning to more advanced models in section 2.3.5.

Understandably, most research in terminal ballistics focuses on modern munitions, but this body of research usually does not account for the benefits of a sharp tip and cutting edge, especially when darts and arrows encounter elastic skin (Hughes 1998; O'Callaghan et al. 1999). The ability of sharper armatures to defeat tough, elastic skin more easily was born out when acceleration could be tracked. Figure 2.5 presents a comparison between four shots from the bison experiment. Armatures 33 and 108 were mounted to a single WDC mainshaft (#1, Table 2.1) on sequential shots that penetrated the thoracic cavity. Armatures 136 and 170 were mounted to a single large river cane mainshaft (#7) that penetrated behind the diaphragm over a period of four shots. Armatures 108 and 136 were made of Burlington chert, 33 of Brazilian agate, and 170 of obsidian. All four impacted the carcass in line with their trajectory and between ribs.

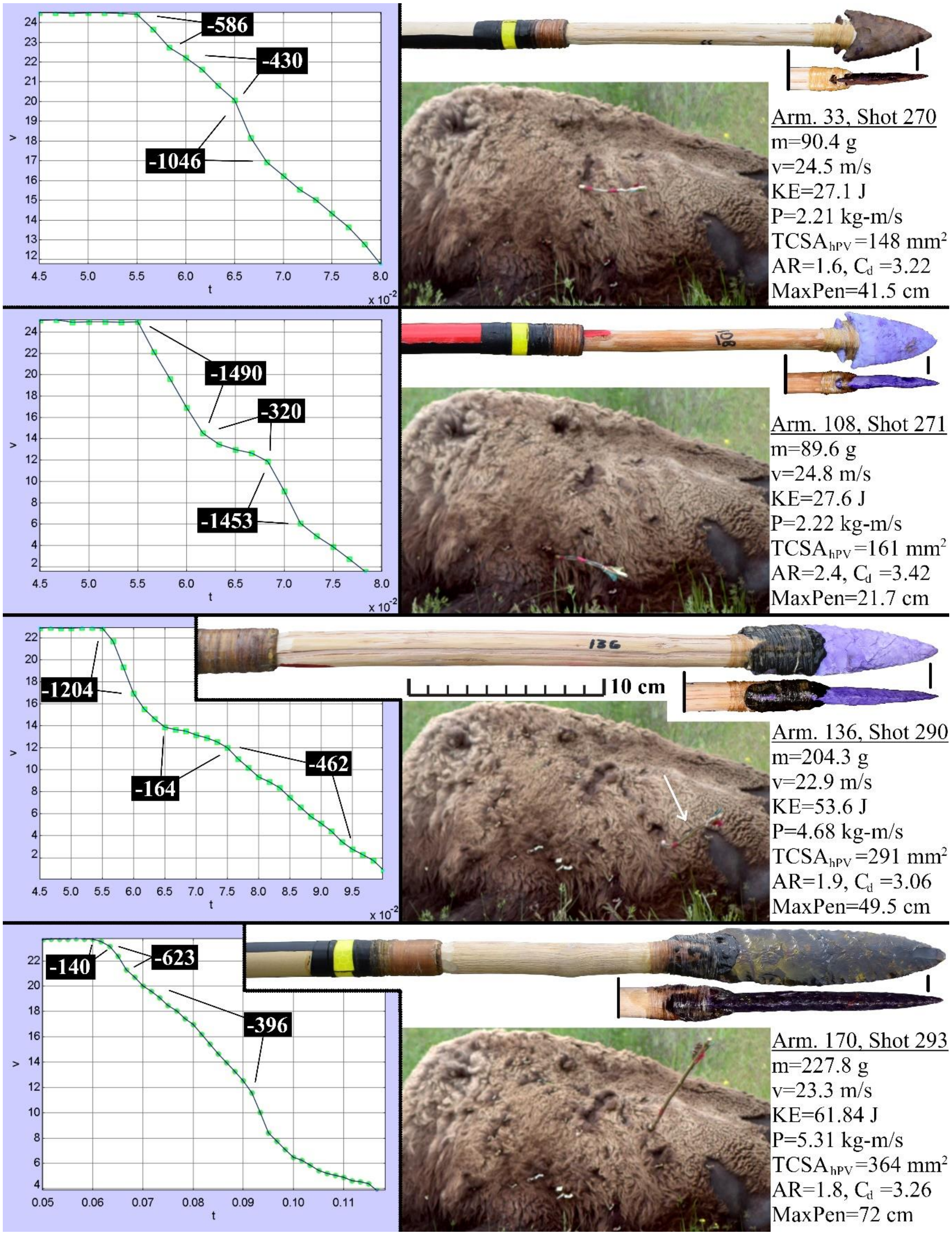


Figure 2.5. A comparison of four armatures used in the bison experiment. Black boxes in graphs contain averaged acceleration (m/s^2) at marked intervals. PR is calculated using TCSA from photogrammetry measured in ParaView ($TCSA_{hPV}$).

Despite having slightly greater velocity and nearly equal mass, the deceleration of 108 was twice as rapid and penetration half as deep as 33, apparently because 33 had a more acute tip and sharper edge owing to the fine-grained structure of Brazilian agate. 33 skipped off the proximal edge of the 9th rib on entry, causing light edge flaking and slightly changing its orientation. On exit it encountered the distal edge of the 8th rib, removing the tip with a longitudinal fracture and producing more flaking on the opposite edge. Both impacts produced hardly a mark on the ribs. Unfortunately, 33's deceleration history is cut short as the most proximal velocity marker entered the body cavity. Despite contacting the edges of ribs 33 retained enough energy to penetrate 5 cm through the skin on the other side. There is no indication that 108 contacted bone until its next shot (Figure 2.6).

The shots with the #7 heavy cane dart gave similar results. 170 penetrated entirely through the bison (18 cm out the other side) with only subtle deceleration occurring as the point entered skin (at time 0.06 in Figure 2.5) and the quickest deceleration occurring when the haft area contacted skin on both entry and exit. Given the length of the point, this dynamic penetration event through outer skin and muscle can be observed over 4 frames of the velocity video. Deceleration was more rapid when 136 encountered skin and was nearly matched on its next shot (Figure 2.6 caption).

This pattern was repeated with other armatures. Another corner notched Brazilian agate point on the WDC dart accelerated at -516 m/s^2 as it penetrated the thoracic of goat1 (one of the few darts to penetrate goat1 effectively), and a corner notched point of Indian Agate (a tough and grainy material, one of three test armatures made by artisans in India and sold in the US as souvenirs) mounted to the WDC dart decelerated at -1533 and -1521 m/s^2 on two sequential shots that hit the thorax of goat2.

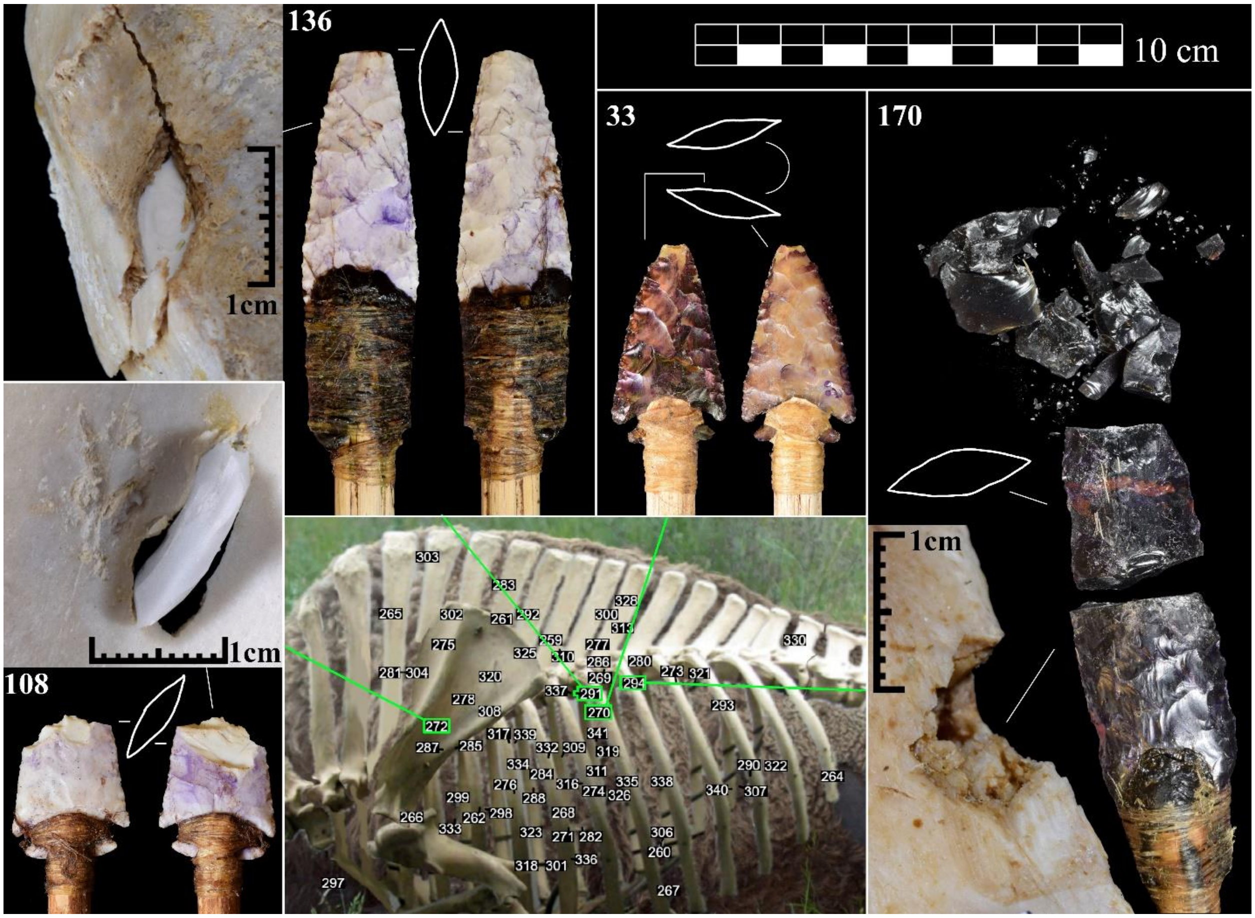


Figure 2.6. The fate of the four armatures shown in Figure 2.5 after their first (33) and second shots (others). Orientation on impact is depicted as white cross-sectional armature profiles. Further indentation and marks to bone occurred after 108 and 170 lost their tips and continued to smash into bone, producing lateral fractures and spin-off. Ballistics: 108 impacted with 28.5 J and penetrated only 6.5 cm, stopping at the scapula (shot #272). 136 impacted with 64 J, decelerated at -1,135 m/s^2 entering skin, and struck a vertebra with 41 J after penetrating 15 cm (shot #291). 170 struck with 67 J and failed to penetrate (shot #294). 33's history is given in the text and Figure 2.5.

For tabulated deceleration, I averaged 2-3 values provided by Tracker over periods of 0.003 to 0.007 sec depending on initial velocity, duration of penetration, and the exact moment the armature encountered skin between the first two markers in Tracker (Figure 2.3). In flight, darts could cover 5 cm and arrows 7 cm between frames of the velocity video. Since the moment the projectile encounters skin rarely coincides with the end of a frame, precisely when acceleration begins to be measured is never consistent. But Tracker calculates acceleration using a finite differences algorithm over four tracked points to reduce error from imprecise marker placement. The averages from these values during initial penetration provide consistent deceleration in like projectiles. Shots from the hog could not be included due to the lower power of the EX-ZR1000 camera, and most shots with darts into goat1 are cut.

From **a**, initial **v**, and **KE**, the average **W** performed by each armature penetrating a common distance of 8 cm can be calculated. Less **W** is obviously required for penetration when armatures are sharper and finer grained materials better achieve this effect, but less **W** is also performed by heavier and slower projectiles. Figure 2.7 provides a visual demonstration of the correlation between deceleration, **P**, and armature sharpness by material type. Heavier darts tend to decelerate less rapidly, but some lighter darts with effective armatures like those of Brazilian Agate decelerate less rapidly than their coarser-grained counterparts, like Burlington, at comparable values of **P**.

Resistance **F** on entry is calculated from the projectile **m** and tabulated **a**. It is closely related to **W** (**W**=**F***displacement). These variables can both give a relative sense of the relationship between penetrating efficacy and armature sharpness relative to **P**, but the **W** performed by an armature, or the **F** experienced on entry also depend on the size of the armature and shaft. An armature with a larger $TCSP_h$ produces a larger WSA, which takes more **W** to accomplish, while a larger $TCSA_h$ should correlate with greater drag, or **F** of resistance. A comparison between mean values of 41 shots with darts and arrows can help clarify (Table 2.3). Average deceleration of darts was 51% less rapid than arrows across the goat and bison experiments, while **P** averaged 177% higher, but darts experienced 117% more **F** on entry, perhaps due to the 123% larger average $TCSA_h$ of their armatures and hafts. Darts did, however,

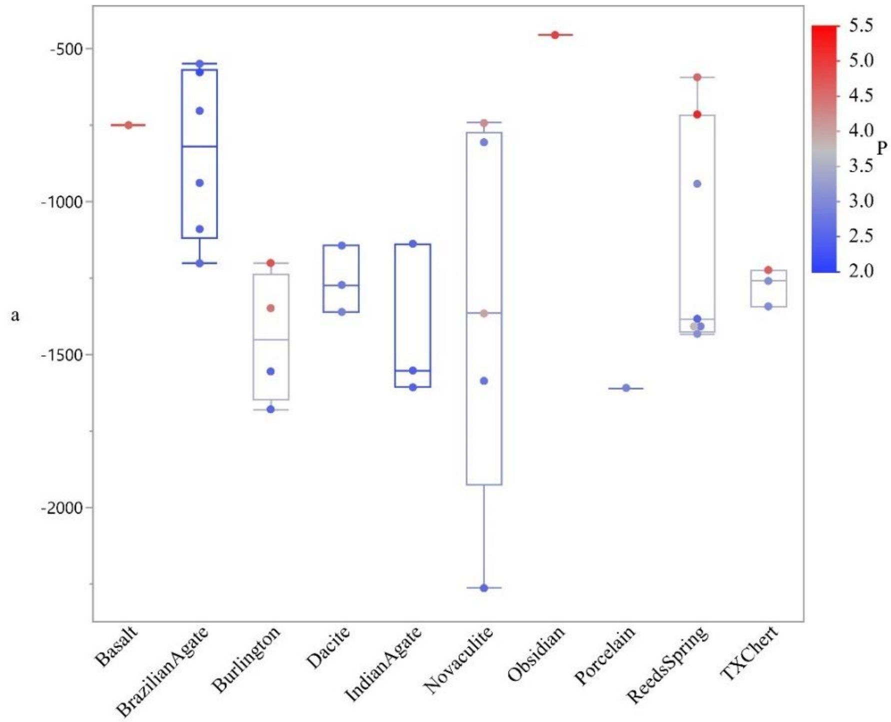


Figure 2.7. Averaged deceleration (a) of 34 dart points and their hafts as they penetrated skin and outer muscle of the bison and goat2, plotted against armature material type and colored by momentum (P).

Table 2.3. Variables of 41 arrow and dart shots into the goats and bison for which acceleration could be measured and bone was not initially encountered.

	Arrows (*N*=11)				Darts (*N*=30)			
	Mean	**Min**	**Max**	**SD**	**Mean**	**Min**	**Max**	**SD**
m (kg)	0.026	0.024	0.030	0.001	0.119	0.085	0.228	0.008
v (m/s)	39.7	37	42	0.44	24.2	20	27.3	0.27
P (kg-m/s)	1.04	0.93	1.2	0.02	2.87	1.73	5.31	0.19
KE (J)	20.5	18.2	25.1	0.6	34.7	17.3	67.6	2.4
a (m/s^2)	-2508	-3378	-1832	153	-1225	-2264	-454	72
F (N)	65.4	50	92	4.2	141.7	50	275	10.2
W (J)	5.2	4	7.4	0.34	11.4	4	21.9	0.82
$TCSA_h$	82	54	131	29	184	112	358	63
$TCSP_h$	57	43	79	13	98	71	153	23

achieve 39% larger WSAs across all experiments (average dart [N=59] WSA=1670 mm^2; average arrow [N=11] WSA=1194 mm^2). When bone was not encountered on entry both darts and arrows could achieve the required WSA through vital organs to be deadly to the bison (~1000 mm^2) (Friis-Hansen 1990). This was even true with small arrow armatures, but darts that penetrated vitals were generally more damaging.

Again, the extent to which resistance **F** on entry slows a projectile depends on its velocity and mass. Figure 2.8 shows that the lightweight cane arrows, which varied little in mass relative to the darts but averaged 64% faster (Table 2.3), were more easily affected by changes in **F**. This means that larger or duller tips should have a greater impact on the penetration of light and fast arrows than on slower heavier darts or javelins. However, these variables obviously affect the latter weapons as well. To reiterate this point, and to show that armature size is not necessarily the primary component of **F** or **W** during penetration, we can return to our qualitative assessment of the four dart points. Armature 170 had 13% higher **P** than 136, but this cannot account for its 48% less rapid deceleration, and the **F** of resistance should have been greater given its 25% larger sectional area. The 61% less rapid deceleration of armature 33 relative to 108 and the 48% less rapid deceleration of 170 relative to 136 resulted from 59% and 42% reductions in **F** respectively, primarily due to the sharper tips and cutting edges of 170 and 33.

Penetration depth in carcass experiments is useful for qualifying measures of penetrating efficacy, but samples for quantitative analysis are more limited when bone is encountered, or the projectile penetrates a significant distance completely through the carcass. The outlier with the greatest penetration in Figure 2.4 is a dart that penetrated roughly half the length of its shaft through goat2. Deceleration helps circumvent this problem, providing an effective measure for both quantitative and qualitative analysis.

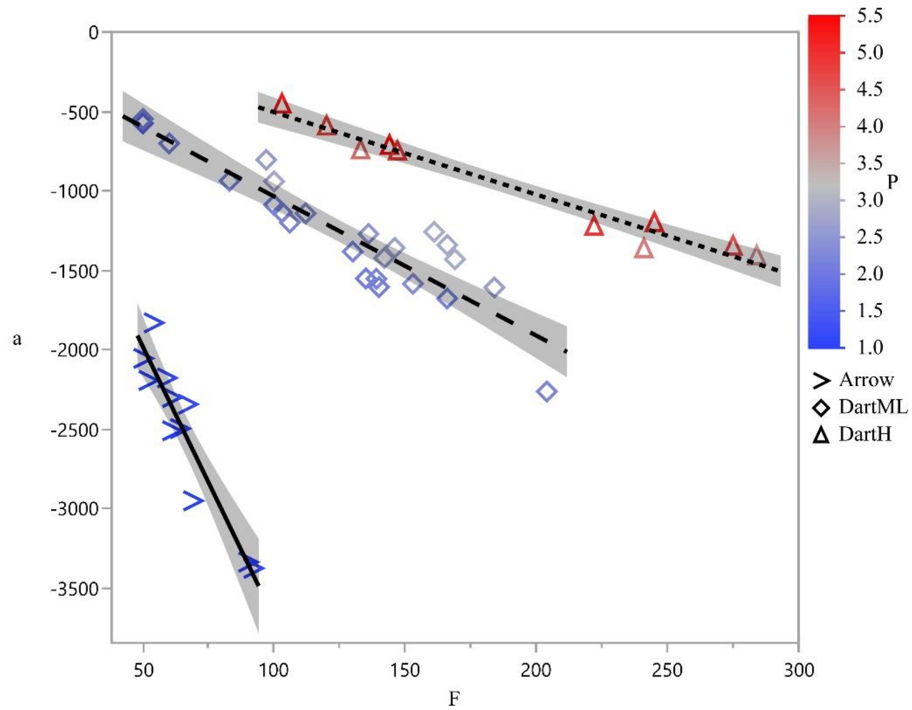


Figure 2.8. The reduced effect of greater entry resistance force (F=m*a, N) on deceleration (a, m/s^2) for heavier and slower projectiles.

2.3.2 Impacts to bone

Sharper armatures are more deadly not only by reducing **F** on entry but because they decrease the rate of blood clotting and provide greater insurance that prey will be incapacitated (Ashby 2009; Friis-Hansen 1990). But finer-grained materials with sharper edges tend to be less robust. Obsidian lacks a crystalline structure, causing it to fail catastrophically when bone is encountered (Loendorf et al. 2018). Armature 170 struck the 10th rib with 66 J on its second shot and exploded dramatically, producing a large amount of debris within 0.5 m of the impact locus and sticking to the hair and skin (Figure 2.6). Other bone impacts on the bison produced debris around the carcass, much of which might be mistaken for production debris. The bison produced altogether more substantial breakage on projectile points than the goats and hog, including 4 of

20 notched dart points that snapped straight across at the haft, leaving bases in the haft, fragments of tips in the body and sometimes embedded in bone, and damaged midsections outside or inside the body. Prior to the bison, I had only witnessed this level of breakage when projectiles missed their mark and encountered rocks. The most durable points were made of chert or siltstone and reproduced thick lanceolate or stemmed varieties. Even when these broke from encountering bison bone, they could usually have been reworked (Figure 2.6:136).

2.3.3 Shouldered mainshaft sockets

Basketmaker darts often have a shoulder at the socket where the removable foreshaft is attached. To understand this, we can look again at armatures 108 and 33. 108 was mounted to a chokecherry foreshaft 9 mm in diameter, 5 mm smaller than the full diameter of the socket of the WDC dart. The second sharp decline in its velocity occurs the moment the shouldered socket contacts skin (Figure 2.5). The dart did not penetrate much beyond the socket. The foreshaft to which 33 was mounted was slightly larger (11 mm), so deceleration is slightly quicker as the foreshaft penetrates and slightly slower when the socket hits skin, and it still managed to penetrate 23.5 cm past the socket. This pattern was repeated with Basketmaker darts on all carcasses. Penetration usually stopped at or shortly after the socket on the hog but could continue past the shouldered socket into the goats and bison. The cane darts in contrast use foreshafts roughly the same diameter as the socket. To assess the transition from foreshaft to mainshaft we can tabulate a third ratio in addition to those given by Friis-Hansen, called the *shaft ratio* (SR=mainshaft distal diameter:foreshaft diameter). A significantly large SR (>1.25) can stop penetration prematurely at the mainshaft socket, but this depends on available mass and velocity, armature efficacy, and target density.

2.3.4 Target inertia

In some cases, atlatl darts “bounced” without showing visible damage from striking bone or for any obvious reason. This happened once on the hog, four times on goat1, once on goat2, and never on the bison. Because goat1 was suspended, the carcass visibly jostled and swung in the slow-motion video from dart impacts, even though it was lowered so its feet were dragging on the ground. Its elastic skin combined with its lower inertia and limp status of the body to resist darts lacking sharpness or energy. Three of the four dart points that bounced off goat1 were reused on goat2 and the bison. Armature 53 (of Indian Agate) bounced off the thorax of goat1 at 22 m/s (KE=26, P=2) but penetrated 38 cm into the belly of goat2 at 24.5 m/s (KE=27, P=2.2). Armature 51 (a robust point of Reeds Spring chert) bounced off the thorax of goat1 at 24 m/s (KE=34, P=2.84) but penetrated 30 cm into the thorax of the bison at the same velocity. Dart armatures made of sharper materials did not bounce off goat1 but did not penetrate as deeply as into goat2. Clearly the threshold velocity for a dart to penetrate skin is inversely correlated with the sharpness of the armature and the inertia of the target. The latter is smaller when the carcass is suspended. At higher velocities and with smaller armatures and shafts, arrows were less affected by the lower inertia of goat1. Penetration depths of arrows between goats1 and 2 are very similar, but a larger sample is needed to fully assess this, since few arrows were shot into goat2.

2.3.5 Modeling penetration

Archaeologists have attempted to find a number of armature metrics for discriminating weapon types (see Hutchings 2016). Two of these are TCSA and TCSP (hereafter TCSA/P). Hughes (1998) lists TCSA/P as pleiotropic variables in weapon evolution that “ride on” shaft size for the reasons discussed by Friis-Hansen (1990); armatures cut a hole for the trailing shaft but oversized armatures create unnecessary drag. Hughes' sample of archaeological hafted TCSA/P was expanded by Shea and Sisk, who added metrics from a controlled thrusting spear experiment and applied TCSA/P to distinguish weapon types from Middle Paleolithic armatures (Shea 2006; Sisk and Shea 2009, 2011). Others have since used TCSA/P to distinguish weapon types from armatures (Lombard 2020; Sahle et al. 2013; Villa and Lenoir 2006; Wilkins et al. 2012). Several experiments have used a controlled approach to test if TCSA/P predict penetration depth in consistent targets and can tell us something about efficacy (Eren, Story, et al. 2020; Mika et al. 2020b; Salem and Churchill 2016; Sisk and Shea 2009; Sitton et al. 2020). Some of these have managed to demonstrate a statistically significant negative correlation between TCSA/P and penetration (but see Clarkson 2016; Loendorf et al. 2018; Wood and Fitzhugh 2018).

To assess the impact of TCSA/P on the penetration of a single weapon technology used in variable hunting contexts, TCSA/P can be plotted against penetration depths from shots with 51 darts across the four carcasses, which impacted with straight trajectory, were not significantly hindered by bone, and did not penetrate significantly through. If larger TCSA/P affects the efficacy of atlatl darts to penetrate prey bodies in a meaningful way, a negative correlation with penetration should obtain, but all TCSA/P measures show *positive* correlations with penetration, indicating that penetration depth tends to increase along with armature cross-section. Figure 2.9 presents a linear regression with $TCSP_h$, which provides the strongest positive correlation with MaxPen of the four TCSA/P measures. Why this should be the case is clearly due to the positive correlation also shown in Figure 2.9 between TCSA/P and mass. Consequently, in this sample TCSA/P is positively correlated with **P** and **KE** within a single weapon technology. This is because heavier darts with larger shafts were usually fitted with larger tips, which penetrated deeper on average and did more damage to the target. To reduce the effects of confounding correlations, TCSA/P can be plotted against the residuals of MaxPen and **P** (R^2=0.37, P-value<.0001) for these 51 darts, but the fit is poor (Figure 2.9).

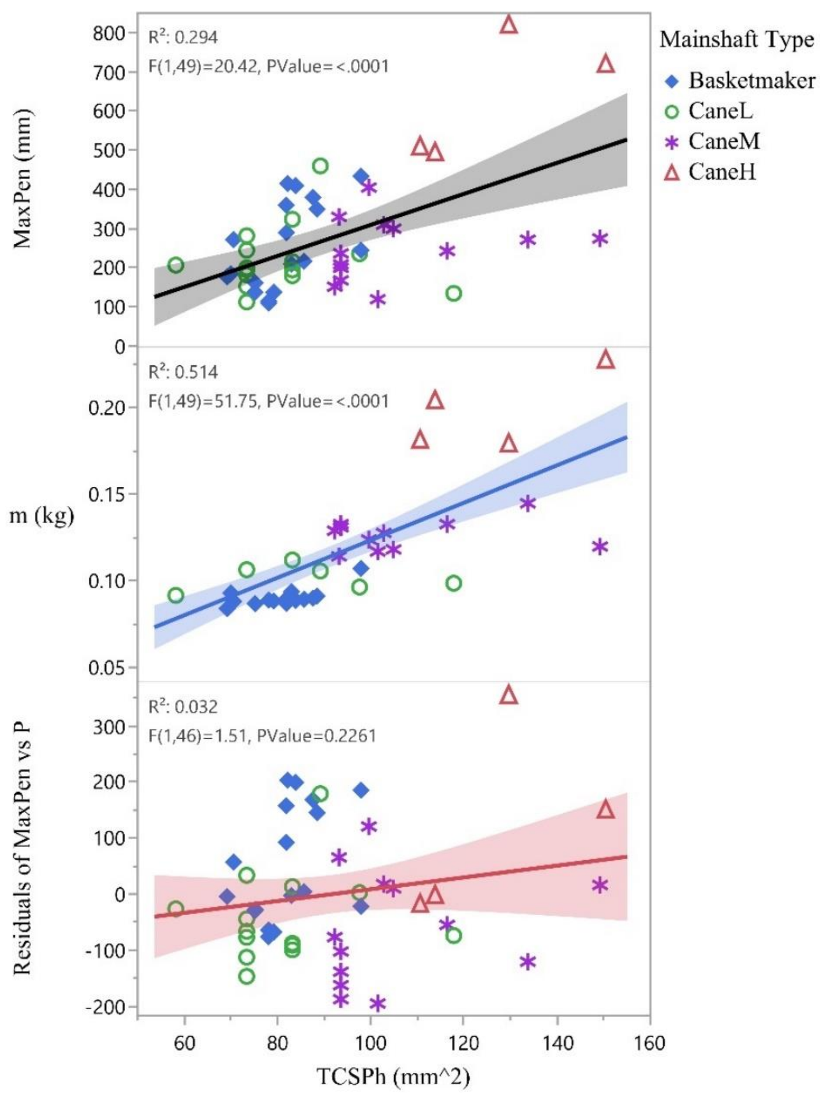


Figure 2.9. A linear regression of 51 dart shots across the four carcasses.

Modeling armature penetrating efficacy using only TCSA/P is an attempt to simplify the drag force acting on a body as it moves through a fluid. We can recall that fluid models of penetration are not necessarily good for darts and arrows with sharp armatures that fracture solid targets at relatively low velocities, but these variables have been suggested as important for dart and arrow terminal ballistics in the literature (e.g. Hughes 1998) and require testing. Another variable in the drag equation is the *drag coefficient* (**C_d**). The **C_d** of complex shapes can be captured experimentally or through computational fluid dynamics (CFD). Most CFD analyses use models built in software (Tu et al. 2018), but the possibility of using photogrammetry models was recently recognized (Aati and Nejim 2020).

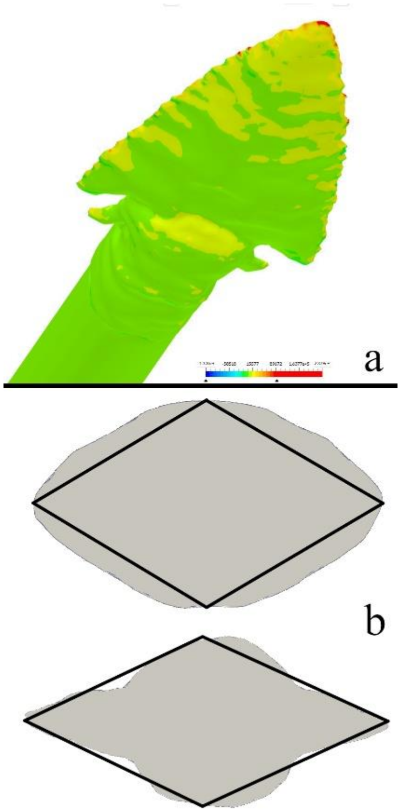


Figure 2.10. A) An example of SimScale output, with distributed pressure on a model of armature 33; B) Head-on views in ParaView of armatures 136 (top) and 33 (bottom) with rhomboid overlay. TCSA of 136 in ParaView is 42% larger while 33 is 5% larger than predicted by the equation.

Prior to the goat2 and bison experiments several hafted points were photographed for photogrammetry. Photogrammetry models were successfully created for 28 of the 33 hafted dart and arrow armatures discussed in section 2.3.1 and plotted in Figure 2.4. Because the CFD analysis in SimScale requires precise values of the cross-sectional area for calculating **C_d**, the 3d models were also imported into ParaView, where both $TCSA_h$ and $TCSP_h$ could be measured from a head-on view. To add to an already excessive acronym I will dub these measures $TCSA/P_{hPV}$ but will try to use it in moderation. The $TCSA_{hPV}$ values average 16% larger and range up to 54% larger than those obtained through the usual

$TCSA_h$ equation, while $TCSP_{hPV}$ values average 5% larger and range up to 34% larger than $TCSP_h$. $TCSA/P_{hPV}$ of armatures with wide blades and narrower hafts (especially corner notched varieties) are closer to values obtained through the equations, while lanceolate types (e.g. Clovis, Dalton, and Cody types) tend to be poorly represented (Figure 2.10).

Figure 2.11 demonstrates that causal factors in the data are problematized by multicollinearity (multiple correlations between variables), which captures the classic critique against realistic experiments. Fortunately, multivariate procedures are available to assess the relative contributions of many correlated variables. Here we use the 28 shots where some ballistic variables can be represented (and others more accurately represented) by the 3d models. All variables of these shots that are calculated from cross sectional measures (including SD, AR, and PR) derive from $TCSA/P_{hPV}$. To try and represent the effects of drag on longer and more flexible shafts, we can also plot total projectile length. Additionally, the center of mass (CM) is the balance point measured back from the tip, which could tell us something about the ability of a longer forward lever to more easily alter a dart or arrow's own trajectory when a resistive target is encountered (Ashby 2005b). Hypothetically, a larger value for the CM should reduce penetration.

First it is useful to examine a heatmap from a multivariate analysis of the correlations between 15 ballistic variables and MaxPen (Figure 2.11). MaxPen is positively correlated with many variables but most strongly with **KE**, and surprisingly a significant negative correlation occurs with the PR. The latter is also least problematized by correlations with other variables that impact MaxPen, which cannot be said of variables like TCSA/P and the $\mathbf{C_d}$. The $\mathbf{C_d}$ correlates positively with mass (R^2=0.35, P-value=.0009) and subsequently with **KE** and **P** for the same reason that TCSA/P does. Larger points experience more drag but are usually attached to larger shafts. Fluid models suggest that diamond shaped lanceolate forms should experience less drag than notched forms (Hughes 1998), but in the CFD analysis notched points were smaller than most lanceolate varieties and had correspondingly smaller $\mathbf{C_d}$s. In other words, the $\mathbf{C_d}$ corresponds first with size rather than shape, and is problematized anyway by a positive correlation with projectile **KE** and **P**.

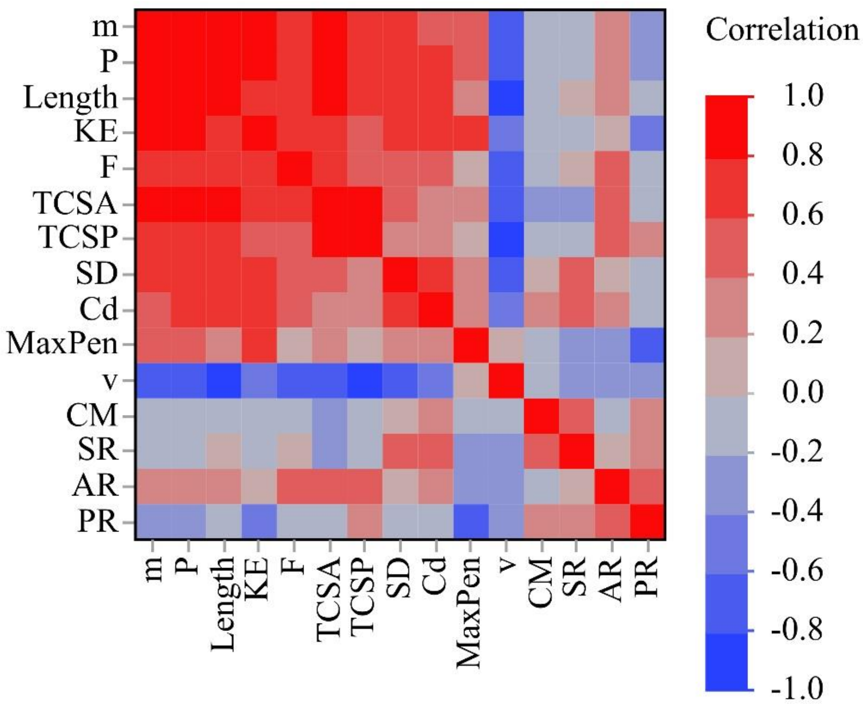


Figure 2.11. Heat map showing correlations from multivariate analysis of 28 shots with armatures modeled using photogrammetry. All cross-sectional measures and functions thereof (AR, PR, SD) were obtained in ParaView.

The same 15 variables were plotted against MaxPen in a multiple regression analysis of these 28 shots. Using the backward selection procedure, most variables are removed because they either fail to meet a P-value threshold of 0.05 or they have high variance inflation factors

(>5), indicating that multicollinearity is negatively impacting the model's precision. In removing them, R^2adjusted improves until we are left with just **KE**, **F**, and the PR predicting ~70% of penetration (MaxPen(y)=7.8(KE)-1.2(F)-228(PR)+657; R^2adj.=0.69, R^2=0.728, P-value=<.0001). With the PR removed, **F** and **KE** still predict 57% of MaxPen (R^2adj.=0.57, R^2=0.6, P-value=<.0001), whereas **KE** alone predicts 35% (R^2adj.=0.347, R^2=0.37, P-value=.0006). Figure 2.12 shows the agreement between penetration and the prediction formula that includes **KE**, **F** on entry, and the PR for these shots.

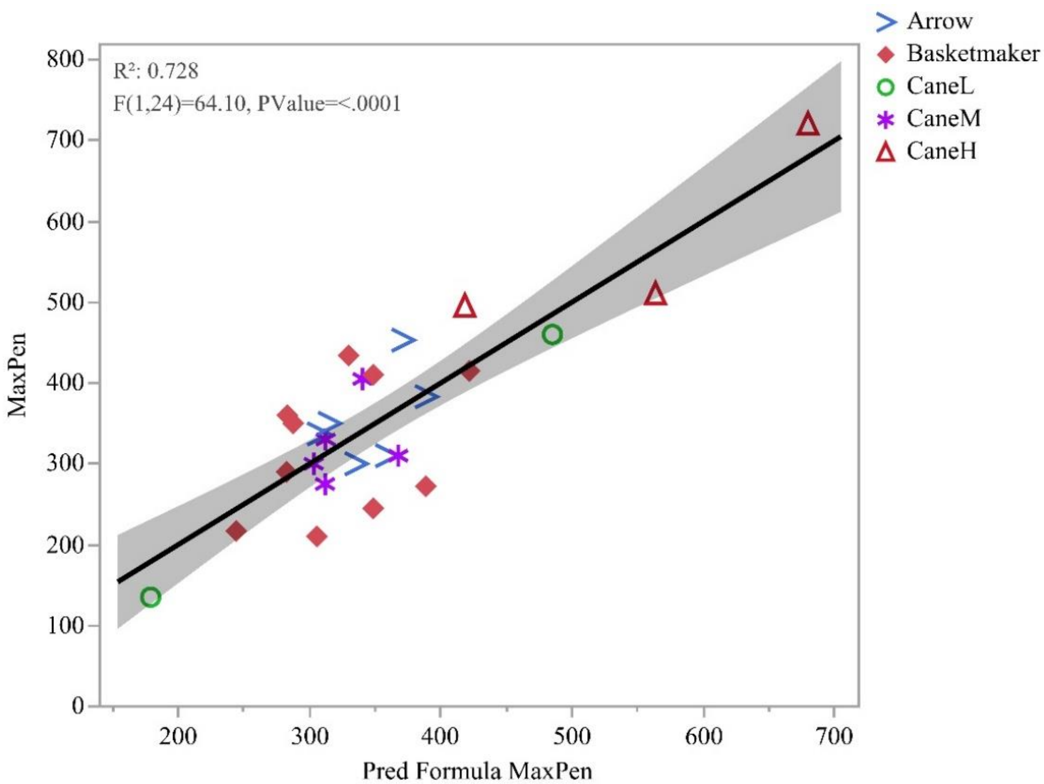


Figure 2.12. Showing the fit between penetration depth (mm) and a prediction formula that includes kinetic energy (KE), force of resistance on entry (F), and the perimeter ratio (PR, derived from photogrammetry) for 28 shots with darts and arrows.

Finally, 10 of these variables can be compared in a partial correlations matrix for these 28 shots. A partial correlations matrix displays the relationships between pairs of variables after adjusting for the impacts of all other variables in the matrix, thus providing a means of controlling for the confounding effects of related variables on each relationship. Table 2.4 provides the correlations, partial correlations, and probability coefficients of 10 variables impacting MaxPen. Prior to adjusting for confounding variables, MaxPen has a strong positive correlation with **KE** as expected and a significant negative correlation with the PR. After adjusting for confounding variables, MaxPen has the strongest positive correlation with **KE** and the strongest negative correlations with **F** and the AR. When plotted against the residuals of a simple linear regression of MaxPen and **KE** for these shots, the AR is indeed significant (Figure 2.13).

Table 2.4. Multivariate analysis of the correlations and partial correlations of MaxPen with ballistic variables of 28 shots with armatures modeled using photogrammetry. All cross-sectional measures and functions thereof are calculated from armatures and their hafts in ParaView.

	MaxPen			
	Correlations	**Correlation Probability**	**Partial Corr.**	**Partial Corr. Prob.**
KE	0.6094	0.0006	0.3802	0.0982
F	0.0301	0.8791	-0.2756	0.2396
TCSA	0.2993	0.1218	0.182	0.4425
TCSP	0.0406	0.8376	-0.1451	0.5417
SD	0.2326	0.2335	-0.0304	0.8987
Cd	0.2286	0.2419	0.0505	0.8325
AR	-0.3668	0.0653	-0.3216	0.1668
PR	-0.5632	0.0027	0.0997	0.6759
Length	0.2612	0.1793	-0.0602	0.801

The three variables of **KE**, hafted armature size relative to shaft size, and armature sharpness capture roughly 70% of penetration for these 28 shots. As energy (and momentum) increase so does penetration. While larger armatures can increase **F** of resistance and reduce penetration, sharper armatures can dramatically reduce **F** of resistance. This finding is by no means extraordinary, but it can affect the way archaeologists interpret armatures. Armature cross section has been used by archaeologists because it is easy to measure and is an important variable in terminal ballistics, but without knowing the **m** and **v** of a projectile to which an armature is attached, cross sections may be problematic indicators of efficacy and can even correlate positively with penetration. In comparison, judging armature sharpness from material type seems straightforward. Since the importance of variable sharpness between materials was not anticipated and no measure was taken, quantifying its relationship with **F** and penetration will have to wait for future research.

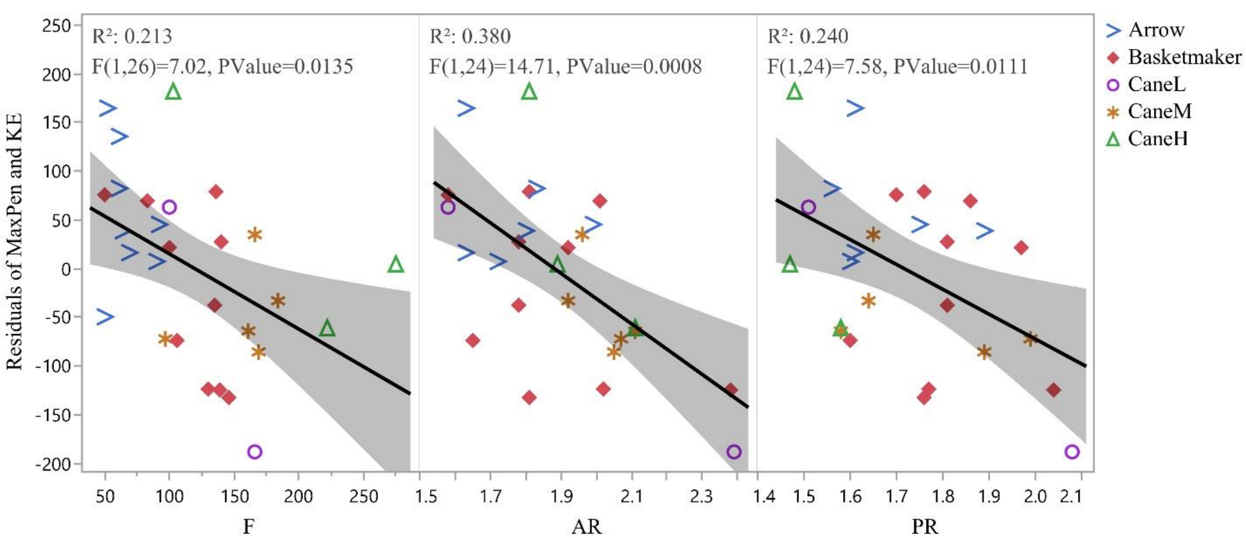


Figure 2.13. Variables plotted against the residuals of penetration (MaxPen) and KE for 28 shots with darts and arrows. Cross sectional variables (AR and PR) are calculated from TCSA/P values provided by ParaView.

2.4 Discussion

Penetration events involving real darts and arrows impacting bodies are dynamic, complex affairs, and modeling them effectively requires consideration of the interplay of many variables. This is not without challenges. Clearly, there are unrecorded variables in these experiments that affect dart and arrow penetrating efficacy, especially variation in and between carcasses. Armature sharpness, shaft skewness during impact, and surface roughness (especially on long and flexible dart shafts) also need to be better characterized. Measuring these variables is necessary for improving validity with this kind of experiment and these variables are not out of reach of future analyses.

Even had additional variables been included, the experiments just described could never address the full range of variables in dart and arrow efficacy. The spread of the data in Figure 2.4 indicates that this is less due to lack of control than to lack of adequate representation of *within-weapon variability* in the experimental arsenal. Arrows in these tests were consistent forms with relatively low mass and energy, and darts with over twice the mass of our heaviest have been used by indigenous hunters (Palter 1977). A larger sample of shots (especially with heavy dart weights) would improve the models described in the results. This is not possible in one or even four carcass experiments. It requires comparison of a similar protocol across many experiments. The models are also limited by the necessary controls found in realistic experiments. Realistic hunting conditions produce more variable shooting conditions than represented here. Accurate shots beyond 15 m with the atlatl are possible but can be challenging even for indigenous hunters (Cundy 1989), but not all shots in the past occurred at 10-12 m broadside to the target.

Despite these problems, several qualitative observations can be formed from the results. In ethnographic hunting cultures, shouldered sockets are accompanied by removable foreshafts that are coated in hunting poison. San hunting arrows provide an example (Figure 1.3). The mainshaft is designed to fall away both so the poisoned segment has a greater chance of remaining in the wound and the mainshaft can be retrieved and reused (Archer et al. 2020; Jones 2007; Wiessner 1983). However, shots with shouldered Basketmaker darts that penetrated the depth of a 20 cm long foreshaft into the thoracic cavity might still have brought down a bison without poison (Bement 2018; Friis-Hansen 1990; Guthrie 1983). The WDC darts appear to be lethal to bison if they are armed with sharp points and do not directly encounter bone. As with historic Plains arrows (Bohr 2014), precise shot placement would be essential for non-poisoned Basketmaker darts to be lethal to bison and some number of shots would likely be deflected by ribs.

The same problem with thick ribs blocking penetration has been recorded by others (Castel 2008; Frison 1974). Of 25 shots that struck the bison's thorax, 8 (32%) were stopped by direct impacts to ribs. This is expected if 70% of a bison's chest area is not protected by ribs (Friis-Hansen 1990). A slightly heavier replica Basketmaker dart from Canyon del Chelly (CDC, #8, Table 2.1) (Quirolo 1987:179) directly impacted a bison rib with straight trajectory (KE=24 J, P=2.06 kg-m/s) and lodged 25 mm into it. The Brazilian Agate point remained in the bone when the dart was retracted. The nature of impact damage to an ancient bison rib and the Folsom point that did the work (Bement 2018) suggests that Folsom darts were probably heavier and carried more energy than Basketmaker darts. Similar damage to a rib occurred once during the bison experiment, when a Dalton point mounted to the heavy ash dart (#3) impacted the distal edge of the 4^{th} rib with high energy (KE=101.4 J, P=6.7 kg-m/s), producing a large nick in the side of the rib and initiating a crack that fractured it in half (Figure 2.14). The thick Dalton point of TX chert sustained minor longitudinal fracturing at the tip and continued to penetrate 34 cm into vitals. Deeper penetration would likely have occurred had dart #3 been less flexible and prone to shaft drag. This suggests that atlatl and dart weaponry can be designed to deal with thick bison ribs. Since the bison used in these experiments was elderly, her bones may have been more brittle than a younger bison, and she lacked the muscle around her hump and shoulders of younger bison. To better test these results it will be necessary to carry out further testing on a younger animal.

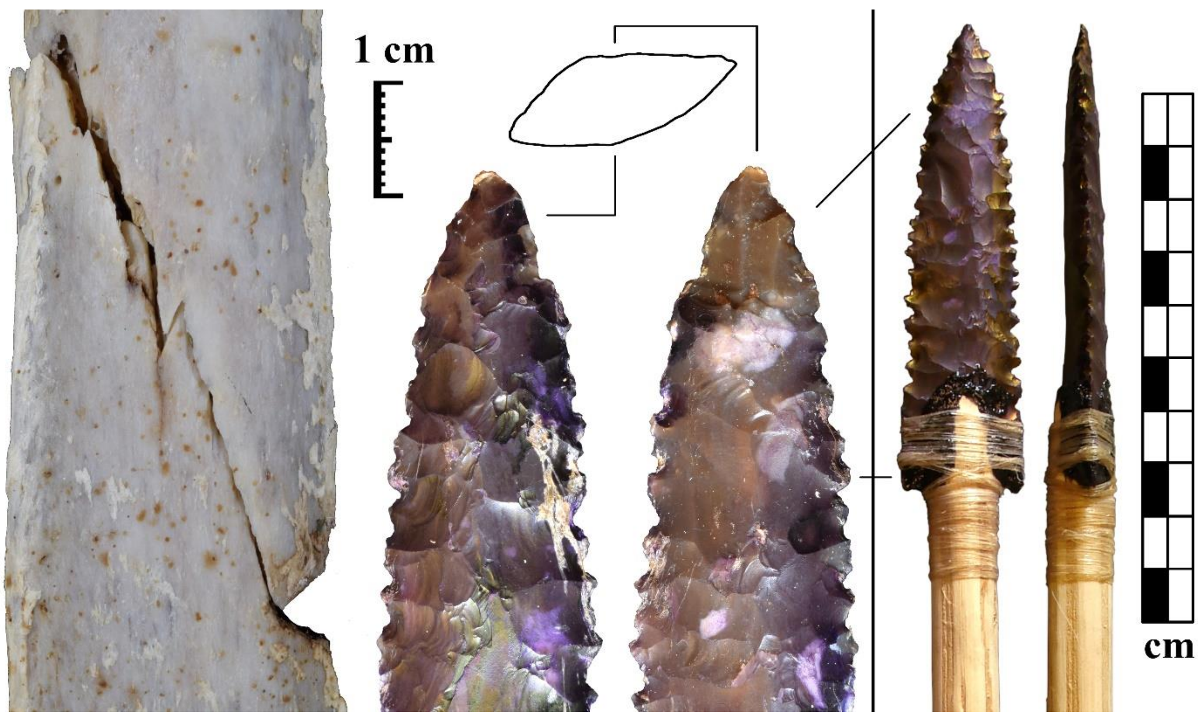


Figure 2.14. A test point made of Texas chert that was mounted to the heavy ash shaft #3 and received minor tip damage after impacted the edge of the 5th rib of the bison and fracturing it in half (shot #299; KE=101.4 J, P=6.65 kg-m/s). The cross-sectional outline of the point shows its orientation on impact. The large nick in the lower right edge of the rib is the point of impact.

Many variables are involved in the penetration of atlatl darts and arrows and most of them cannot be deduced from stone armatures alone. To an extent, simplifying assumptions help navigate the unknown, such as an assumption that ancient hunters could generally launch darts with straight trajectory, reducing the negative effects of shaft drag on penetration. But carrying this reductionism too far can produce misleading results. The experiments in this article clearly problematize an assumption used to validate the constrained nature of some controlled tests, stating that **KE** and **P** should remain relatively equal with changes in the mass of atlatl darts because, ceteris paribus, an atlatlist cannot generally throw a heavier dart harder than a lighter one (Eren, Bebber, et al. 2021; Eren, Story, et al. 2020). Efficacy can thus be a focus purely of the armature sizes tested in the controlled experiments. However, in this project and in a large sample of contemporary atlatlists (Whittaker et al. 2017:Table 2), heavier darts carry *substantially* more **KE** and **P** than lighter ones, even when launched by the same person. This is corroborated by a simple throwing experiment in which 13 adults and youths threw rubber balls of 10 difference weights (60 to 500 g) at maximum effort (Toyoshima and Miyashita 1973). The lighter balls flew faster, but balls over 300 g carried more **KE**. The highest **KE** was recorded for two different throws with the 350 and 450 g balls by two adults. A similar experience led Frison (1989) to choose darts of 400+ g for experiments with Clovis armatures on African elephant carcasses but to discard a 900 g dart that was too heavy. A similar trend can be found for various bow designs and arrow weights (Baker 1992). Heavier darts and arrows tend to be more efficient to launch until a point of diminishing returns. When this point is reached depends on the specific characteristics of the launching mechanism (bow, atlatl and atlatlist). This does not mean that the heaviest permissible projectile for the launching mechanism will always be used. Different conditions favor different strategies of projectile weight and design. Heavier darts and arrows retain energy better during flight and penetration through bodies, but lighter projectiles, like Basketmaker darts, may be easier to transport and deploy and more effective against smaller and swifter prey. The design of projectile weapons reflects these and other compromises (Whittaker et al. 2017).

In a recent paper, Eren and colleagues (2021) tabulated penetration depths from many experiments and used the data to argue that Clovis weapons would be rather ineffective for hunting Pleistocene proboscideans. This is a statistical argument that is problematized by the nature of the compiled data. Particular focus is given to a controlled experiment involving shots into potter's clay with arrows that weighed less than Basketmaker darts (mean=77 g) but traveled at the upper end of dart speeds (mean=34 m/s, KE=44.5 J, P=2.6 kg-m/s) (Eren, Story, et al. 2020). With Callahan's (1994) experiment on an elephant excluded due to freezing and thawing of the carcass and Frison's (1989) not included due to lack of adequate penetration data, nothing approximating hypothetical Clovis big game darts or their targets is among the wide variety of experiments from which these authors draw only penetration depths, without reference to variables such as target and projectile composition. It is due to this lack of representation, and the lack of comparability of the fracture mechanics of target simulants used in some of the referenced controlled experiments to the bodies of hunted prey (see section 2.2.1.4), that the authors find penetration depths of stone-tipped projectiles >20 cm "anomalous" (Eren, Meltzer, et al. 2021). In the tests described in this paper, the heavy ash dart (#3) could penetrate >240 cm through the center of goat2 (the entire length of the shaft!), but the width of the carcass comprised only 23 cm of this distance. This caliber of dart is truly overkill for this size of animal and lighter darts formed the greater part of the test arsenal. As Table 2.2 indicates, the goats and bison offer a surprisingly good comparison, but including shots on the hog dramatically hampers a combined statistical analysis. Extending the analysis with more data on variable weapon performance across carcass types may be useful for examining the general characteristics of effective hunting weapons, but specific questions related to certain prey species requires more appropriate targets. We can reasonably suspect that neither the shots from this study, nor the additional goat, dog, and reindeer carcass experiments referenced by these authors (Eren, Meltzer, et al. 2021:Table 2), belong in a statistical analysis of how heavy, well-designed Paleoindian atlatl darts might perform against Pleistocene proboscideans. Those animals had a robust anatomy as the authors discuss, but also high inertia and a deep body cavity, factors which improved penetration in this study. More work is required in reverse engineering Paleoindian weapons and testing their ballistics against more appropriate targets before this topic can be adequately approached.

Measuring deceleration during penetration into solid targets is a special ability of experiments that deploy projectiles with long shafts and high-speed cameras. Dynamic deceleration of modern munitions is hard to track through solid targets, which is part of the reason for the reliance on simplified controlled tests into clear and homogenous simulants. But such tests have contributed to misrepresentations of just how modern munitions incapacitate living targets (Bartlett and Bissell 2006; Carlucci and Jacobson 2018:600). Controlled experiments in ancient weaponry also must be tempered by examining shots into realistic targets. Clearly, controlled experiments can be designed to show a significant negative relationship between TCSA/P and penetration into targets like clay and gel, but without externally validating these tests they do not help us understand how the interplay of TCSA/P with other variables determines the efficacy of variable projectiles penetrating prey bodies. This is important because archaeologists deploy TCSA/P as metrics that operate across variability of weapon form and application, even though armature cross section is recognized as only one of several important variables in equations for modeling penetration (Friis-Hansen 1990; Hughes 1998). TCSA/P as indicators of weapon types, and of weapon efficacy, must be shown to have external validity. Four problems arise in doing so:

First, atlatl dart TCSA/P from Hughes' and Shea's studies is drawn primarily from a limited sample of the Late Archaic atlatl and dart weapon system in the US Southwest, which is a relatively small iteration of the weapon, while the spear sample is drawn from a controlled experiment (Shea et al. 2001). In absence of archaeological or ethnographic samples, experimental analogs can demonstrate the capacity of various hafted armatures to perform in given contexts, although greater external validity than achieved by Shea and colleagues is recommended. Table 2.5 provides a comparison of TCSA/P of armatures in this study with samples used to distinguish weapon systems from archaeological armatures. These data show a large amount of overlap in TCSA/P from what is still a constrained sample of weapon variability. This further exacerbates an overlap in TCSA already noticed between atlatl darts and ethnographic light javelins (Lombard 2020). Darts and other projectiles are adapted to specific conditions of use, including intended prey. When darts have more than adequate mass and velocity for their intended application, they can be fitted with armatures with relatively large TCSA/P and still perform. This was demonstrated when two armatures with TCSA values well within Sisk and Shea's experimental thrusting spear sample (116 and 197 mm^2) penetrated the full depth of the thoracic cavity of the hog on the medium cane dart (the largest outliers for CaneM in Figure 2.9 top), producing large wound surface areas (Pettigrew 2015). This corroborates evidence that armatures with very large TCSA/P have been used on atlatl darts in Australia (Newman and Moore 2013). The TCSA/P sample thus suffers simultaneously from a preservation bias and bias in accepted application of experimental analogs.

Table 2.5. A comparison of arrow, spear, and dart tip cross-sectional area (mm^2). Specifications of numbered mainshafts are found in Table 2.1 and Table A-3.

	Shea 2006			**This study**				
	Arrows	Darts	Spears	Arrows	WDC(#1)	M.Cane(#5)	Heavy(#3&7)	All darts
Mean	33	58	168	41	71	113	120	86
Min	8	20	50	18	52	69	66	18
Max	146	94	392	134	90	197	294	294
StDev	20	18	89	24	11	30	45	12
N	118	40	28	32	39	51	66	188

Second, the leading terminal ballistic studies to date are understandably of modern munitions, which typically deploy fluid models of penetration. Dart and arrow models should account for armature sharpness. This is challenging given the fragility of sharp edges on archaeological specimens, not to mention the difficulties associated with measuring sharpness (Reilly et al. 2004; Stemp et al. 2019). Figure 2.7 indicates that finer-grained materials are generally sharper and more efficient at cutting through skin. Paleoindian preference for armatures made on finer-grained stone than other tools (Bamforth 2002a) suggests that ancient hunters recognized this fact. The presence of "exotic" knappable stone for projectile armatures in other prehistoric contexts should perhaps be reconsidered in light of this. This topic warrants further research using direct measures of sharpness in different raw material types (e.g. Stemp et al. 2019).

Third, TCSA/P originally uses thickness measures taken at the haft. This is sensible given the extent to which a pronounced haft area creates drag on entry. But hafting metrics can be difficult to extrapolate from archaeological armatures and equations using a rhomboid to approximate the cross sections of armatures and their hafts can give inaccurate results.

Clearly, TCSA/P can affect penetrating efficacy. The same is true of variables like C_d, but the effects of these variables are dependent on other, often interrelated variables. The ratios PR and AR correlate negatively with penetration of a wide variety of projectiles because they represent TCSA/P relative to shaft size, and in these experiments larger shafts that carry more energy tended to be fitted with larger tips, despite that this was not planned. But on their own, these measures carry limited explanatory power. This brings up the fourth problem: a broad view of dart and arrow efficacy cannot be based solely on variables operating in isolation. Many variables operate together to ensure efficacy. For example, like most states in the US, Colorado requires a certain width of arrow armature (7/8 inch) and poundage of bow (minimum 35 pounds) to increase the odds of a quick death for hunted prey (Colorado Parks and Wildlife 2021). Even wider broadheads have been found to increase the odds that a hunter will retrieve an animal (Pedersen et al. 2014). Smaller armatures produce smaller WSAs and thus are considered less efficacious for modern bowhunting, as are arrows without sufficient mass or velocity to create adequate wound surface areas through vitals. Hunting larger prey will benefit from even larger WSAs, which can be achieved by increasing TCSP, mass, and velocity (Friis-Hansen 1990). This clearly problematizes another assumption used to validate controlled experiments, stating that hunting efficacy can be reduced to penetration depth alone and thus, ceteris paribus, armatures with smaller TCSA/P are more efficacious (Eren, Meltzer, et al. 2021; Eren, Story, et al. 2020; Mika et al. 2020b).

The exploratory tests described here, which have kept many variables in play and provided ample opportunities to reverse engineer effective weapons, indicate that well-designed darts and arrows impact with straight trajectory, have durable shafting, hafting, and armatures, are fitted with sharp armatures of sufficient size to create adequate WSAs through vitals, and have sufficient **KE** and **P** to cause the armature to penetrate. These variables can be matched to different sizes of prey as needed. This leads to challenges for archaeologists who study the efficacy of old weapons, since the mass and velocity of a projectile are hard to deduce from stone armatures, let alone other variables affecting penetration. But the way to address these challenges is not to ignore these variables. Archaeological studies of ancient weapons improve when attention is paid to within-weapon variability, how it operates in realistic contexts, and what it could mean for human adaptation.

2.5 Conclusion

Internal and external validity are prerequisites to understanding ancient weaponry through experiment. This cannot be achieved through controlled approaches alone. This paper has demonstrated that improvements in observation can help bridge the trade-off between internal and external validity if an experiment is properly designed, and the results are more comparable with the archaeological record. This provides an appropriate way to take a broad look at the variable forms, functions, and applications of ancient tools. Some of the variables recognized as important in these exploratory tests, such as armature sharpness, can now be subject to validation through appropriate experiments that implement more controls, but the results of those tests should not be divorced from other variables that make ancient weapons effective. Additionally, further iteration of this or similar protocol would enhance the results of the experiments described in this study.

Several improvements could be made to the protocol described in this study. First, carcasses need to be set up in a way that is more analogous to living bodies and consistent across experiments. Laying the carcass down on all fours may be the best approach. If so, a consistent method to prop up lying carcasses should be found. Second, aspects of carcasses affecting the penetration of darts and arrows, such as skin thickness and hair, need to be quantified for inclusion in the statistical analysis. Third, changes in carcasses after death that affect the comparison with living prey need to be characterized. Fourth, it would be particularly helpful to quantify the angle of the projectile on impact and the effects of shaft flexibility (e.g. Key et al. 2018). Fifth, the choice of camera is important to ensure accuracy when measuring velocity and acceleration. The EX-F1 is relatively easy to operate but struggles to produce clear frames in cloudy skies or at the velocities of arrows. Finally, a more thorough record of armatures prior to use will include both 3d modeling and measurements of edge sharpness. It is important to remember that experiments occur on a spectrum from control to realism; some level of control is necessary to make the results of experiments on the realistic end statistically comparable, including factors such as shooting distance and limitations on the variability of the test arsenal.

These tests demonstrate that small, Late Archaic atlatl and dart systems like those from the US Southwest were likely powerful enough to hunt bison without the addition of hunting poison. Certainly, Basketmaker equipment was sufficient against the more common game animals like deer, antelope, and bighorn sheep. Addressing these questions necessitated careful replication of artifacts and learning to use them effectively. Weapons are built for human users to use in variable contexts, and if we are to fully understand them it is in that regard. But this requires commitment to develop skill and engineer effective weapons on the part of the experimenter. Taking on this commitment can benefit archaeologists in a number of ways. Many goals can be accomplished simultaneously using an appropriately designed realistic experiment, although we are still faced with the challenge of capturing enough instances of a phenomenon for statistical analysis, making comparability between experiments an essential concern.

CHAPTER 3. TRIAL-AND-ERROR TESTING OF SKIN SIMULANTS FOR MODELING ATLATL DART ARMATURE PENETRATING EFFICACY

3.1 Introduction

Hunting and defense weapons have a deep history in the hominin lineage. Numerous researchers have suggested that the evolution of weapons through time helped lead to the success of our species (see O'Driscoll and Thompson 2014). Often all that remains of ancient composite hunting weapons are stone armatures (cutting tips). Key to our understanding of ancient hunting and defense weaponry is an understanding of what makes a stone armature effective against living targets.

Archaeological experiments with ancient weapons can be subdivided into two approaches: controlled and realistic. Controlled approaches are attempts to isolate phenomena of interest in laboratory settings. Realistic approaches deploy replica weapons and targets that are closer to those we are ultimately interested in. Both have their strengths and weaknesses: for example, it can be difficult to specify which of many variable(s) produced the observed outcomes of realistic experiments and it can be equally difficult to be certain that the outcomes of controlled experiments represent things that occur in the "real world." In the following controlled experiment, the latter type of uncertainty derives from the difficulty of finding an adequate target to simulate the bodies of prey animals. This is an ongoing challenge with profound implications for the findings of many controlled archaeological weapons experiments. If controlled target simulants are to be useful in the study of ancient hunting and defense weaponry, archaeologists must demonstrate they are *scalable* to the bodies of prey animals or human combatants originally targeted by those weapons.

Here I describe a simple controlled experiment to assess one aspect of armature efficacy: cutting tips and edges. Edge morphology can be described using simple criteria like straight or serrated and dull or sharp. Common sense tells us that sharp edges should penetrate and fracture solid targets (cut) more efficiently. Archaeologists who study ancient armatures tend to focus on geometric attributes (shape and size) or microscopic and macroscopic signs of use, while neglecting what seems like an important variable for armatures that work by cutting paths through targets. Edges are neglected for a practical reason; they are fragile and therefore less likely to survive unscathed on stone tools that can be thousands of years old (Hughes 1998; Shea 2006). A recent set of realistic experiments carried out by myself and colleagues with replica atlatls and bows (Chapter 2) found armature sharpness to substantially reduce the force of resistance, and thus, presumably, to increase the lethality of stone tipped atlatl darts and arrows that penetrated bison and goat carcasses. Although edge preservation remains a problem in assessing the sharpness of original artifacts, the results from those experiments suggest that finer-grained materials tend to be sharper, which would allow for an easy initial assessment of efficacy based on edge sharpness.

It is customary to further validate findings from exploratory experiments using a controlled approach that isolates variables such as edge sharpness. If armature material type really correlates with more effective cutting edges and improves terminal ballistics (the ballistics of target impact and penetration), one expects it to be reproducible and quantifiable in a controlled setting. Controlled approaches generally require a target that is homogenous enough to provide consistent impact data. However, this requires a target that is not only internally homogenous but also scalable to the phenomena being studied (Jussila 2004). Scalability in firearm terminal ballistics has been most concerned with penetration depth, which may correlate with the destruction of tissue caused by high energy projectiles (Janzon et al. 1988). The latter is related to observation of cavities forming around the projectile, although some firearm terminal ballisticians realize that cavitation in clear simulants may not provide the best sense of firearm lethality in real tissues (Bartlett and Bissell 2006; Carlucci and Jacobson 2018).

Target simulants may be deployed for reasons not necessarily having to do with increasing control. There is also concern with the ethics and safety of using large numbers of animal carcasses. Surprisingly little meat is wasted when a carcass is used fresh and butchered after an archaeological weapon experiment (Chapter 2), which substantially reduces ethical concerns when animals raised for meat are used in projectile experiments, but some may still wish to perform experiments under more convenient, sterile, and controlled conditions.

Archaeological weapon investigators have used a variety of target simulants, including ballistics gelatin (Clarkson 2016; Goldstein and Shaffer 2017; Iovita et al. 2014; Loendorf et al. 2018; Sano and Oba 2015; Schoville et al. 2017; Waguespack et al. 2009), clay (Eren, Story, et al. 2020; Mika et al. 2020a; Mullen et al. 2021; Sitton et al. 2020; Werner et al. 2019), foam (Carrère and Lepetz 1988b; Loendorf et al. 2018; Sisk and Shea 2009), and a host of others. Unfortunately, archaeological weapon investigators have not adequately shown that *any* of these targets are scalable to the terminal ballistics of ancient piercing weapons that penetrate prey bodies. This contrasts starkly with the extensive efforts of firearm terminal ballisticians to report details regarding the source, storage, specific methods of manufacture, calibration, and temperature during the experiment of ordinance collagen-based ballistics gelatin (Jussila 2004); archaeologists almost never do this (Mullen 2021; but see Schoville et al. 2017; Wilkins et al.

2014). If archaeologists establish calibration criteria for target simulants now, we would be only 40 years behind the firearm terminal ballisticians (Maiden et al. 2015). But first we need to find simulants that will work for the scenarios we wish to model.

Perma-Gel®, a synthetic gelatin designed as an alternative to collagen-based ordinance gelatin, was used in this set of experiments. Perma-Gel can be melted and reused many times over while maintaining a high degree of homogeneity and consistency between uses. Although synthetic ballistics gelatin has been found by firearm terminal ballisticians not to correlate linearly with ordinance gelatin (Mabbott 2015), I expected Perma-Gel to at least give consistent results when shot velocity and projectile mass were held constant. This turned out to be the case when the proper setup was found. But Perma-Gel is a highly viscoelastic material that produced far shallower penetration than any carcass I have tested, along with some odd results when skin simulants were placed over it.

This underscores the problems with extrapolating directly from experiments on materials like collagen or clay to the settings that archaeologists are interested in understanding. Penetration depths into 10% collagen-based gelatin are found to be scalable to porcine muscle tissue in firearm testing (Cronin and Falzon 2011; Maiden et al. 2015), but relatively slow-moving cutting projectiles do not perform the same way in gelatin as bullets (Karger et al. 1998). I did not expect sharper edges to have a profound impact on the fracturing of a gelatin target and this was confirmed by the experiment. Furthermore, while gelatin mimics muscle for bullet penetration, large masses of muscle are not generally the target of projectile attacks on animals or humans (Mabbott et al. 2016). Hunters are primarily interested in impacts through vital organs, targets that are rarely covered by thick layers of muscle. Modern traditional bows have proven efficacious for hunting deer and other prey (e.g. Bear 1980), but deer frequently survive attacks by hunters when arrows shot from traditional bows impact the shoulder area (Ditchkoff and Welch 1998). Impacts with muscle masses are usually likely to result from missing the target, making it unlikely that ancient hunters designed their points to penetrate the kinds of material that targets like gelatin and clay are hoped to mimic (Key et al. 2018; Mabbott et al. 2016). Firearm terminal ballisticians are also concerned with the dynamics of penetration through such highly complex elements as bone, internal organs, and skin. Internal organs present a complex array of tissues at varying orientations but are generally less resistive than muscle. Skin is a dense and ductile material that can rob much of a projectile's energy (Fenton et al. 2020; Kneubuehl 2011). Sharper armatures on darts and arrows would presumably reduce this effect, and realistic experiments suggest this to be true (Chapter 2).

Skin, bone and muscle operate together as a highly heterogenous and interconnected structure to retard the forward motion of a projectile (Fenton et al. 2020). Perma-Gel® has been found to have a similar compressibility to high velocity shock impacts as porcine muscle (Appleby-Thomas et al. 2016). Thus, the gelatin served as a backing on which to test various skin simulants placed over its exterior, which I hoped would provide a measure of sharpness scalable to penetration of skin *in vivo* by way of changes in penetration depth when no simulant was attached. Following Jussila and colleagues (2005), I report testing of various types of leather and nitrile rubber over the gelatin that might show the effects of sharper edges on test armatures.

Given the social nature of Western science, the literature presents a polished image of a final experiment, while the trial-and-error aspect leading up to it is rarely reported. This is unfortunate because the trial-and-error component in which researchers "learn to see" a phenomenon is essential to understanding how researchers come to know what they do and our ability to fully interpret the findings (Gooding 1990). In addition, no controlled experiment can ever be perfectly repeated due to the specific “preconditions” under which experiments are performed (Prigogine 1997). Many of the important preconditions that impact the outcome of an experiment are also left out of published findings (Gooding 1990). The following paper focuses on the trial-and-error approach (with emphasis on the error) and I present the most important preconditions I was able to observe in Appendix B.

3.2 Background

3.2.1 Establishing metrics for stone armature hunting efficacy

Archaeologists have tended to focus on cross-sectional measures of armatures for determining efficacy and distinguishing between weapon types. Tip cross-sectional area (TCSA, mm^2) and tip cross-sectional perimeter (TCSP, mm^2) are derived from equations relying on the maximum thickness and width of armatures (Sisk and Shea 2009). Cross-sectional area is used in fluid models of bullet penetration (but without the excessive acronym) (Kneubuehl 2011:94). Friis-Hansen (1990) recognized the importance of TCSA on the drag force acting on a stone armature, and used TCSP to calculate the wound surface area (deadliness) an armature could produce at a given depth of penetration (WSA=TCSP*wound length). He also developed the following ratios between armature and shaft cross section: The Area Ratio (AR) between armature and shaft cross-sectional area (TCSA:SCSA) and the Perimeter Ratio (PR) between armature perimeter and shaft circumference (TCSP:SC). The PR must be large enough (>1) that the hole cut by the armature reduces friction on the trailing shaft, while an excessively large AR (an armature much larger than the shaft that carries it) produces unnecessary drag.

Hughes (1998) mentioned that TCSA and TCSP (hereafter TCSA/P) could be useful in distinguishing between the armature sizes of various weapon technologies (arrow, atlatl dart and spear). Samples of these measurements from ethnographic and archaeological hafted armatures as well as experimental armatures were further developed by Shea (2006) and Sisk and Shea (2009, 2011) to distinguish weapon systems in Middle Paleolithic armature assemblages. Several researchers have since used these measurements both to distinguish weapon systems (e.g. Lombard 2020; Sahle et al. 2013; Villa and Soriano 2010; Wilkins et al. 2012) and to study armature penetrating efficacy (Eren, Story, et al. 2020; Mika et al. 2020a; Mullen et al. 2021; Sitton et al. 2020).

However, there is immense variation within these general categories of weapon technologies. Realistic experiments with carcasses and various darts and arrows demonstrate that TCSA/P is only one of many variables affecting projectile penetration, even within the same weapon category (see Chapter 2). TCSA/P is more useful when the size of the shaft (generally correlated with energy and momentum in these experiments) is taken into consideration. This can be done by using the AR and PR with the thickness measure for TCSA/P taken at the haft as established by Friis-Hansen (1990). But this requires the ability to estimate the size of an armature's haft and trailing shaft.

Sharpness must be another determinant of the ability of an armature to cut a path through tissue, but sharpness is difficult to measure and no standardized method exists (Atkins 2009; Hainsworth et al. 2008; Reilly et al. 2004; Stemp et al. 2019). Cutting force varies depending on the direction of the stroke and the material being cut (Reilly et al. 2004). Despite similar morphologies, the efficacy of razors for shaving facial hair and potato peelers could not be adequately understood by relying solely on a standardized cutting test (Atkins 2009). For archaeologists this could make measurements of sharpness, or interpretations of tool efficacy based on sharpness, challenging without first knowing what a tool was used for.

Edge angle measured at various distances from the edge (Dibble and Bernard 1980) and whether an edge is straight (ground) or wavy (knapped stone or serrated) impacts the operation of a cutting tool. But sharpness is perhaps more importantly a function of the microtopography of an edge. Stemp (2019) has come closest to offering a viable way to measure edge sharpness directly on stone tools as a function of edge cross section under high magnification. However, Stemp's methods require further development and the necessary equipment, a confocal microscope, is not necessarily easy to procure. Here, I attempt to measure armature sharpness as a function of cross-section at the very tip (see section 3.3.2) and as a simple function of the resistance force operating on an armature as it passes through simulants. Armatures must penetrate directly through targets, so the latter method seems a rather straight-forward approach when hunting armatures are the topic of interest. However, the effectiveness of this approach depends on the specific material characteristics of the target simulants relative to the biological tissues encountered in prey (Reilly et al. 2004).

Early iron trade points were preferred by Native Americas for their longevity, although chipped stone and especially obsidian were found to be sharper and more efficacious for hunting and combat (Bohr 2014:74, 121). Cox and Smith (1989) noticed the effects of edge dulling on knapped Perdiz arrowpoints fired into a stack of 10 fresh deer hides from close range with a low poundage bow. Within only four shots, penetration was noticeably reduced and points could even break from more rapid deceleration. Sharpness was an important factor in this and another test on a fresh deer carcass. Some arrow points may even have been used for butchering, which fits with ethnographic accounts of Native hunters butchering bison with stone tipped arrows (Brink 2008:177). Cox and Smith found Perdiz points to be effective for butchering deer, but after some use, they became dull. Unlike larger dart points or knives it is harder to resharpen small arrow points, so either from butchering or being fired at game, edge attrition could have resulted in the discard of numerous arrow points that appear otherwise complete (Cox and Smith 1989).

More thorough research on effective stabbing implements is found outside of archaeology. Hunters are highly interested in effective arrow armatures. This has been thoroughly pursued by big game bowhunter Ed Ashby (2006, 2007, 2009) who finds a straight-edge, beveled, razor sharp broadhead with a chisel tip most efficacious for bringing down prey swiftly. The work of forensic pathologists is also highly applicable. Knight (1975) built a device with springs and a sliding scale to measure the force required for different knives to create incisions in cadavers. Tip sharpness was found to be the most important variable to reduce the force required to penetrate skin, but the variability in skin thickness and underlying structures also played an important role. However, the results were later found somewhat problematic because the contraption used by Knight stored energy in the springs that was released after penetration began (O'Callaghan et al. 1999). O'Callaghan and colleagues (1999) tested an experimental knife with a built-in force transducer to penetrate human tissue, finding that the greatest force (49.5 Newtons) was required to penetrate skin while less force was required to penetrate underlying fat and muscle (35 N). As the knife penetrated, multiple peaks in force were recorded. Further work has since been undertaken, demonstrating the variability in the force necessary to penetrate skin and underlying layers and the continued importance of tip geometry (Gilchrist et al. 2008; Hainsworth et al. 2008).

Clearly, armatures need to be sharp to penetrate humans and animal prey. Cross section could play a role in the force required to fracture tissues as an armature penetrates. I also suspected that surface area would be an important measure of the ability of armatures to penetrate viscous materials like gelatin. This metric is most easily obtained from 3d models.

3.2.2 Homogonous target simulants: ballistics gelatin, clay and soap

Perma-Gel used in this study a thermoplastic paraffin-based gelatin that can be used at room temperature and recast by melting. Synthetic gelatins like Perma-Gel are more user friendly and less expensive than collagen-based gelatins, which require careful manufacturing methods, observation of temperature conditions, and are not reusable. However, synthetic gels have not replaced collagen-based gels in standard ordinance testing due to discrepancies in penetration depth (Courtney et al. 2017; Mabbott 2015). The company that produced Perma-Gel has now dissolved, but a similar synthetic gelatin is offered by Clear Ballistics LLC.

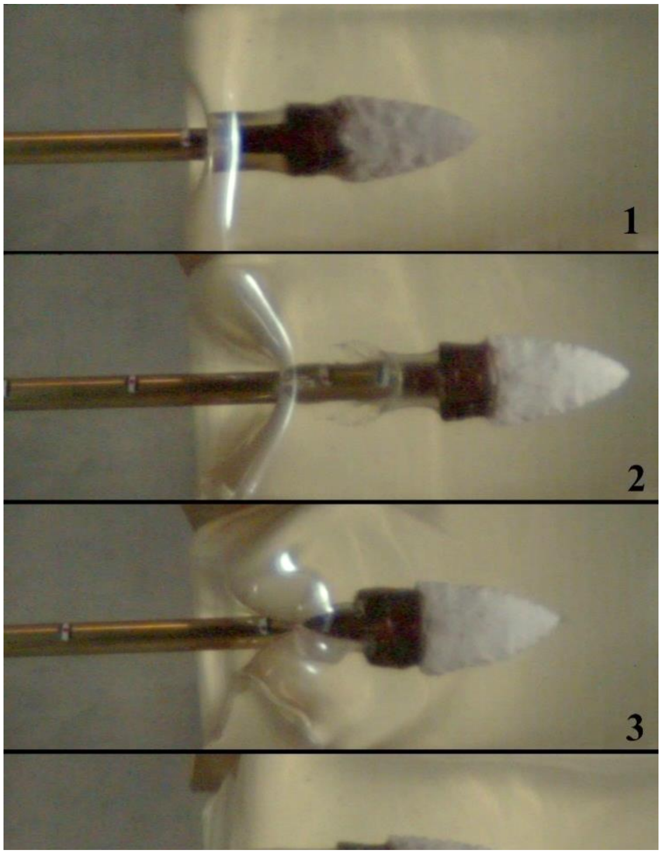


Figure 3.1. Showing the compression of Perma-Gel and pull back from maximum penetration depth of a glass armature.

Few prior tests have been performed on Perma-Gel. Ryckman (2012) fired ½ inch steel spheres into Perma-Gel to test the effects of cavity formation relative to collagen based gel. Clear differences were noted, including a larger temporary cavity and pull-back from peak penetration depth. But overall, the material effects were similar. This “pull-back” (the projectile reversing direction some distance after penetration has stopped; Figure 3.1) appears to be a function of elastic compression and rebound (viscoelasticity) of the material.

Appleby-Thomas and colleagues (2016) tested the strain rate of Perma-Gel by way of plate impact tests and spherical projectiles fired through bone simulants backed by Perma-Gel. Perma-Gel was found to be comparable to porcine muscle at high impact stresses but at lower velocities the materials diverged. Mabbott (2015) tested steel BB penetration into Perma-Gel and 10% and 20% calibrated collagen gel. Penetration was always lowest into the 20% collagen gel, but penetration between Perma-Gel and 10% collagen gel was comparable at around 550 m/s. However, above and below this mid-range the results diverged. Higher velocities produced slightly deeper penetration into Perma-Gel than 10% ordinance collagen gel while lower velocities produced substantially shallower penetration into Perma-Gel, yet still deeper than 20% collagen gel. The standard 250 Bloom 10% collagen-based ordinance ballistics gelatin at 4º C was therefore chosen as a reliable soft tissue simulant for further testing (250 Bloom refers to the strength of the gelatin, while the percentage is of gelatin to filtered or distilled water) (see also Carr et al. 2018; Cronin and Falzon 2011; Jussila 2004). Mabbott (2015) also found penetration into Perma-Gel increased slightly after remelting. I noticed a slight increase in penetration after an initial remelting and before beginning the formal trials, after which point penetration depths appeared consistent over six recastings of each block. The initial discrepancy prior to remelting may be due to compression of the material from being stored. In my case, the material had noticeably flattened out after being stored for 7 years. I did not measure the blocks prior to recasting, but they were at least 2 cm shorter and wider than after recasting.

Most applicable to this study, Karger and colleagues (1998) shot arrows with field points, modern broadheads, medieval bodkins, and medieval crescent shaped cutting tips into 10% collagen gelatin, ballistic soap (another standard simulant popular among European researchers), and 4 fresh pig carcasses. Soap and gelatin were found to correlate poorly with shots into the carcasses. Soap always produced the lowest penetration, but for the pigs and gelatin the results depended on the armature used. Field points averaged 10 cm deeper penetration into gelatin than through the carcasses while broadheads averaged 10 cm deeper penetration into the carcasses than gel. Medieval triangular and chisel-tipped bodkins also showed >10 cm penetration in the carcasses. Ballistics gelatin and soap are therefore not scalable to bodies where arrows with various armatures are concerned.

Lastly, Key and colleagues (2018) and Mullen (2021) working at the Kent State laboratory tested the relative differences between meat, clay, and gelatin targets. Key and colleagues (2018) fired arrows fitted with field points and stone points that were ground to shape on lapidary equipment into both store-bought beef rump roasts and moist potter's clay. The results showed significantly better penetration into clay than meat for the field point, but comparable penetration for the stone point. This suggested that clay can be used to model stone point penetration into biological tissue. Using an Instron materials tester, Mullen (2021) tested the force required for a modern broadhead and a ground stone tip to penetrate meat, 10% and 20% synthetic gelatin manufactured by Clear Ballistics LLC, and potter's clay. The only statistically insignificant difference in the force of penetration occurred when the ground stone point penetrated meat and 20% gelatin. The 20% gelatin was, however, more consistent than penetration forces into meat. The large range of resistance force in meat and consequent overlaps with the other materials suggested that any of the homogenous materials could be used as proxies for living tissue. Clay is cheaper and more easily acquired than gelatin and has been used in several recent experiments at Kent State to test armature penetrating efficacy (Bebber and Eren 2018; Eren, Story, et al. 2020; Mika et al. 2020a; Mullen et al. 2021; Werner et al. 2019).

Clay is recognized as problematic in firearm wound ballistics, not only because it is a much denser medium than soft tissue and has completely different flow behavior when struck by a bullet, it is also likely to be inconsistent between batches, making results very challenging to reproduce and compare (Kneubuehl 2011:173). Importantly, the experiments at Kent State used a limited range of armature types to validate clay, including ground chert, which may or may not be as sharp as knapped chert. Additionally, store bought meat that is not connected to a skeletal structure or overlying skin is not necessarily a good analog for hunting situations in which projectiles are directed at vital organs. For comparison, Roma Plastilina modeling clay has been used as a flesh simulant for knife stab wound studies by police departments. But Ankersen and colleagues (1998) demonstrated that a completely dull (squared off) experimental knife tip experienced less resistance force when penetrating this material than sharp knife tips. Modeling clay is therefore not scalable for stabbing and cutting implements that cut through bodies, where extremely sharp knife tips experience less force of resistance penetrating skin and underlying tissue (Ankersen et al. 1998; Gilchrist et al. 2008; Hainsworth et al. 2008; Knight 1975; O'Callaghan 1999).

3.2.3 Skin simulants

Although terminal ballisticians typically focus on blocks of homogenous material like gelatin and soap, some express interest in other heterogenous structures in the body such as skin. This is sensible because skin forms the immediate barrier to penetrating the soft vital tissues. Fenton and colleagues (2020) describe how the tough collagen fibers in the deep fascia of skin dynamically change orientation during an impact event, aligning in the direction of the impact and becoming increasingly stiff. If the applied force is large enough the fibers will rupture. The deep fascia is also connected to the underlying muscle tissue and bone structure. These complexities of skin on bodies *in vivo* simply cannot be replicated by simulants. Knight (1975) attempted to test knives on a polyethylene “epidermis” over a foam “dermis” but quickly abandoned these materials and relied instead on cadavers. Despite physiological changes after death, recently deceased cadavers or animal carcasses provide more accurate approximations of living skin than synthetic materials or leather, not to mention that a representation of the underlying structures to which skin is attached remain present. The skin of various animals is not necessarily representative of human skin (Fenton et al. 2020). This of course is not an issue if hunted animals are the object of study and a reasonable proxy to a prey species can be found.

Although specially made polymers have been developed to simulate the skin density of interest (e.g. Mahoney et al. 2018), more affordable and accessible simulants like leather and rubber have been suggested for penetration studies (Jussila et al. 2005). Formal testing of such materials involves tests of “strength” that can be compared with the properties of living skin, but these are still problematized by the inherent variability of skin properties in various locations on individual bodies (Fenton et al. 2020). However, consistent simulants are desirable to isolate the efficacy of piercing and cutting weapons. Fenton and colleagues (2020) recommend polymeric simulants which are more internally consistent than leather. Gilchrist and colleagues (2008) tested knife tip geometry on stabbing force in 4 mm polyurethane, which has a similar J-shaped stress-strain curve to human skin. The simulant was held tight in clamps for their test.

Most applicable to this study, Jussila and colleagues (2005) tested accessible materials comprised of leather and rubber over a ballistics gelatin base. Some archaeological weapon experimenters have also tested leather or hide over gelatin and foam targets (Goldstein and Shaffer 2017; Iovita et al. 2014; Loendorf et al. 2018; Sano and Oba 2015; Sisk and Shea 2009; Waguespack et al. 2009). The majority of these tested a generalized idea of a target simulant, gelatin with a leather or hide covering and inset bones, not the specific effects of applying the covering. Sisk and Shea (2009), for example, shot arrows with Levallois flakes into a foam archery target with a 1.7 mm leather covering and measured penetration with the goal of testing TCSA/P. They did not report shooting into the foam without the covering.

Loendorf and colleagues (2018) fired arrows from a mounted bow into foam and blocks of synthetic ballistics gelatin made by Clear Ballistics LLC, with and without a 2.6 to 3 mm thick rawhide covering. A sharpened wood tipped arrow was used to calibrate the bow, but otherwise arrows were tipped with obsidian, siltstone, chert and basalt. The primary goal was to assess the durability and wounding ability of raw material types. Variation in penetration into the uncovered gel was not substantial, but obsidian tended to perform better. When the rawhide cover was applied, obsidian performed worse than the other materials and frequently incurred damage or failed catastrophically. The other materials could also fail when penetrating rawhide. Tougher materials like siltstone and basalt were less likely to fail, but the simple wood point held up the best. Obsidian is therefore suggested to be a good material for cutting through soft tissue but a poor choice when durability is required. Chert offers a compromise between sharper obsidian and rougher materials like siltstone or basalt. These findings make sense, but since the target cover was tough rawhide, the results do not provide a comparison with shots into living skin. The durability information is nevertheless useful, especially considering the use of rawhide armor by pre-industrial combatants (Bamforth 1994; Jones 2010; Loendorf et al. 2018).

Waguespack and colleagues (2009) shot arrows first into a ballistics gelatin torso without a covering, then with a tanned caribou hide “draped over” the target to test penetration of stone and simple sharpened wood arrows fired from a mounted compound bow. Several problems arise with this experiment. First, no description of the type of gelatin, its condition or manufacture is given. Because the target was a torso shape, it varied in thickness, with the thickest section in the chest area. This seems important for the penetration data because arrows were capable of penetrating completely through the target. Because the target was standing up, the penetration depth could vary with the location of impact due to the elasticity of the gel and the inertia of the target at various locations (for a discussion of the importance of target inertia see chapter 2). It is also difficult to know what affect variation in the distance from the draped hide to the gel may have played in the results, or the variability in the thickness of the complete caribou hide for that matter. Nevertheless, both stone and simple wood-tipped arrows were capable of completely penetrating the target. This is important because many ethnographic hunting cultures used sharpened wood projectiles, but there are definite problems with an interpretation that knapped stone tips represent costly signaling rather than functional efficacy (for a thorough critique see Salem and Churchill 2016).

3.3 Methods

I performed the experiment in the Hale Science building at the University of Colorado Boulder during July of 2021. Tile lines on the floor helped align the target and crossbow (Figure B-3 in Appendix B). Following the work by Carrère and Lepetz (1988) several archaeologists have used calibrated crossbows to test ancient projectile weapons and produce samples of impact damaged armatures and bone. “Calibrated” in this sense does not entail any consistency between experiments but suggests matching of desired ballistic profiles of the archaeological weapons being investigated. Although ancient weapon technologies were internally variable and impacted with variable velocities, shooting mechanisms in controlled experiments are generally chosen to reduce such variability. The degree to which either of these conditions are met depends entirely on the goals of the experimenter, the construction of the shooting apparatus and projectiles, and prior knowledge about realistic weapons ballistics. In fact, crossbow designs across experiments are highly variable. Some utilize commercially available bows mounted in various ways and others deploy specially made limbs, mounting frames, and release mechanisms.

The crossbow was constructed of a large steel prod mounted to an oak stock that could be drawn with a hand-crank winch. A constant draw length of 55 cm produced a typical but somewhat fast atlatl dart velocity (mean=28.7 m/s, std dev=0.27) (Whittaker et al. 2017) that gave acceptable penetration into the gel. The end of the crossbow was situated 95 cm from the gel face to allow enough room for the bolt to clear the end of the stock. The gelatin blocks were lain horizontally on a specially made wooden stand that held them at a height so their centers were aligned with the leveled crossbow. A lid of the same material as the bottom board (plywood with bamboo veneer) was attached to the backboard and allowed to rest on the blocks. The viscoelasticity of the gel caused it to grip the smooth vernier and reduce variable compression parallel to the bolt's trajectory between the top and bottom of the blocks, improving consistency in penetration depths.

Test armatures were comprised of 16 stone and glass points that mimicked the Scott's bluff type (Figure B-1 and B 2; Appendix B), an archery field point, and modern broadheads with serrated and straight edges (100 grain 2 blade Stinger® Killer Bee and Buzz Cut). The stone and glass armatures were knapped by a skilled and experienced flintknapper, John Whittaker (Table 3.1). The armatures were hafted to short sections of 13 mm oak dowels using hide glue and sinew coated in several layers of shellac to smooth the haft. As the armatures were knapped in separate batches, they were not all the same size or mass. However, all foreshafts were weighted to 30±0.2 g by gluing lead fishing sinkers into holes drilled in the base. The foreshafts were mounted in a single mainshaft weighing 94 g with a 306 mm long 13.4 mm diameter brass “sleeve” (Figure 3.2). Penetration depth never exceeded the length of the brass. Over the course of the experiment, only one glass armature (#197) incurred damage when it experienced a bending fracture inside the haft after being shot into the gel. Armature were initially oriented horizontal to the ground, so the break most likely occurred due to vibrations in the mainshaft levering the point inside the gel. The experiment proceeded by shooting all points oriented vertically into the center of the gel blocks with shots placed ≥1 cm apart. This produced consistent penetration depths. After each shot, I noted the time, placed a small piece of electrical tape on the shaft at the exterior of the target, extracted the shaft and measured penetration to the nearest mm with a ruler.

Table 3.1. Specifications of armatures used in the experiment. FP=field point and BH=broadhead. All measurements in mm.

Arm.	**TCSA**	**TCSP**	**AR**	**PR**	**SA**	**$TCSA_{tip}$**	**$TCSP_{tip}$**	**SA_{tip}**	**Tip Width**	**Tip Thickness**	**Material**	**Blade**
191	191	54	1.3	1.3	3161	1.4	4.8	3.7	2.02	1.09	Braz. Agate	straight
192	199	55	1.4	1.3	3602	2.7	7.0	5.2	3.04	1.34	Burlington	straight
193	178	53	1.2	1.2	3146	1.1	4.4	2.9	1.96	0.95	Burlington	straight
194	175	50	1.2	1.2	2845	2.3	6.1	4.7	2.48	1.39	Burlington	straight
197	265	76	1.8	1.8	4807	2.8	7.2	5.7	3.01	1.63	Glass	straight
198	262	73	1.8	1.7	4911	1.4	5.0	3.5	2.22	1.04	Glass	straight
199	258	76	1.8	1.8	4895	2.5	6.9	5.0	3.02	1.32	Glass	serrated
200	250	73	1.7	1.7	4558	2.3	6.7	4.7	2.98	1.23	Glass	serrated
201	250	74	1.7	1.7	4969	2.3	6.8	4.9	3.08	1.24	Obsidian	straight
202	238	71	1.6	1.7	4868	3.1	8.0	6.2	3.49	1.6	Obsidian	straight
203	230	69	1.6	1.6	4288	2.4	6.7	5.0	2.96	1.33	Obsidian	straight
204	228	66	1.6	1.5	4204	1.1	4.6	3.1	1.97	1	Obsidian	straight
205	216	62	1.5	1.4	4170	3.1	7.3	5.6	3.14	1.55	Obsidian	straight
206	222	66	1.5	1.5	4519	1.6	5.9	4.3	2.52	1.14	Mozarkite	straight
207	250	70	1.7	1.6	4093	2.3	6.7	4.7	2.96	1.27	Mozarkite	straight
208	242	69	1.7	1.6	4399	2.1	6.6	5.0	2.95	1.16	Mozarkite	straight
FP	61	28	0.4	0.6	1309	1.5	4.3	3.0	1.35	1.38	Steel	N/A
BH1	84	53	0.6	1.2	2467	0.5	3.1	1.7	1.38	0.58	Steel	straight
BH2	84	53	0.6	1.2	2467	0.5	3.1	1.7	1.38	0.58	Steel	straight
BH3	84	53	0.6	1.2	2467	0.5	3.1	1.7	1.38	0.58	Steel	straight
BH4	84	53	0.6	1.2	2427	0.5	3.1	1.7	1.38	0.58	Steel	serrated
BH5	84	53	0.6	1.2	2427	0.5	3.1	1.7	1.38	0.58	Steel	serrated
BH6	84	53	0.6	1.2	2427	0.5	3.1	1.7	1.38	0.58	Steel	serrated

Figure 3.2. Burlington chert armatures (192 and 193) in the socket of the mainshaft (left) and the tapering foreshaft to hold screw-in arrow points (right).

A Chronos 1.4 high-speed camera connected to a nearby computer allowed all projectile impacts to be filmed in slow-motion orthogonal to the firing line. The camera recorded video in 640x240 pixel resolution at 8810.57 frames/sec. Measurements of projectile velocity were obtained using the open-source Tracker program (https://physlets.org/tracker/). In Tracker, videos are calibrated to the 5 cm scale painted on the mainshaft and the video frame rate, while the Autotracker operation is used to place markers over a small target painted on the mainshaft. High speed video allows accurate bracketing of an event of interest, but a high frame rate also produces more erratic velocity data, as markers set close together generate highly sensitive velocity readings. To resolve this, the step sequence in Clip Settings is set to include five frames of the video, with the final frame in the final sequence capturing the moment when the armature distal to the haft, the complete length of the cutting blade on a steel broadhead, or the field point up to the tapered shoulder on the adapter has entered the outer target (Figure 3.3). Markers are then carefully adjusted over the center of the target and velocities are recorded for the moments prior to impact (initial velocity, V_i) and after penetration of the outer target (final velocity, V_f). These data are entered into a Microsoft Access database where penetration duration (PEN_t=armature length/V_i) and deceleration ($a=(V_i-V_f)/PEN_t$) are calculated. Some inaccuracy ($\pm$~100 m/s^2) can be expected in the deceleration data given the high sensitivity of V_f to precise marker placement over this short impact event. For more details see Appendix B.

3.3.1 Photogrammetry for armature ballistic measurements

Cross-sectional metrics can be useful as expressed in section 3.2, but the equations rely on a simplified rhomboid shape for armature cross section (Sisk and Shea 2009). This can result in substantial inaccuracies, especially when measuring thickness at the haft as Friis-Hansen (1990) originally did. Having performed photogrammetry on hafted armatures for the realistic experiments, I found cross-sectional area of lanceolate forms to be as much as 55% larger than predicted by the equation while corner notched types with much wider blades than their hafts were closer to the equations (Chapter 2). The circular area of a bullet is understandably more safely derived from equations, but hafted stone armatures present more complex and highly variable shapes.

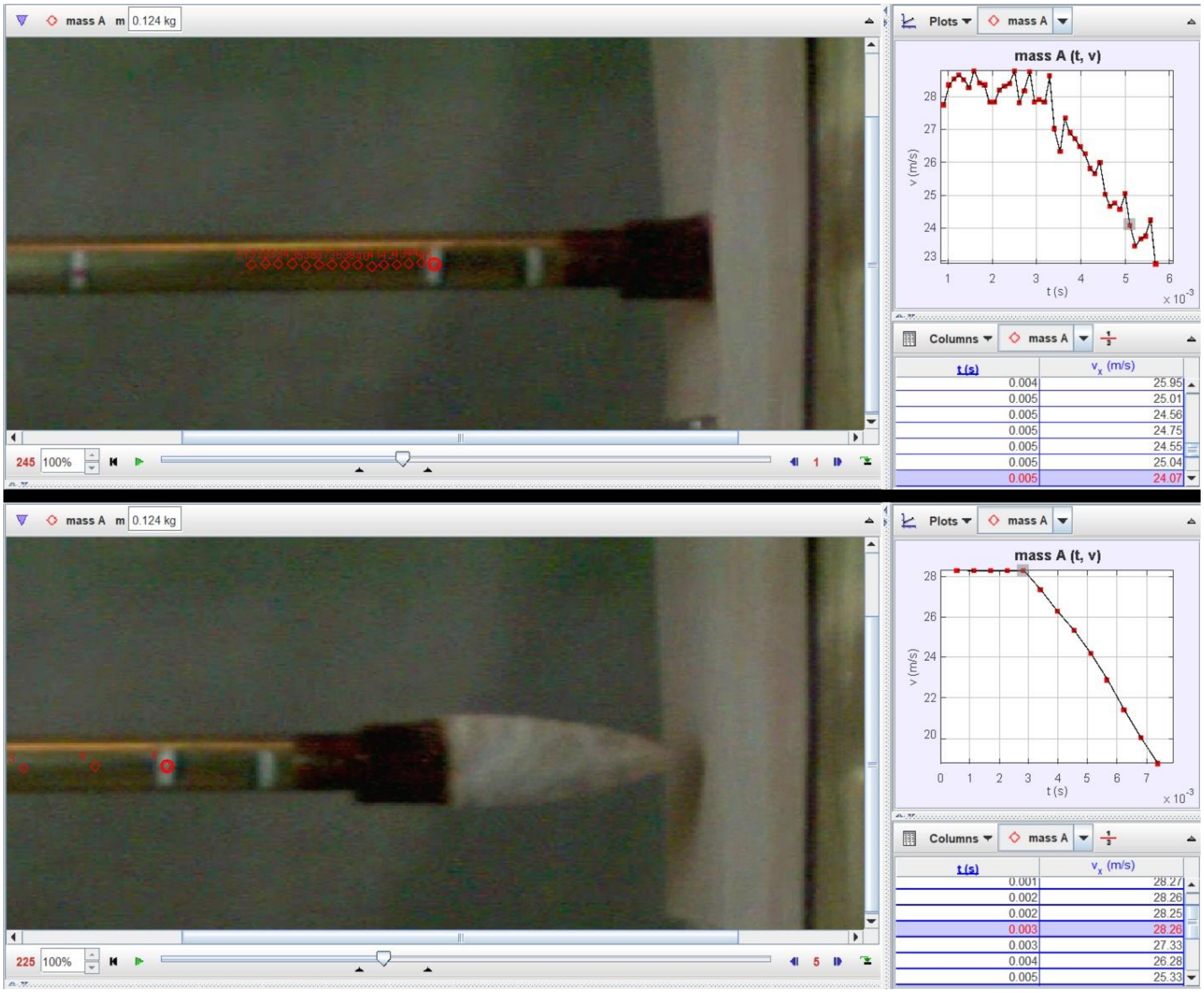


Figure 3.3. Screen clippings from Tracker showing the analysis of a stone armature (#192) penetrating 3 mm tooling leather backed by Perma-Gel. Top: the moment when the "blade" of the armature up to the haft has entered the target is set as the final frame in a larger step sequence. Bottom: increasing the step sequence to five frames improves accuracy of velocity data.

TCSA/P are better derived from scaled 3d models of hafted armatures. Photogrammetry offers a relatively approachable solution. I used a simple approach of rotating only the armatures and keeping the camera, lighting, and black backdrop stationary. The models were then meshed in Agisoft Metashape. As much as in regular artifact photography, glassy or reflective materials can be challenging to photograph. Sublimated ammonium chloride has long been used to apply a thin opaque white to artifacts, which dramatically enhances details such as flaking patterns. The material is easily washed off, but it must be applied under a fume hood (Ives 1941). Porter and colleagues (2016) found developer spray to be an effective alternative. I simply used white marking chalk mixed with water and applied it with a soft paint brush to give the exteriors of armatures and their hafts a thin opaque coating. This dramatically improved the 3d models of all armatures, not just the ones made of shiny materials (Figure 3.4), although if care was not taken the chalk could build up in crevices or accumulate as small lumps in various locations.

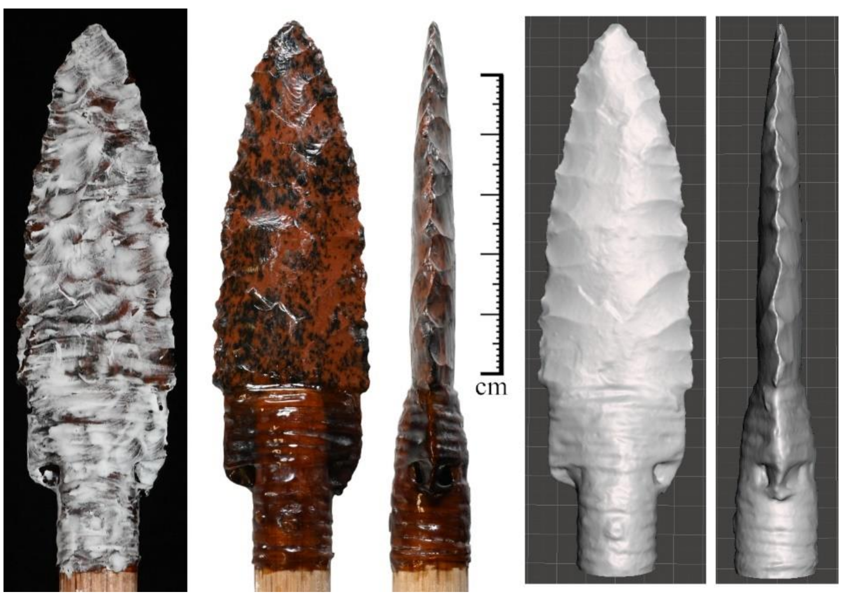


Figure 3.4. Showing the agreement achieved between a shiny obsidian armature (#205) and the 3d model from photogrammetry by applying a thin coating of chalk.

The 3d models were further processed using two open-source programs, Meshmixer and Meshlab. After being properly oriented to the X,Y,Z grid and scaled to the maximum width measured on the armature with calipers, the models were imported into the open-source ParaView program, where accurate measures of TCSA/P could be obtained (for details on how this is performed see Appendix A). Meshlab also offers a “Compute Geometric Measures” filter, which I used to obtain the surface area of the meshed models. This value is subtracted from the area of the foreshaft cross section (127 mm^2) to arrive at the true surface area of the armature and haft.

3.3.2 Macrophotogrammetry for tip sharpness measurements

Models of small objects can also be constructed using macro and microphotogrammetry (Galantucci et al. 2018). The only attempt I made to quantify edge sharpness directly was done using macrophotogrammetry to model the tips of armatures. The method was once again relatively simple, with stationary camera and lighting and a thin layer of chalk applied to the tip (Figure 3.5). I attached a 1 cm scale (having checked its accuracy with calipers) near the tip to facilitate scaling the models in Meshlab. To sidestep any necessary image stacking I used a very small aperture on the macro lens (f/45), which reduced image quality but dramatically increased depth of field. These models show good agreement with the armature tips viewed under a microscope (Figure 3.5).

A number of researchers have attempted a variety of ways to measure the sharpness of tools that puncture materials (see Anderson 2018; Hainsworth et al. 2008). These include tip angle, tip radius, width within 1 mm of the tip, and TCSA/P within 1 mm of the tip. Stone armatures present a special case because they can have highly irregular tip shapes relative to needle-like objects or steel knives. This presents problems for measuring the angle or radius in a reproducible way. Depending on one’s perspective, the tip radius of a stone tool can vary dramatically. For this reason, I relied on measures of tip cross-sectional area and perimeter 1 mm from the tip ($TCSA/P_{tip}$). This was performed by carefully aligning the scaled models to the grid in Meshmixer and performing a 90° plane cut, which produced 3d models of the tips 1 ± 0.01 mm in length. The tip models were imported into ParaView to arrive at $TCSA/P_{tip}$.

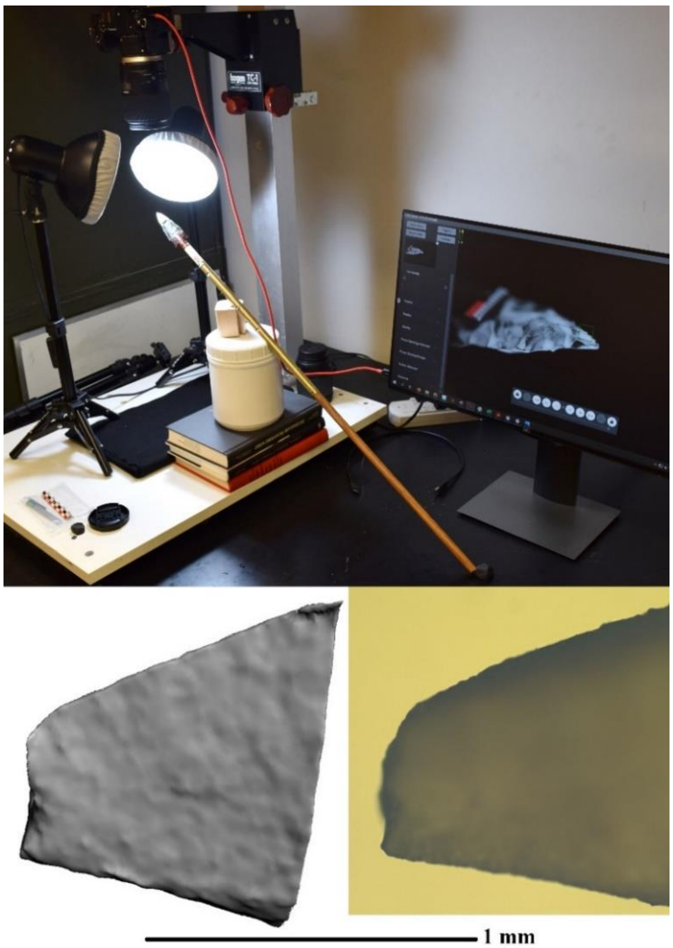


Figure 3.5. Top: The arrangement used to create 1 mm macrophotogrammetry models of armature tips. Bottom: Showing the agreement between a 3d tip model of armature #206 (left) and a microphotograph of the same tip at 100x (right).

It is questionable how reliable this measurement is for quantifying a stone armature’s ability to pierce an object. Given the irregularity of knapped stone tools, some may end in what appears a flat or slightly angled surface, while others may come to a sharp edge. Where to take a measurement of tip angle in these cases is hardly straight forward. I attempted to solve this irregularity while minimalizing sampling bias by measuring the surface areas of the 1 mm tip models using Meshlab, subtracting $TCSA_{tip}$ to obtain the actual surface areas of the tips. Tip surface area has been shown to correlate with less stabbing resistance in metal knives, but using scanning electron microscopy to obtain closer measurements of the tips (O'Callaghan 1999).

3.3.3 Target simulants

The Perma-Gel blocks were purchased in 2014 and used in a brief series of penetration tests. Since then, the gel has undergone notable temperature changes, being stored in a plastic tub and kept in garages. Nevertheless, penetration depths recorded here are comparable to depths achieved with atlatl darts in 2014 (Pettigrew 2015:Table 1). One of the advantages claimed for synthetic ballistics gelatin is its high material stability even despite undergoing temperature changes (Forensics Source 2020). These tests involve two blocks used sequentially during test days, with one being shot while the other melted in an electric roaster oven at 250º F. The cooled blocks measure 39x29x12 cm. Temperature in the room was consistently 76º F, but I found the internal temperature of the blocks dropped very slowly after melting the day prior. Testing proceeded once the internal temperature reached 82º F, which seemed to produce consistent results.

Following Jussila and colleagues (2005), five materials were tested as skin simulants over the Perma-Gel: 1.6 mm and 3.4 mm thick A60 nitrile rubber, 1.6 mm thick cowhide upholstery leather, and 1.8-2.1 mm and 3.2-3.6 mm thick vegetable tanned cowhide tooling leather. Of these, the 1.6 mm thick nitrile rubber was found to give very little resistance to the armatures and did not enter the formal testing. Jussila and colleagues (2005) did not test such thick tooling leather, but I reasoned that these materials might give a measure of the effects of edge sharpness if the thinner materials failed to produce noticeable differences in the force of penetration relative to shots into the uncovered gel. The leather pieces I purchased appeared and felt highly consistent, but leather is recognized as inherently inconsistent in thickness and strength, not only due to processing inconsistencies but also where the leather derives from on the animal. Nitrile rubber should be a relatively consistent material but has different properties than skin that could make results non-comparable.

3.4 Results

The following account presents the results in what is hopefully is a more sensible way than the experiment proceeded. The experiment ended with a final impromptu but illuminating broadhead sharpness test that in hindsight should have been carried out nearer the beginning (section 3.4.2). This simple test could be performed in future attempts to establish viable target simulants for low velocity cutting projectiles.

3.4.1 Penetration into Perma-Gel without a skin simulant covering

Having found a proper target arrangement, penetration depths into the uncovered gelatin were generally highly consistent. All penetration depths across different target types are provided in Table 3.2. Figure 3.6 demonstrates that penetration into uncovered Perma-Gel is strongly correlated with all cross-sectional measurements of hafted armatures (P-value <.0001), including Friis-Hansen's (1990) ratios, the AR and PR, as well as surface area (SA). Although Friis-Hansen used the cross-sectional area to represent drag, as it is used in firearm terminal ballistics, TCSP has been suggested as a better measure of armature penetrating efficacy (Sisk and Shea 2011).

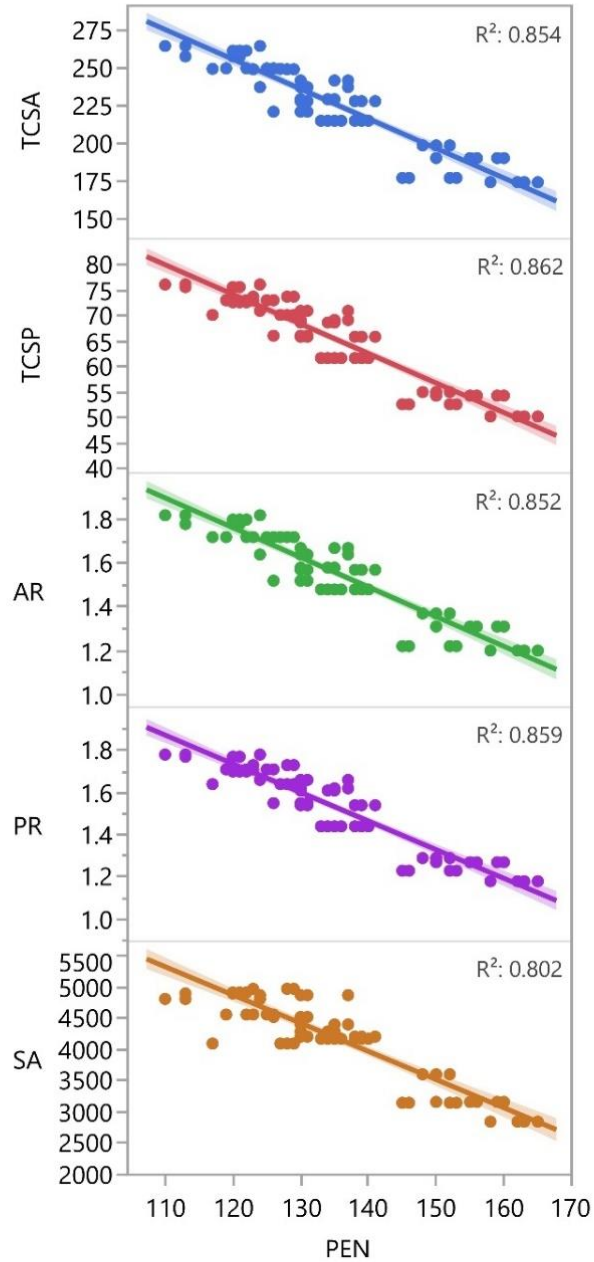


Figure 3.6. Showing the correlation between penetration (PEN, mm) into gelatin with no covering and cross-sectional metrics of stone and glass test armatures.

Table 3.2. Penetration (PEN, mm) and deceleration (a, m/s^2) through the outer target from the formal experiment. FP=field point and BH=broadhead.

	No cover				**Upholstery**				**2mmTooling**						**3mmNitrile**				**3mmTooling**					
	PEN			*a*	*PEN*			*a*	*PEN*			*a*			*PEN*			*a*	*PEN*			*a*		
Arm.	N	Std Dev	Mean		N	Std Dev	Mean		N	Std Dev	Mean	N	Std Dev	Mean	N	Std Dev	Mean		N	Std Dev	Mean	N	Std Dev	Mean
191	4	3.2	153	-400	2	0.7	159	-541	4	4.8	141	3	85	-984	2	0.7	151	-1171	2	4.2	120	2	110	-1822
192	2	2.8	150	-339	2	2.8	153	-816	4	4.3	134	3	201	-1345	2	1.4	139	-1400	2	1.4	110	2	351	-2385
193	3	3.8	148	-612	2	2.1	156	-629	4	6.8	137	3	105	-1151	3	4.5	145	-1186	2	0.7	116	2	125	-2318
194	2	4.9	162	-333	3	5.5	166	-492	5	7.7	138	3	153	-1065	2	2.1	159	-872	2	1.4	122	2	365	-2430
197	1		110	-528															1		96	1		-1889
198	2	0	121	-650	2	2.8	123	-595	4	2.4	111	3	150	-1187	2	2.8	120	-1385	3	3.0	98	3	384	-2116
199	2	5.7	117	-689	2	4.2	114	-737	5	3.7	101	4	372	-1612	2	7.1	112	-1442	3	3.2	94	3	172	-2293
200	2	4.2	122	-584	2	3.5	119	-805	4	4.9	110	3	154	-1263	2	6.4	114	-1379	3	1.7	96	3	237	-2077
201	3	3.2	127	-681	2	6.4	131	-571	4	7.5	116	3	72	-1441	2	2.8	122	-1310	2	2.8	103	2	182	-2415
202	2	4.9	128	-610	2	3.5	133	-619	5	5.2	119	4	246	-1306	2	7.1	126	-1262	2	4.2	104	2	237	-2397
203	2	3.5	133	-537	2	2.8	132	-574	4	3.9	121	3	102	-1124	2	3.5	125	-1147	2	3.5	101	2	350	-2353
204	3	4.9	136	-615	2	2.8	142	-590	4	2.4	129	3	62	-903	2	1.4	133	-1035	2	7.8	113	2	322	-1813
205	2	4.2	137	-562	2	2.8	138	-657	4	3.3	126	3	95	-1253	2	1.4	131	-1233	2	7.8	104	2	390	-2395
206	3	2.6	129	-520	2	2.8	130	-910	4	4.8	120	3	80	-1432	2	2.1	128	-1585	2	8.5	96	2	407	-2733
207	2	7.8	123	-487	2	6.4	120	-1200	4	4.7	106	3	278	-2111	2	8.5	106	-2453	3	7.9	87	2	1193	-3684
208	2	3.5	133	-535	2	7.8	128	-847	5	3.4	114	2	370	-1645	2	10.6	122	-1465	2	17.0	95	2	362	-2650
BH1	7	4.8	158	-239	5	2.1	172	-745	2	2.8	153	2	57	-960	2	2.1	164	-847	4	4.3	142	4	238	-1299
BH2	3	2.9	158	-313															4	4.0	143	4	637	-1434
BH3	3	2	155	-237	4	3.8	163	-374	2	0.7	148	2	52	-524	2	4.9	159	-663	1		136	1		-1000
BH4	2	4.9	168	-253															2	3.5	153	2	99	-1083
BH5	1		170																1		144	1		-1173
BH6	1		171																1		148	1		-1033
FP	7	4.2	151																2	1.4	119	2	287	-2070

TCSP appears slightly more correlated with penetration depth than TCSA in Figure 3.6, but this varies depending on which shots are examined. Upholstery leather did not produce a substantial change in penetration depth for stone and glass armatures relative to no covering (a mean reduction of 7 mm), but TCSA becomes slightly more significant (R^2=0.82) than TCSP (R^2=0.811) for these shots. It seems to matter little which cross-sectional measurement is used to predict penetration depth. Penetration into the uncovered gel is primarily a function of the armature size, which is best captured by cross-section followed closely by surface area. The better correlation between TCSP observed by Sisk and Shea (2009) in their foam archery target may be due to the greater inaccuracies found in TCSA than TCSP when these values are approximated by a rhomboid equation than when taken from accurate 3d models. Hafted lanceolate points can be 55% larger in TCSA and 34% larger in TCSP when taken from models than calculated by the typical equations (chapter 2).

The significant correlation between cross section and penetration into the gel is confused by adding the steel armatures (Figure 3.7), the field point and modern broadheads. Given their much smaller cross sections, these armatures, especially the field point, should have penetrated more deeply. Their shallower penetration is probably in part a function of the tapered wooden foreshaft to which they were attached (Figure 3.2). Notably, the PR of the field point (0.6: Table 3.1) does not meet Friis-Hansen's (1990) criteria of PR>1 to cut its shaft free from friction. Penetration is likely slightly deeper for the steel broadheads than the field point given their thinner blades protruding in front of the armature. In any case, when the steel armatures are included, surface area now best captures penetration into the uncovered gel (R^2=0.693), followed by the AR (R^2=0.671), TCSA (R^2=0.669), PR (R^2=0.587) and TCSP (R^2=0.585).

A small test was performed to determine the effects of drag on the exposed tapered wooden foreshaft used with the steel arrow points. This was inspired by the discovery of Waguespack and colleagues (2009) that penetration of stone tipped arrows was only marginally better into gel than sharpened wood. I wondered if the smoother surfaces of the stone points improved penetration. The exposed wood of the foreshaft with the adapter for the screw-in arrow tips (Figure 3.2) had simply been sanded with 180 grit paper and left unsealed. At 20:00 hours after the gel had sufficiently cooled from remelting the day prior, three sequential shots with the

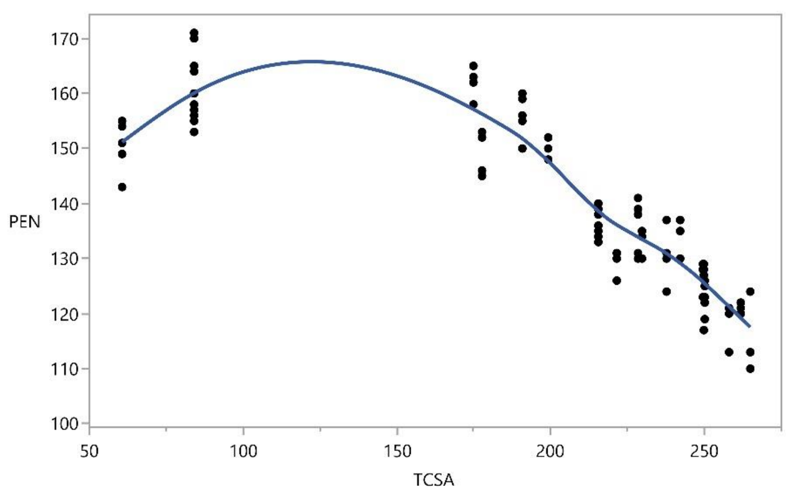


Figure 3.7. Showing how the addition of the steel field point and broadheads (smallest and second smallest TCSA respectively) relative to the glass and stone armatures on the right confuses the fit between TCSA and penetration depth in uncovered gel.

field point penetrated 155, 154, and 155 mm into the uncovered gel. The wood was then given two coats of shellac. Two days later the foreshaft, now with a sufficiently cured slick finish, was tested again on a fresh block of gel at 17:40 and penetrated 149, 149, 143 and 151 mm. If the gel had been warmer the second day penetration should have been slightly deeper. The shellac coating slightly reduced penetration for shots with the broadheads as well, from 165 to 158 mm with a straight edge broadhead and 171 to 164 mm with a serrated edge. This appears to be due to the viscoelasticity of Perma-Gel and the increased purchase afforded it by smoother surfaces.

3.4.2 Broadhead dullness/sharpness study

Before summarizing shots with stone armatures into skin simulants it will be helpful to understand how duller armatures affect penetration into the target simulants used in this study. A test began on July 23rd near the end of the formal experiment and continued the 24th. This was performed with the straight edge Stinger® Killer Bee broadheads, which came as a set of three sharp from the factory. I made no attempt to sharpen the edges further before use.

On July 23rd beginning at 18:09 BH1 and BH2 were shot into the uncovered gel, then into 3 mm thick tooling leather over the gel. The edges and tips were then ground 5 strokes straight down on a rough grit sharpening stone and shot again. This process was then repeated a second time for BH1. On the 24th at 12:31 the thoroughly dull edge of BH1, which could now be easily seen with the naked eye and safely rubbed over skin (Figure 3.8) was shot several more times into both gelatin blocks, neither of which had been remelted the day prior. Shots were directed between prior penetration channels for this final test, but penetration remained highly consistent and comparable to shots on the 23rd. Over four shots the dull armature, BH1, penetrated 156 and 157 mm into the uncovered gel on the 23rd and 153 and 155 mm on the 24th. The final test on the 24th entailed sequential shots with BH1 and BH3, the latter still sharp from the factory, into the other skin simulants.

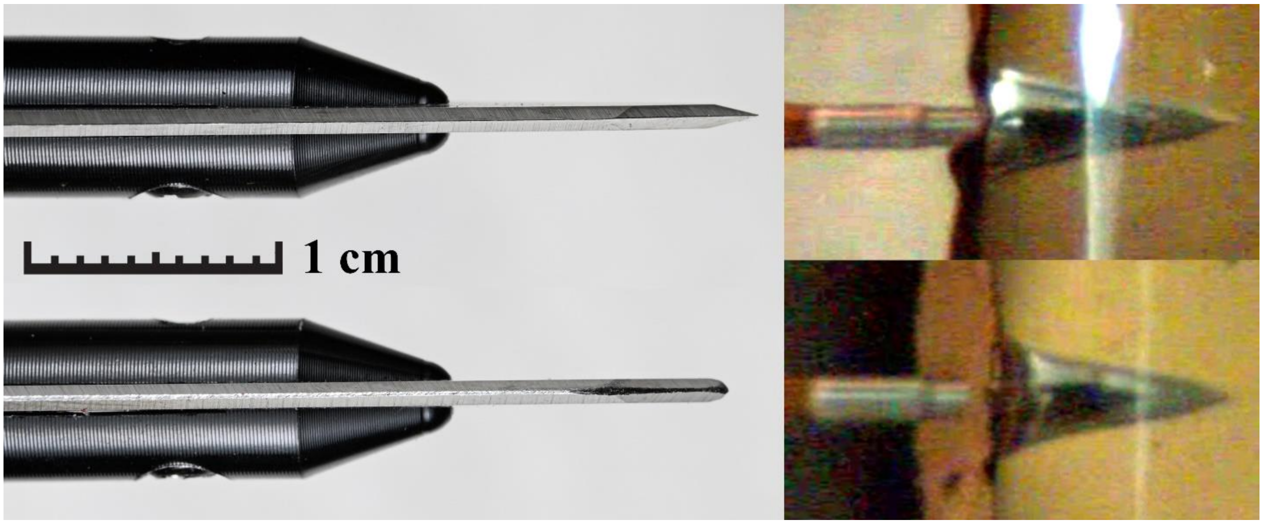


Figure 3.8. Left: the factory sharp tip and edge of BH3 (top) and the dulled tip and edge of BH1 (bottom). Right: the same points penetrating upholstery leather over gelatin, with visible leather pull-in around BH1.

These two tests gave the perplexing results that although deceleration increased as the dull broadhead penetrated leather and rubber coverings relative to the sharp broadhead, penetration depth in the gel did not decrease but remained constant (Table 3.3). When shooting into upholstery leather on the second day, penetration was 10 mm deeper for the duller broadhead than the sharp one, and penetration was also deeper than into the uncovered gel! There are at least two possible explanations: 1) the gel may have compressed more as the dull point pressed into the upholstery leather, allowing the dull armature to penetrate deeper through elastic compression and rebound of the gel, or 2) the smaller incision in upholstery leather by the dull armature pulled the material further into the gelatin and reduced friction on the trailing shaft. This latter effect can be seen in high-speed videos of both armatures penetrating (Figure 3.8) and I regard it as the more likely explanation.

Table 3.3. Results from the broadhead sharpness study. Penetration (PEN) in mm, velocity (v) in m/s, and deceleration (a) in m/s^2.

Day	Arm.	Edge	TargetCover	PEN	V_i	a
23-Jul	BH1	sharp	N/A	165	28.8	-187
	BH1		3 mm tooling leather	145	28.5	-1100
	BH1	dull	N/A	156	28.8	-200
	BH1		3 mm tooling leather	143	28.7	-1400
	BH1	duller	N/A	157	28.8	-220
	BH1		3 mm tooling leather	145	28.3	-1587
	BH2	sharp	N/A	160	28.3	-313
	BH2		3 mm tooling leather	146	28.6	-1060
	BH2	dull	N/A	155	28.6	-313
	BH2		3 mm tooling leather	145	28.2	-2387
24-Jul	BH1	dull	N/A	153	28.4	-240
	BH1		N/A	155	28.2	-237
	BH3	sharp	N/A	153	28.2	-200
	BH3		N/A	155	28.2	-307
	BH1	dull	3 mm nitrile rubber	165	28.3	-827
	BH1		3 mm nitrile rubber	162	28.6	-867
	BH3	sharp	3 mm nitrile rubber	162	28.4	-693
	BH3		3 mm nitrile rubber	155	28.1	-633
	BH1	dull	2 mm tooling leather	155	28.5	-1000
	BH1		2 mm tooling leather	151	28.3	-920
	BH3	sharp	2 mm tooling leather	148	28.4	-560
	BH3		2 mm tooling leather	147	28.5	-487
	BH1	dull	upholstery leather	169	28.5	-753
	BH1		upholstery leather	174	28.5	-813
	BH1		upholstery leather	173	28.6	-780
	BH1		upholstery leather	170	28.1	-680
	BH1		upholstery leather	172	28.4	-700
	BH3	sharp	upholstery leather	158	28.4	-327
	BH3		upholstery leather	163	28.3	-420
	BH3		upholstery leather	166	28.5	-380
	BH3		upholstery leather	166	28.4	-367

3.4.3 Measuring armature sharpness by deceleration

The formal testing of stone and glass armatures penetrating skin simulants proceeded by three rounds of shooting each armature once into upholstery leather, 3 mm nitrile rubber, and 2 mm tooling leather. Finally, the armatures were shot twice each into 3 mm tooling leather. This program was established to smooth any effects from edge attrition as the experiment proceeded. Edge attrition can clearly affect the performance of stone armatures (Cox and Smith 1989), although rubber and processed leather should not be as wearing on edges as unwashed and unprocessed animal hides, which can contain abrasive grit. Some exceptions in the implementation of this test occurred due to measuring errors, or in one instance, corruption of a velocity video file. Some armatures therefore had to be shot twice into a simulant. The glass armatures (198-200) were also shot a third round into the 3 mm tooling leather for the serration study to be described in the next section.

Table 3.3 indicates that armature sharpness cannot be measured by penetration depth into the gelatin even after application of a skin simulant covering. On its own, Perma-Gel cannot capture edge sharpness as predicted, but the high viscoelasticity of this material also makes penetration depth problematic relative to a covering. Although the supple but tough upholstery leather has been selected as a workable proxy for human skin over ordinance gelatin in firearm testing (Jussila et al. 2005), duller armatures can stretch the ductile leather a significant distance into the gel before penetrating, while sharper armatures may traverse this material quickly and interact with the gel. Perma-Gel provides a consistent target backing to support the skin simulants but does not itself interact with armatures in a manner like biological tissue. Investigation of the results therefore proceeds by measuring deceleration through only the outer few centimeters of the target.

This method still captures interaction with both the skin simulant and gelatin backing. However, more resistive target coverings may capture more qualities of cutting efficiency, in effect drowning out the effects of the underlying gelatin. The 3 mm tooling leather is a very stiff and thick leather that I found challenging to cut through with a pocketknife. None of the other target coverings give the high deceleration readings found in 3 mm tooling leather (Figure 3.9). Although Mozarkite points are slightly smaller on average than the glass points a deceleration less rapidly in penetrating the outer few centimeters of uncovered gelatin, the sharper glass points perform much better when upholstery leather, 2 mm tooling leather, and nitrile rubber are placed over the gel. However, larger armatures still seem to experience more rapid deceleration through these target coverings. This is likely partially a result of the deceleration readings through these coverings capturing more interaction with the gelatin backing. In comparison, deceleration can be less rapid for the glass points than Burlington chert through the 3 mm tooling leather, despite the much smaller TCSA of the latter (Figure 3.9).

Figure 3.9 presents the troubling result that each gelatin and skin simulant combination measure different aspects of armature efficiency. Thick tooling leather seems more promising for capturing the cutting efficiency of armatures, but leather is not an internally consistent material. Both tooling leathers could produce inconsistencies between shots. All armatures decelerated more rapidly on the second round of shooting into 3 mm tooling leather, producing the high outliers and visible overlaps in deceleration between materials shown in Figure 3.9, although edge attrition after the first round of shooting through this more resistive material cannot be ruled out. Nitrile rubber provides a more internally consistent medium, but as the dull and sharp broadhead test demonstrated (Table 3.3), deceleration through nitrile rubber is less pronounced between dull and sharp armatures than deceleration through leather.

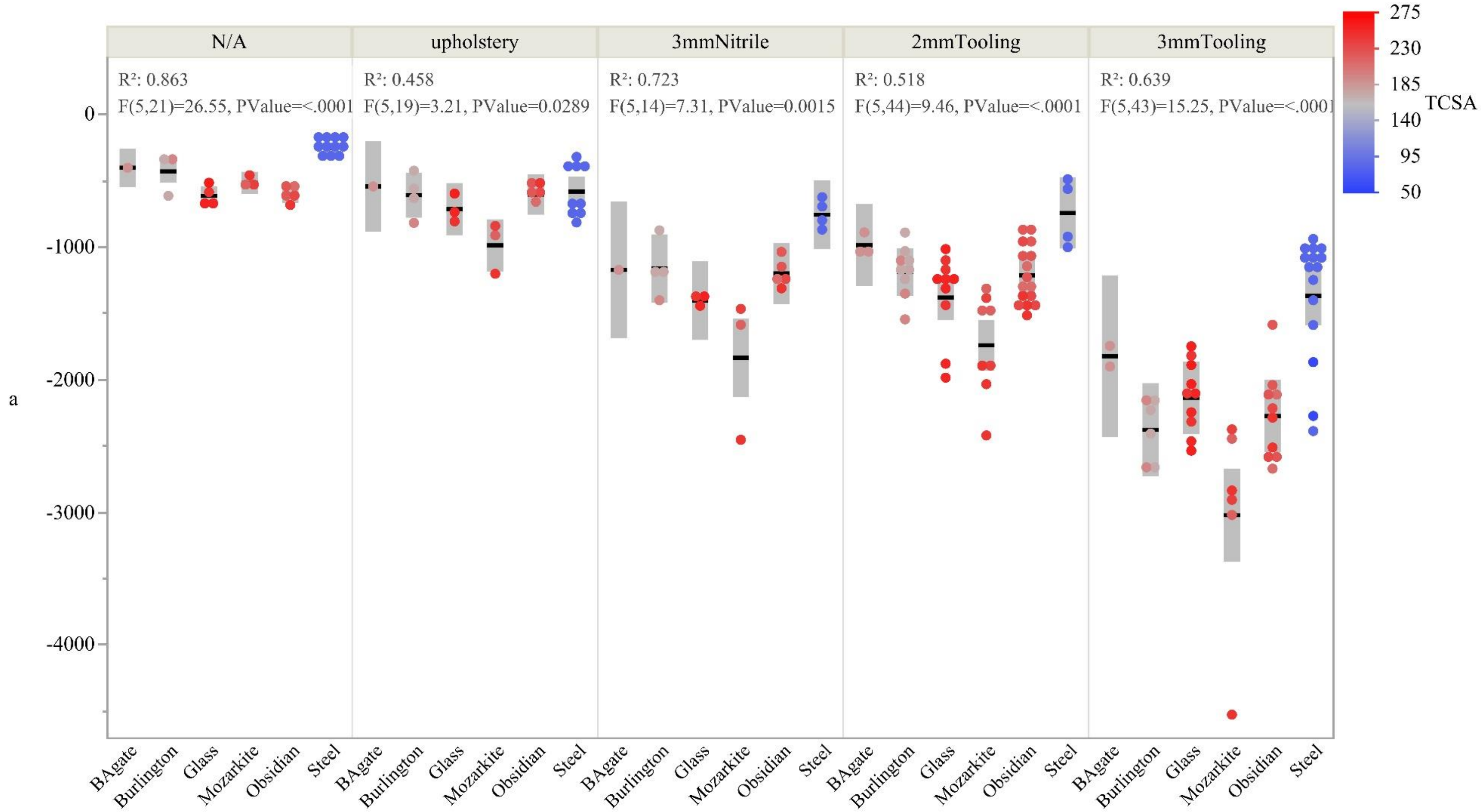


Figure 3.9. Deceleration (a, m/s^2) experienced by glass, stone and steel armatures penetrating skin simulants, colored by TCSA. Low outliers for steel in skin simulants represent the dulled broadheads and field point.

Deceleration in tooling leathers provides results that corroborate the performance of finer-grained armature materials penetrating carcasses (Chapter 2). An obsidian point with the smallest cross section (204) approached the low deceleration experienced by the thin and very sharp steel broadheads penetrating 3 mm leather. The Brazilian agate point (191), with a cross sectional size comparable to the Burlington chert points, performed better than the latter in 2 and especially 3 mm leathers, but not in nitrile rubber. This aligns with the efficiency of Brazilian agate and Burlington chert armatures used in carcass experiments (Figure 2.7) and provides further reason to question the applicability of nitrile rubber as a scalable skin simulant for low velocity cutting projectiles that target biological tissue.

The problem of whether tip cross-section or sharpness is a better measure of armature efficacy can be further explored by plotting deceleration through target coverings against TCSA. We may recall that TCSA gives a significant negative correlation with penetration depth into uncovered gelatin (Figure 3.6). An initial negative correlation occurs for all simulants until the steel broadheads are removed from the analysis, which are both very sharp and have small cross-sections. It has already been demonstrated in section 3.4.2 that blade sharpness plays no role in the ability of steel broadheads to penetrate gelatin. However, the sharpness study (Table 3.3) did demonstrate that sharpness plays a significant role in the reduced resistance force they experience penetrating target coverings. This is further demonstrated by the fact that the steel field point, although having the smallest TCSA of all armatures, decelerated as rapidly as the large glass armatures through 3 mm leather despite penetrating far deeper than those points into uncovered gelatin (Table 3.2). Once the steel points are removed, a negative correlation still obtains with deceleration through 2 mm leather and weaker correlations remain in upholstery and nitrile. Removing a low outlier from a Mozarkite point (207) that decelerated rapidly across target coverings improves the fit in 3 mm nitrile (R^2=0.31, P-value=0.033). But no correlation obtains in 3 mm leather (Figure 3.10).

Tip cross-sectional metrics are an ineffective way to predict the deceleration of these various armatures when penetrating the target coverings. We are left with the necessity of better quantifying armature sharpness to use as a predictor of efficacy. Prior work in forensics has indicated that the sharpness of the tip is the most important variable in the force necessary to penetrate skin with a hand-held knife (Gilchrist et al. 2008; Hainsworth et al. 2008; Knight 1975; O'Callaghan 1999). This can be examined by way of the metrics obtained from the macrophotogrammetry models of armature tips. Of all these metrics ($TCSA_{tip}$, $TCSP_{tip}$, SA_{tip}, tip thickness, and tip width) the best correlation obtains between tip width of the stone and glass armatures and deceleration (Figure 3.11). But weak correlations are only suggested for the leather coverings and only meet a P-value threshold >0.05 in 2 mm tooling leather. This suggests that quantifying the sharpness of various armature materials will need to rely on methods to measure the microtopography of edges (Stemp et al. 2019).

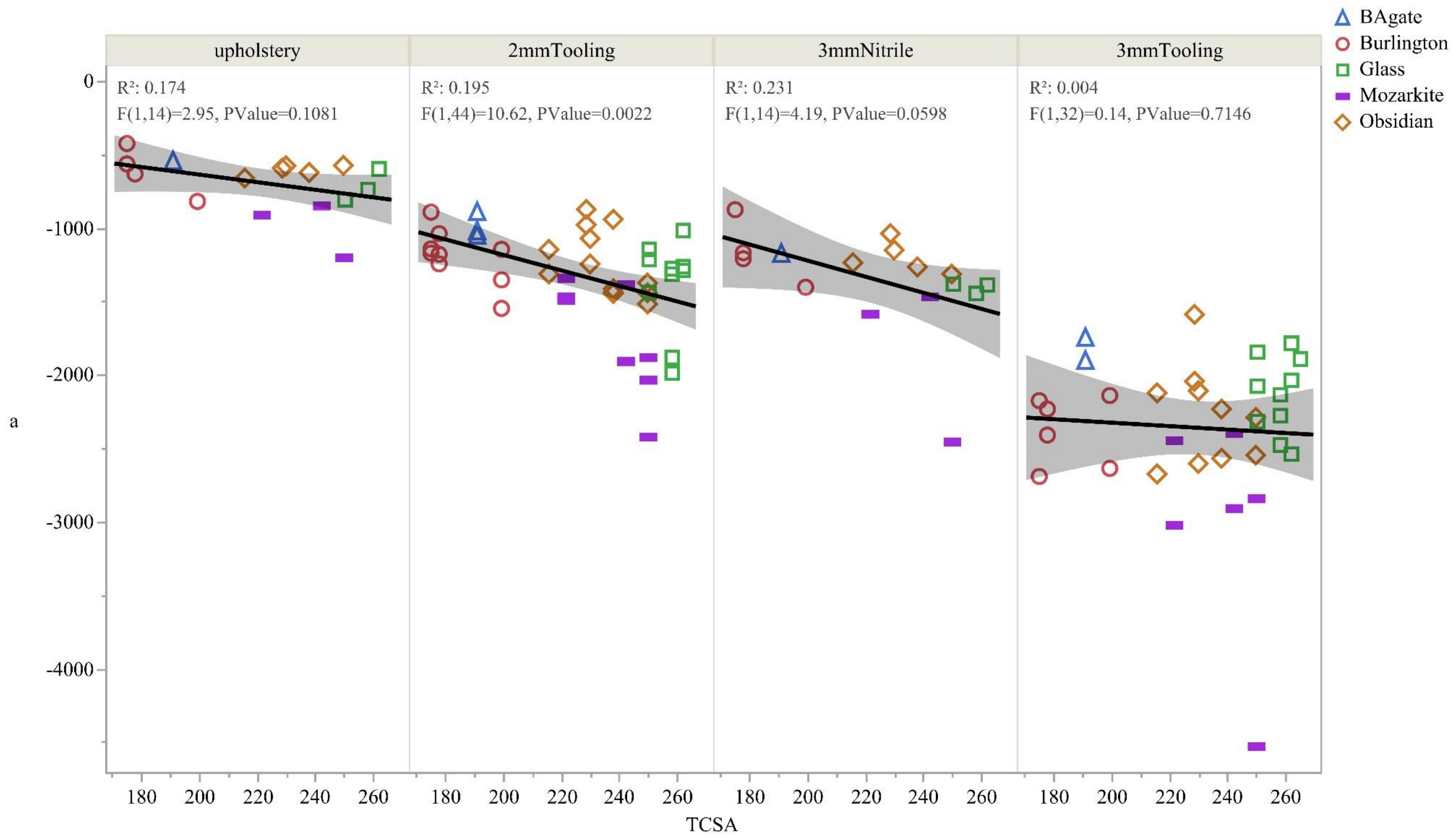


Figure 3.10. A linear regression fitting deceleration (a, m/s^2) through four skin simulants against armature tip cross-sectional area (TCSA, mm^2) for the stone and glass armatures.

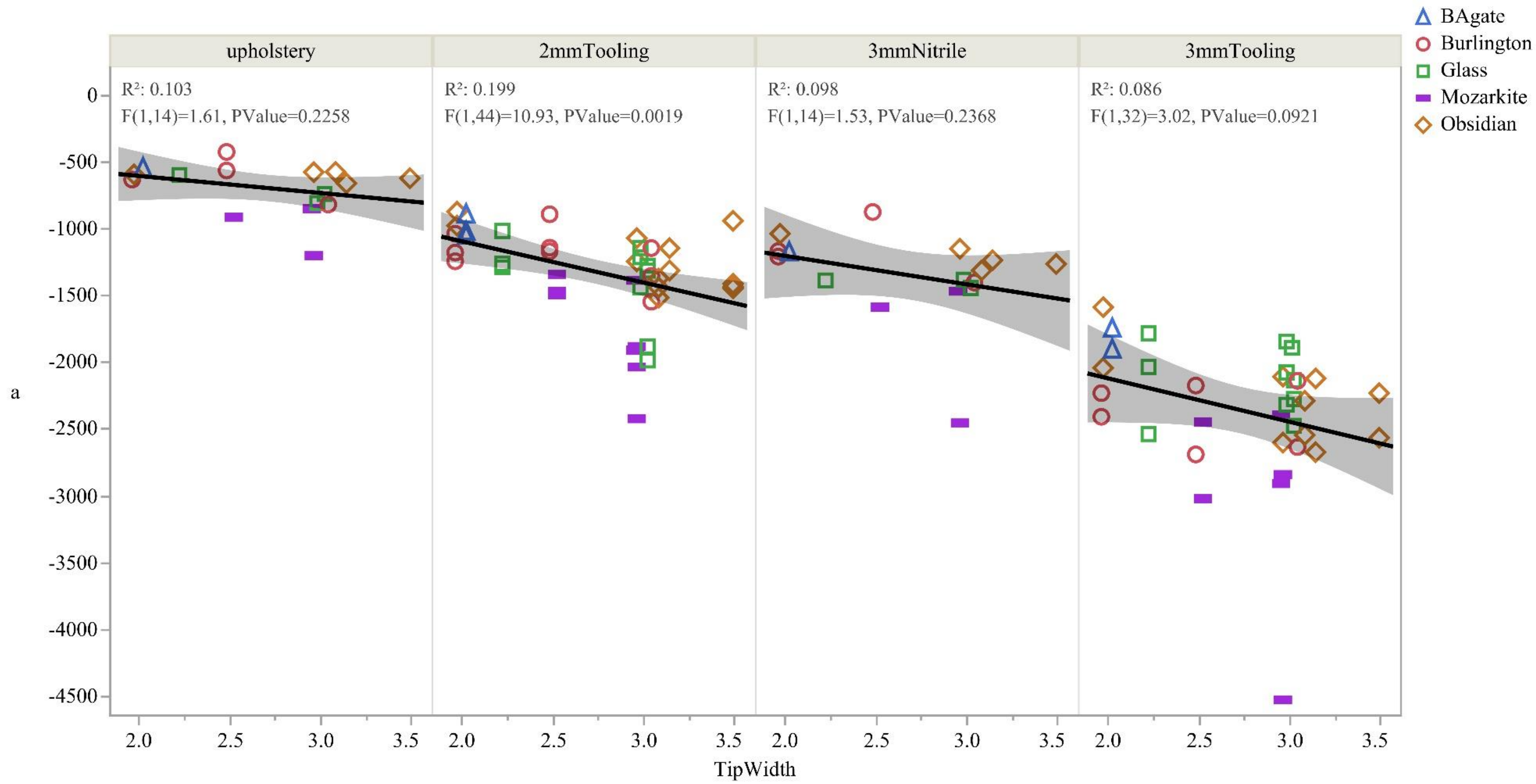


Figure 3.11. A linear regression fitting deceleration (a, m/s[2]) against the widths of armatures measured 1 mm from the tip.

3.4.4 Testing serrations

The final study to mention is a test of straight versus serrated edges. The two types of Stinger® broadheads were the same in every respect except edge morphology. Viewing the tips through a stereomicroscope at 100x did reveal slightly different characteristics for each broadhead, with one outlier; BH6 came with a rolled tip that was not noticed until it was placed under the microscope. Otherwise, the broadheads appeared and felt very sharp. The glass points produced by John Whittaker came as a set, two with straighter and two with more serrated edges. As mentioned, one of these (197) experienced a bending fracture during initial shots into the uncovered gelatin. This blade was glued back into the top of the haft with hide glue and survived a calibration shot into the uncovered gel followed by a shot into 3 mm tooling leather. Of course, relative to the straight edges on metal or ground stone armatures, knapped stone armatures generally have serrated-like edges, but some knapped armatures in the past were given prominent and purposeful serrations.

Initial tests into the uncovered gelatin demonstrated that the serrated broadheads penetrated slightly deeper (>10 mm) than those with straight edges (Table 3.4). This may be a function of the scalloped blades of the serrated broadheads reducing the smooth surfaces for gelatin to grip. This effect could not be demonstrated for the different types of glass points. Glass armature 198 is slightly longer than the others with a more acute point and was efficient at penetrating target coverings. Like 198, 197 has a "straight" edge, but is closer in shape to the serrated glass armatures 199 and 200. Penetration into uncovered gel is not significantly different for these armatures, but when 3 mm tooling leather was placed over the gel the serrated glass armatures appear to decelerate slightly more rapidly, although these figures are only slightly outside the margin of error of the deceleration measurements (±~100 m/s^2). No significant difference in deceleration through 3 mm leather obtains for the straight and serrated broadheads.

Table 3.4. Results from the edge serration study. Penetration (PEN) in mm, initial velocity (V_i) in m/s, and deceleration (a) in m/s^2.

Arm	**Edge**	**TargetCover**	**PEN**	**V_i**	**a**
197	straight	N/A	124		
198		N/A	121		
199	serrated	N/A	120		
200		N/A	119		
BH1	straight	N/A	158		
BH2		N/A	160		
BH3		N/A	157		
BH4	serrated	N/A	171		
BH5		N/A	170		
BH6		N/A	171		
197	straight	3mm tooling leather	96	28.36	-1889
198		3mm tooling leather	101	28.66	-1781
199	serrated	3mm tooling leather	95	28.43	-2274
200		3mm tooling leather	95	28.29	-2074
BH1	straight	3mm tooling leather	136	28.78	-1107
BH2		3mm tooling leather	137	28.49	-1140
BH3		3mm tooling leather	136	28.36	-1000
BH4	serrated	3mm tooling leather	150	28.32	-1153
BH5		3mm tooling leather	144	28.2	-1173
BH6		3mm tooling leather	148	28.43	-1033

3.5 Discussion

The experiment just described highlights problems for archaeological weapon experiments that rely on target simulants. Gelatin is, to an extent, accepted by firearm terminal ballisticians as a workable simulant for representing munitions behavior in soft tissues, but this requires consistent production methods and calibration to achieve repeatability between experiments and better ensure target stimulants are scalable. Ongoing investigations continue to demonstrate the relative strengths and weaknesses of ballistics gelatin for modeling bullet penetration in heterogenous biological tissues. Bullet penetration into tissues can be modeled as penetrating fluid media and gelatin responds hydrodynamically to bullet penetration (Appleby-Thomas et al. 2016; Kneubuehl 2011), but the successful application of a material for modeling the terminal ballistics of modern munitions in soft tissue does not promise that it will faithfully model the ballistics of stone, glass, or metal cutting armatures mounted on low velocity projectile shafts in the same tissues.

Aside from bone, skin is the toughest barrier a projectile will encounter when penetrating the body of a prey animal or human victim. The forensics of stab wounds has repeatedly demonstrated the dramatic effects of sharper tips and edges in reducing the force necessary for a knife to penetrate the tough dermis of skin and underlying tissues (Gilchrist et al. 2008; Hainsworth et al. 2008; Knight 1975). As force is applied to skin, the fibers align and become stiffer, changing from ductile to more brittle and eventually fracturing. The viscous nature of gelatin does not capture the ability of a sharper armature to fracture skin and underlying tissue more efficiently. Studies of the efficiency of armatures that cut through tissue require target simulants that clearly demonstrate the effects of sharper tips and edges.

Ashby (2005a) reported finding no simulant that would reliably mimic prey bodies for modeling the behaviors of hunting arrows. He instead prefers testing hunting arrows on freshly killed prey. Karger and colleagues (1998) demonstrated that neither ballistics gelatin nor ballistics soap was scalable to the penetration of arrows and crossbow bolts that penetrated fresh pig carcasses. Scalability does not necessarily require a perfect correlation between penetration depth in a simulant as through a body, but in the latter experiment, an archery field point could penetrate more deeply in ballistics gelatin than into carcasses, while the opposite was the case for any of the sharp cutting armatures. This is apparently due to the greater purchase that viscoelastic gelatin has on armatures with greater surface area. Despite sharper tips and edges significantly enhancing penetration into heterogenous biological tissue, these same armatures performed relatively poorly in ballistics gelatin.

This problematizes the use of clay as a target simulant as well. Like gelatin, moist potter's clay lacks characteristics of biological tissue that enable sharper armatures to excel at penetrating. In fact, duller armatures can experience less force of resistance penetrating clay than sharper ones (Ankersen et al. 1998). When a field point penetrates more deeply into clay than into meat while a ground stone point gives similar results (Key et al. 2018), this should raise concerns about the scalability of clay for the express purpose of testing the performance of various armature morphologies in penetrating biological tissue. One instance of comparable penetration depth between a target simulant and biological tissue does not adequately demonstrate the scalability of a simulant. Firearm terminal ballisticians have abandoned target simulants for less pronounced demonstrations of non-scalability (e.g. Mabbott 2015) than the variation noticed by Key and colleagues between field points and stone points in clay and meat. At minimum, it must be demonstrated that an experiment is measuring the same characteristics that make an armature capable of defeating both a target simulant and the realistic target being modeled.

Tip cross-sectional area and perimeter are metrics used by many archaeologists to distinguish armatures and determine their efficacy, but among the research on efficacy are shots into homogenous targets that have never been properly scaled to human or prey animal bodies (Sisk and Shea 2009; Sitton et al. 2020). When cutting armatures are tested against materials that capture the benefits of sharper tips and edges, TCSA/P are less important measures of penetrating efficacy. But given the lack of demonstrated scalability between the target simulants used by archaeologists and biological tissue, it is perfectly reasonable to ask what has been discovered by the experiment just presented. Apart from learning about the difficulties involved in configuring the many components of a controlled experiment to produce reliable and consistent results that are scalable to a phenomenon of interest, the experiment has demonstrated that knapped volcanic and man-made glass points have the capacity to decelerate less rapidly when penetrating thick tooling leather over a gelatin backing at ~28.5 m/s than rougher materials like Burlington chert and Mozarkite, despite the former having as large or larger TCSA/P than the latter. Extending these findings beyond this domain is inadvisable without first understanding precisely why this is the case and repeating the process to be sure.

It may be that the failure mechanisms (strain rate sensitivity) of thick vegetable tanned cowhide pressed into a synthetic gelatin backing is such that the results are not capturing edge sharpness but some other variable, such as the smoother surface of glass. Stab wound studies show that subtle differences in the factory sharpness of knife tips viewed at microscopic resolution correlate with the amount of force necessary to penetrate skin simulant (Gilchrist et al. 2008; Hainsworth et al. 2008). But the measurements of tip sharpness in this study correlate only weakly with more efficient penetration into tooling leather. Although these measurements follow previous methods to examine tip sharpness, more accurate approaches may be necessary (O'Callaghan 1999; Stemp et al. 2019).

More reassuring are the behaviors recorded for actual atlatl darts with stone and obsidian armatures penetrating recently deceased bison and goat carcasses, in which finer-grained armature materials demonstrated the capacity to dramatically reduce the force of resistance during penetration (Chapter 2). Force of resistance (F_r=mass[kg]*acceleration[m/s^2], measured in Newtons [N]) is dependent on the projectile's mass and velocity and the strain rate sensitivity of the target, as much as on the ability of armatures to concentrate force in a small area (Anderson et al. 2016; Atkins 2009). Target materials must be tested under such dynamic loading conditions and compared against more realistic experiments to understand how they will perform as simulants for low velocity projectiles with cutting armatures. Static loading conditions, such as produced with an Instron materials testing machine, and test materials of clay and *in vitro* muscle tested long after death (store bought meat) (Mullen 2021; Thomas et al. 2017) are not representative of the conditions of projectile impact on a living target. For example, F_r can be lower when cutting armatures penetrate fresh biological tissues at higher velocity (Ankersen et al. 1998; Knight 1975).

For shots with atlatl darts and arrows into the outer skin and tissue layers of the bison, F_r could vary dramatically from <30 to >250 N, depending on the orientation of the projectile, its velocity and mass, where the impact occurred, and the sharpness of the tip and cutting edge. Impacts to the thorax between ribs could experience less F_r than to the abdomen, but the sharpness of the armature seemed more important. After penetrating outer tissues, F_r could drop dramatically through internal organs depending on further factors such as the specific tissues encountered in the body cavity and drag on the trailing shaft. A sharp Brazilian agate point mounted to an atlatl dart experienced 50 N of force (a=-586 m/s^2) penetrating the skin over the outer thorax of the bison and dropped to 39 N (a=-430 m/s^2) penetrating the vital organs. A stemmed Burlington dart point experienced 275 N (a=-1204 m/s^2) penetrating the skin above the abdomen and 80 N (a=-462 m/s^2) through the interior (Figure 2.5).

The forces experienced by armatures penetrating through 3 mm tooling leather (180-240 N) are generally much higher than those recorded on the bison, as they are when penetrating the interior of the gelatin. At the mass and velocities recorded in this experiment, the bolts would likely have penetrated entirely through the bison if bone was not encountered. Shots into the thinner tooling and upholstery leather seemed more agreeable, but the data from these simulants harder to interpret as armatures more quickly traverse them and interacted with the gel backing. A backing material is not necessarily required to measure F_r when penetrating a skin simulant (Gilchrist et al. 2008), but no backing requires a consistent way to clamp material in place without introducing too much or too little tension. Elasticity of a skin simulant with no backing produces additional problems for experimental design and scalability of the results. Still, there are limitations in what can be said from testing a simulant with or without a homogonous backing. Both methods remain problematic analogs for prey animal bodies, where skin is supported by underlying tissues and skeletal structure. Ideally, further controlled tests will focus on finding a target medium to mimic shots through *in vivo* skin, muscle, and internal organs, or alternatively, through freshly deceased complete animal carcasses. A composite structure may be needed as a reliable simulant, which may be difficult and expensive to produce. Archaeologists generally require low cost, accessible, and consistent (from the factory or easily produced) materials for testing ancient weapon ballistics.

If the findings from shots into thick tooling leather are measuring similar characteristics of armature efficacy to those measured in the carcass experiments, it would help demonstrate that what many archaeologists are in the habit of referring to as “exotic” tool stone were often sought by ancient people for a functional reason. They perform better when penetrating and incapacitating prey because they produce sharper knapped edges. Testing this concept further, it may be easier to use fresh carcasses that can be butchered afterwards and consumed, simultaneously reducing the ethical problems of such an experiment while increasing the research scope to including butchery, use-wear, and skeletal lesions with detailed impact histories. While variability is inherent in a carcass, this is also the case of the real application of the technologies we are trying to understand (Ashby 2005a; Bamforth 2010; Keeley 1980). Even given this variability, phenomena of interest can be isolated using statistical procedures when the necessary variables are recorded. Tissues go through changes after death that make them imperfect representations of living tissues, but even shortly after death, an animal carcass is far more scalable to the body of a living animal than any of the simulants thus far put forward, including expensive specially made polymers (Fenton et al. 2020). As such, the results from such experiments are more easily interpreted without requiring a background in materials testing, which most archaeologists lack. It goes without saying that understanding edge sharpness by material type will also benefit a great deal from direct measurements of edge sharpness on stone tools.

3.6 Conclusion

Controlled archaeological weapon experiments that use target simulants must validate their targets against “real-world” applications. When this is not done, the findings from such experiments may be prone to capturing information that is not pertinent to the phenomena they set out to model. This problematizes many past archaeological weapon experiments. A good example are the cross-sectional metrics (TCSA and TCSP) that are frequently used to distinguish weapon systems based only on armatures and to study their efficacy. While these metrics are highly pertinent to the ability of armatures to penetrate gelatin, foam, and clay targets, they appear less important when armatures of variable sharpness fracture (cut) materials like leather or biological tissues. The controlled experiment described here supports the finding from realistic experiments that armatures of finer-grained materials, frequently called “exotic” tool stone by archaeologists, tend to be sharper and better capable of fracturing biological tissues. But in the simple experiment outlined in this paper, the findings are most problematized by the properties of Perma-Gel, a synthetic ballistics gelatin used as a target backing for leather and rubber materials tested as skin simulants. Stone and glass atlatl dart armatures do not behave the same way when penetrating Perma-Gel as they do when penetrating animal carcasses, which also makes the penetration of skin simulant covers over Perma-Gel challenging to interpret. Secondly, the results are problematized by the uncertainty that thick tooling leather is a scalable simulant for living prey animal skin. Without data from realistic experiments in carcasses to compare against, these problems in controlled archaeological weapon experiments would not be so clear.

CHAPTER 4. WHAT CAN ARCHEOLOGISTS LEARN FROM EXPERIMENTS WITH OLD WEAPONS? BRIDGING THE GAP BETWEEN CONTROL AND REALISM

4.1 Introduction

Few of the residues of ancient humans and their ancestors get as much attention as those derived from hunting weapons. Improvements in weapons are among the suite of traits used to identify higher cognition and modern behavior in ancient humans (Lombard and Haidle 2012). Weapon advances are also thought to have allowed our species to migrate to distant corners of the globe (Churchill 1993; Marlowe 2005; Shea and Sisk 2010). This has not been without problems. Part of the interest in weaponry is a product of preservation bias. Stone armatures (cutting tips) are among the few categories of ancient material culture capable of withstanding the elements. Hunting big animals probably wasn't merely a way of showing off, but other ancient pursuits such as gathering plant food were absolutely essential (Gurven and Hill 2009). Attempts to recognize a behavioral revolution through a suite of material signatures is increasingly acknowledged as problematic due to prior expectations for modern behavior in our species and the assumption that technology implicates "modernity" (Mcbrearty and Brooks 2000; Milks 2020; Villa and Roebroeks 2014). But these problems do not preclude the assumption that weapons used in hunting and defense have been important to our survival and success.

Archaeologists have never escaped the need for contemporary analogs to interpret past lives (Ascher 1961; Wylie 2002). Ethnographic accounts, as well as the experiences of archaeologists in building and testing weapons, are the analogs archaeologists use to infer weapons from artifacts and interpret their application. In this paper, I focus on the experimental program archaeologists have used to study ancient hunting and fighting weapons. My research has tended to focus on terminal ballistics (the ballistics of target impact and penetration) but I will also consider research into the internal and external ballistics of old weapons (their launch and flight through atmosphere). Weapon experiments are generally problematized by a lack of rigor, a lack of comparability between experiments, a lack of comparability with archaeological materials, and inability to account for equifinality (the possibility that multiple past behaviors led to the phenomena of interest). In attempts to navigate these problems, experiments follow different protocols. Some archaeologists call for stricter controls over variables and others for more realism, but thus far a good argument has not been made for a general protocol.

There is a good reason for this. Experiments with ancient weapons do not all have the same goals. Weapon experiments generally try to do one of two things: provide samples of armatures and/or trauma to bone (hunting lesions) with known impact histories that can be compared with archaeological samples, or test weapon performance. These are not mutually exclusive goals and both are necessary for effective interpretation of old weapons.

Archaeologists have replicated and tested ancient weapons since at least the end of the 19th century (Cushing 1895; Pitt-Rivers 1906). But by the end of the 20th century archaeologists were attempting to introduce increasing levels of laboratory control into their experiments. I associate control primarily with apparatuses that fire projectiles with consistent force (generally accompanied by consistency in projectile design) and secondly with consistent target media in the form of homogonous simulants. The opposite of the controlled approach uses human operators of weapons that are closer to the originals, and secondly, target media that are closer to things targeted by weapons in the past (generally the bodies of prey animals) (Figure 4.1).

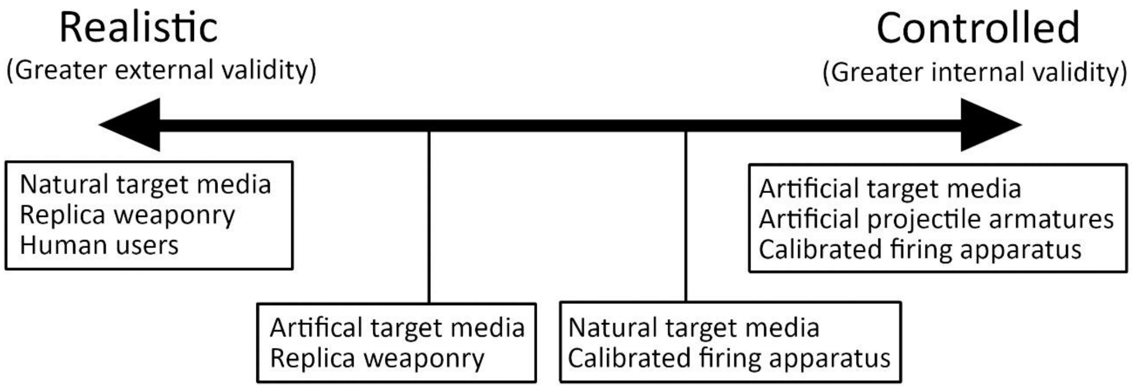


Figure 4.1. A diagram showing the spectrum from realistic to controlled methods used in archaeological weapon experiments.

The distinction between *controlled* and *realistic* (the latter has also been termed *actualistic* or *naturalistic*) is not a distinction between hard opposites. Experiments fall somewhere along a spectrum depending on how they are designed. The criteria in Figure 4.1 are somewhat arbitrarily assigned, but they do provide a general structure for how archaeologists have thought about and approached old weapon experiments. There are real differences between these two ends of the spectrum, particularly in how they achieve *validity*, reassurance that the results are meaningful (Eren et al. 2016):

- Effective controlled approaches meet the standards of *internal validity*; they provide the needed confidence that the causal mechanisms they observe are not influenced by other variables. To do this, controls are implemented to isolate phenomena of interest. For example, if an experiment sets out to understand variation in armature design it might be helpful to hold the velocity and mass of the shaft constant, while shooting into a homogenous target.

- Effective realistic approaches meet the standards of *external validity*. Externally valid experiments ensure that the results can be generalized to conditions occurring in the "real world." Rather than holding variables constant, the variability in weapon design, use, and prey bodies is usually part of the investigation.

In addition to validity, experiments are also held to the standards of *reliability*; they should be repeatable and the results reproducible under the same conditions. Controlled experiments are generally thought of as more reliable than realistic ones.

The logical positivist school of thought of the early to mid-20th century demands that effective experiments attempt to falsify hypotheses (e.g. Popper 2002). Both realistic and controlled experiments can establish and attempt to falsify hypotheses. But as a central criterion for viable archaeological experiments (Outram and Harding 2008), the necessity to test a specific hypothesis precludes useful exploratory and experiential approaches. This is unfortunate because exploratory approaches have become standard in some fields in the natural sciences, such as biology, having largely replaced the hypothetico-deductive model (Franklin 2005). Outram and Harding (2008) recommend that while not truly experimental, experiential approaches such as reenactment can be valuable and also beneficial for public outreach, while Reynolds finds such pursuits "at best theatre, at worst the satisfaction of character deficiencies" (Reynolds 1999).

Here I will stress that practical experience with the ancient tools we seek to understand is not only valuable, but necessary. In fact, experiments that meet the positivists' criteria for "standard science" (Steinle 1997), attempting to falsify hypotheses in reduced settings, can produce erroneous and misleading results if practical experience with old technologies is not achieved. While some might wish to discard analyses that do not set out with a particular hypothesis to falsify, exploratory methods can help us both gain practical experience and get a sense of what needs further testing. This does not mean that all experiential undertakings equate with "experimental archaeology," but even unsystematic practical experience, leading to better-informed interpretations and further hypotheses to address, is a perfectly viable and essential goal of experiential and exploratory methods. Applying these methods effectively still necessitates a high degree of rigor that is no mean feat to achieve (Outram and Harding 2008). And in any case, no matter how an experiment is approached conceptually, tinkering (exploration) is a fundamental and inseparable part of the process leading up to any polished scientific experiment (Gooding 1990). These essential components of exploration and practical experience cannot be left out of the process even if we want to!

Any experiment can fail to meet the prerequisite for being "effective." Both controlled and realistic experiments can suffer from lack of skill in execution, bad setup, and lack of observational power, resulting in loss of control over variables. The thought that experiments on the controlled end of the spectrum by their very nature solve this problem while realistic experiments do not is a primary component of *the controlled experimenter's fundamental conceit* (Eren et al. 2016). The opposite type of fundamental conceit, *the flintknapper's fundamental conceit* (Thomas 1986), places too much trust in experiences obtained by tinkering with and using old tools. Any approach requires rigor and adequate background research to be effective.

Both controlled and realistic approaches require unique skill sets if they are to produce valuable results. But the skills required of controlled experiments are often very different from the ancient skills we study. This is important because many old weapon experiments begin as student projects. Is it better for a student to spend time delving into material science to validate some homogenous target simulant, or in hafting hundreds of stone tools to use on realistic targets or cutting media? Which approach will lead to the most applicable insights for an archaeologist?

Either approach will likely require skills not necessary in the past, such as the effective operation of high-speed cameras and statistical software. And in any case, controlled approaches must be externally validated through either ethnographic accounts or realistic approaches. Imagine constructing a calibrated crossbow to test past javelin armatures at consistent velocities. How do you know your crossbow is calibrated to javelin velocities? You know because of data from realistic approaches (e.g. Milks et al. 2019). This does not mean we are slaves to imperfect analogs. Inevitably, results from both approaches must be tested against the tangible archaeological record (Chapman and Wylie 2016).

The trade-off between external and internal validity can be mitigated by comparing results from realistic and controlled approaches (Eren et al. 2016; Pettigrew et al. 2015). However, there may be a more efficient solution to some of the questions experimental archaeologists are interested in while maintaining validity of the results. Improvements in observation can break down the barrier between external and internal validity for realistic experiments.

In the following I first delve into some of the philosophy of scientific experiments, a frustrating topic for many due to the complex verbiage and esoteric concepts that frequent philosophical literature (Chang 2004), but nevertheless highly relevant to the topic at hand. I will then look at some examples from past archaeological weapon experiments to discuss what has been effective, ineffective, and where more work is needed.

4.2 Philosophy of science and tinkering with old weapons

Archaeologists began applying more control to archaeological experiments in the 1970s (Dibble and Bernard 1980; Saraydar and Shimada 1971; Speth 1972), with efforts increasing through the 1980s (Eren et al. 2016). As the paper by Eren and colleagues shows, calls for increasing rigor in archaeological experiments are generally attached to calls for increasing control. Table C-1 compiles the weapon studies that archaeologists have carried out through the years with a focus on *terminal ballistics*, the ballistics of target impact and penetration (for reviews of *internal ballistics* [the launching of the projectile] and *external ballistics* [the projectile's flight through atmosphere] of ancient projectile weapons see Baker 1992; Christenson 1986; Cotterell and Kamminga 1990; Cundy 1989; Hughes 1998; Milks et al. 2019; Pettigrew et al. 2015). Figure 4.2 draws from the data in Table C-1 to demonstrate the increasing trend towards controlled weapon experiments since the early 2000s, although realistic approaches have remained popular as well.

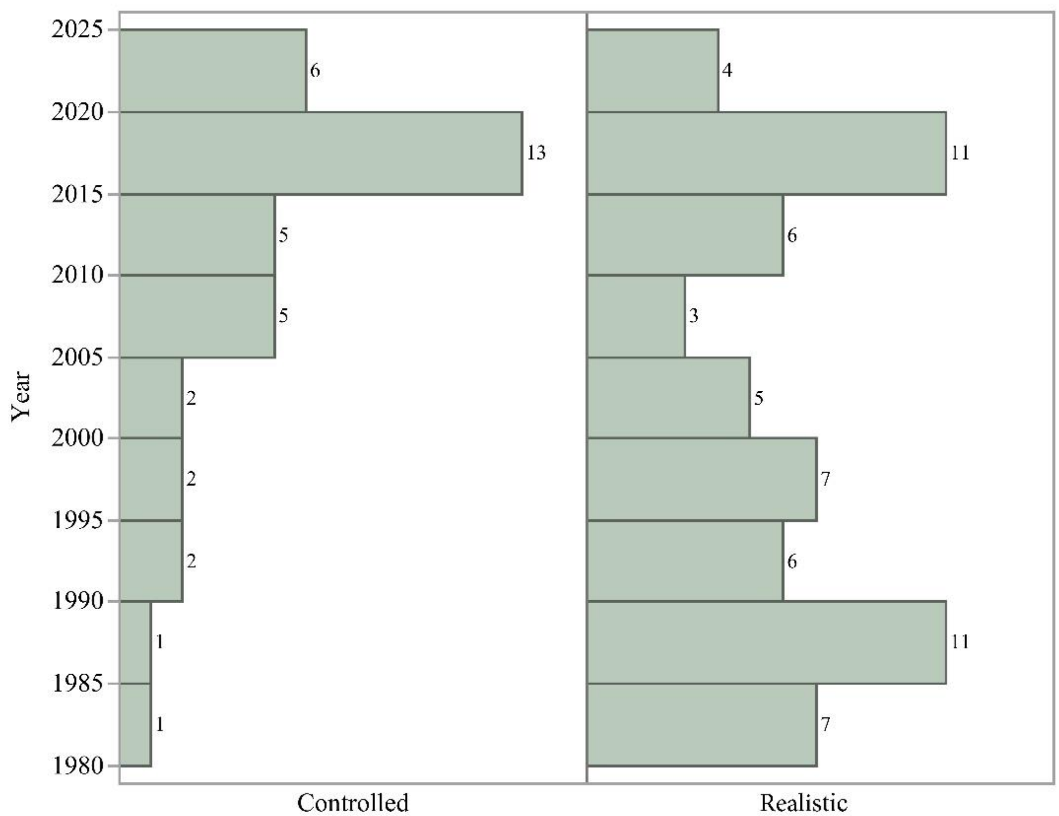


Figure 4.2. Showing the trends in archaeological weapon terminal ballistic studies over 5-year increments.

People have probably tested their weapons in ways that would qualify as realistic experiments for a very long time. The invention, refinement, and evolution of increasingly complex projectile weaponry must have been the product early research through experimentation. A single example will suffice. During their exploration of what is now the southeastern United States in the 16th century AD, conquistadores under the leadership of Hernando De Soto captured a Native Apalache man and promised to release him if he would demonstrate his abilities with his bow and arrows. The archer must have had a powerful war bow, because he shook his fists as if to drum up strength before drawing his arrow. At 50 paces his arrow completely penetrated a tightly woven basket draped with a coat of mail and retained enough velocity to be dangerous to anyone on the other side. A second coat of mail was layered over the first. His second arrow penetrated both coats, with the shaft lodged halfway through the target. The archer claimed his second arrow was not released properly and requested to shoot again, ensuring that on a second attempt he could pass the arrow completely through as he had done on the first (southeastern archers were competitive at crafting bows and arrows that could penetrate armored targets at a distance, see Herrin 2000; Jones 2010). The Castilians declined his offer in order to preserve their expensive coats of mail. This simple test confirmed the Castilians' suspicions, having already noticed the capacity of southeastern arrows to break through their chainmail on the field of battle. They subsequently replaced their chainmail with fabric armor, which was superior at stopping arrows (Clayton et al. 1995:Part II 235).

Through this example we can begin to assess the suitability of either realistic or controlled approaches for archaeological weapon studies. First it is apparent that the experiment of the Apalache and the Conquistadors does not fully meet the standards of validity or reliability. The target used in the test was not a perfect analog for the body of a Castilian wearing chainmail (lack of external validity) and it would be impossible for us to repeat this experiment with any degree of precision (lack of reliability), given especially the variability introduced by the human archer and the unrecorded parameters of his weaponry (lack of internal validity).

But these critiques are unfounded. If the Castilians had desired to apply a measure, for example energy, required for various southeastern arrow points to penetrate coats of mail, this would have benefited from a controlled approach, and the results could help in designing better armor. But for the test to be useful they would need to account for the variability in impact angles, southeastern archery equipment, and the archers deploying it. They would need to draw on data from field observations about Indigenous weaponry and its application, not to mention variation in chainmail armor construction, to externally validate their controlled studies. A more direct approach to the phenomenon the Castilians were interested in was to have a Native archer shoot his bow at a typical range in battle. This told them precisely what they wanted to know and what they had already suspected from field experience, southeastern arrows *could* penetrate coats of mail, and quite easily at that.

4.2.1 Irreversibility and universal laws

The controlled experiment holds a seminal place in Western science. Some even claim that true science requires the implementation of repeatable controlled experiments (see Müürsepp 2012:152). But it can be impossible to implement this version of “true science” in certain fields of study. Anyone familiar with developments in American archaeology from the 1970s through today will recognize the polarized and politicized nature of this debate (Chapman and Wylie 2016; Wylie 2002). Whether classic controlled experiments do what they have been purported to has been challenged even in the natural sciences, while suitable methods for introducing controls are increasingly recognized as applicable to realistic and exploratory methods.

Since Newton's discoveries in the 17th century, physics holds a privileged place as the fundamental base of the sciences (Okasha 2016). All sciences ultimately study physical subjects to which the fundamental laws apply. Through the 20th century it was thought that with perfect knowledge of Newtonian physics it would be possible to predict the past and know the future. The first substantial challenges came in the early half of the 20th century with the discovery of General Relativity and Quantum Mechanics. In brief, Newtonian physics does not apply at extremely small or large scales, or at extreme velocities. If the universe can be reduced to fundamental physical particles and thus fully understood through the natural laws as Newton claimed, then the quantum state may challenge our notions of reality, but this is currently debated.

The problem of sciences that do not study topics as fundamental as the natural sciences lies in their inability to reduce processes down to universal laws. Such reductionism is thought by some to be essential for the refinement of scientific knowledge (Rosenberg 2012:61–78). But attempts to apply universal laws to human behavior by processual archaeologists in the 1970s and 80s led to "low-level generalizations" that one archaeologist famously dubbed Mickey Mouse Laws (Flannery 1973). Alternatively, non-strict laws may be applied that operate under specific conditions to provide causal explanations for phenomena, but application of these laws require the use of *ceteris paribus* (all else remaining equal) clauses that reduce their explanatory power, since under different conditions the operation of those laws may change. Additionally, in situations where all else does not remain equal the same or similar phenomena may result from different processes entirely (equifinality). Ceteris paribus laws can be impossible to disprove since it is frequently unknown whether all else truly remains equal. Archaeologists will be fully familiar with this problem. Alternative to ceteris paribus laws, statistical probabilities are common in the social sciences (Rosenberg 2012:81–96) and remain an effective approach for archaeologists who study old tools, along with other aspects of human behavior. In section 4.3 I provide some examples of the application of ceteris paribus clauses and statistical probabilities in archaeological weapon studies.

The challenge in finding and applying universal laws are not unique to the humanities. Philosophers have also challenged Newtonian reductionism in the natural sciences by citing the context-dependency of any natural phenomena occurring in complex and variable contexts. It is even claimed by some that *all* laws come with weakening ceteris paribus clauses (Cartwright 1983). This has important implications for how archaeologists conceptualize and carry out experiments. The essential problem lies in the peculiarity of every historical event. According to Prigogine (1997), time fosters ever-changing unique conditions and is therefore irreversible. Irreversibility problematizes Newtonian reductionism, especially through the constant example of human agency. Human behavior and the things we affect cannot be predicted through universal laws. But if all conditions are unique along the arrow of time, laws can never be applied in true Newtonian fashion. This debate has resulted in a dualism in science since the Classical Greeks (Prigogine 1997).

For experimental sciences the irreversibility paradox highlights the inherent flaws in repeatability as a result of changing preconditions of the experiment (Müürsepp 2012). Experiments cannot be repeated if every experiment is carried out in an at least slightly unique way. If experiments cannot be repeated, how can they meet the standards for reliability? It may be that conditions can be reproduced closely enough with proper recording of preconditions for results to be generally reproduced (a condition that could also be applied to realistic approaches!). But true repetition and reproduction is never achieved. This challenges the seminal place of the controlled lab experiment (Müürsepp 2012).

For experimental archaeologists, preconditions include such things as the specific composition of porcelain clay and firing temperatures used to produce test armatures (e.g. Khreisheh et al. 2013), subtle temperature variations in gelatin targets resulting in slightly different consistencies (Jussila 2004), or the specific energy and angle of impact of an experimental projectile fired from a calibrated crossbow (a variety of “homemade” crossbow, or mounted bow, designs have been used by experimenters). But pre-conditions even include the qualities of observational equipment and the prior expectations of the researcher.

Preconditions are part of the “noise” (variability) inherent in realistic approaches. Controls are meant to introduce stability by reducing noise. Generally, the more stable an experiment, the sounder its results are thought to be. But Prigogine’s critique highlights the problem that controlled approaches can reduce but can never fully eliminate noise (Mets 2012).

The conditions of all controlled experiment are unique, and they all contain some noise, but so what? One might say an experiment is or is not controlled *enough*. Let us now consider the actual purpose of the controlled experiment.

A properly functioning controlled experiment sets up what Cartwright calls a *nomological machine*; “a fixed (enough) arrangement of components, or factors, with stable (enough) capacities that in the right sort of stable (enough) environment will, with repeated operation, give rise to the kind of regular behavior that we represent in our scientific laws” (Cartwright 1999:50). To achieve stability, nomological machines employ *shielding* (controls) to remove (enough) disturbances that the phenomena of interest will exhibit the regular behavior we are looking for. Once the machine is set running, it provides the grounds for validating universal laws.

The appropriateness of the machine metaphor has been questioned by Rouse (2008), who worries that well-functioning machines have to come from somewhere. They are purposefully built to fulfill *laboratory fictions*. But the fundamental aspects of Rouse's presentation of laboratory fictions seem to agree with Cartwright's. A controlled apparatus must be constructed just so to create the necessary conditions for laws to be revealed. This is not unlike saying that scientists construct the phenomena they wish to observe through their experimental machinery (Gooding 1990). Rouse finds laboratory fictions to mediate between theoretical models and worldly circumstances, and like Gooding, to be essential in the process of opening new scientific domains. Controlled experiments do encounter a reality outside of theory, but the world of artificial control is separate from the "real" world it is made to represent.

Some laws are arrived at through a single controlled experiment, but generally an entire experimental program is required to arrive at an accepted law (Rouse 2008:45). Often there is a long process of tinkering with the apparatus, interpreting observations, and deciding on the language necessary to describe the observations before a theory can be developed. This is a fundamentally social process that tends to be left out of the published results. The objective is generally to make the results theory-dependent and context free (Gooding 1990). One can extend this typically social process of tinkering outside the development of individual experiments and apply it to the evolution of entire scientific domains, such as the invention of a standard way to measure and conceptualize temperature (Chang 2004). Exploration and tinkering to gain experience in a field is a necessary component of any science.

4.2.2 Laws or capacities?

The narrow conditions found in controlled experiments can sometimes be found in nature. Bodies moving through the vacuum of space (the foundations for Newtonian physics) are one example. But such conditions are rare. For most real-world conditions the laws we recognize are accompanied by a dizzying array of other factors. Such experiments therefore identify what Cartwright refers to as *capacities* of things to act a certain way, their abilities, tendencies, and propensities, rather than "laws."

The example of the Castilians and the Apalache provides one example. No "law" was identified through the experiment, but the results demonstrated the capacity of Southeastern arrows to penetrate chainmail. Trying to apply the concept of law-like behavior to this phenomenon would be inappropriate. Like the Castillians, archaeologists tend to be interested in capacities, tendencies, and propensities.

Applying laws to human behavior has been notoriously misguided. Cartwright (1999) draws from economics to provide a sense of the challenges of applying universal laws to the complexities of social reality. Anthropology, too, provides numerous examples of the failure of universal laws to model human behavior. The classical dualism described by Prigogine (1997) between reversibility of natural laws and irreversibility of human nature demonstrates that this is by no means a new problem. Newer is the application of this critique to fields such as physics, primarily through Prigogine's irreversibility revolution (Müürsepp 2012). More useful than laws in the social sciences is the application of statistical probabilities to predict human tendencies (Rosenberg 2012).

This is not to say that controlled approaches should be avoided in archaeological experiments. Only that we should be mindful of what they can tell us. When they are effective, controlled approaches allow the complex variability in realistic scenarios to be bypassed. Control is about efficiency, and efficiency leading to publishable results is usually desirable in the culture of science (Franklin 2005). But controlled experiments should not be taken as a silver bullet, something archaeologists are often searching for (Chapman and Wylie 2016). Radiocarbon dating appeared to offer a silver bullet to the dating of sites and artifacts until it was realized that archaeologists still needed to know something of how the process works and how the concepts should be applied in any context.

As the example of the Castilians and the Apalache archer illustrates, the application of either control or realism depends on the goals of the experimenter. Natural capacities inferred from controlled approaches can be effective components in modeling past events, but they should not be the only components, and not every experiment must be an attempt to implement controls. Some topics are difficult to study using a controlled approach, especially when results are sensitive to subtle variations in the preconditions of the experiment (Müürsepp 2012). Improvements in observation can help reduce the noise inherent in both controlled and realistic approaches. This is the topic to which we now turn, and which comprises our final bit of philosophical travail.

4.2.3 Exploratory approaches

Franklin (2005) identifies a different route scientists are heading; exploratory methods made possible by improvements in "wide instrumentation." Like the controlled experiment, exploratory methods have a long history in Western science. In the 17th century, Francis Bacon dreamed of a utopic society of scientists with a three-tier social structure, where masses of minions would collect information from real-life occurrences and distribute it to second tier record keepers, while an elite group of thinkers would construct theories from the results. With improvements in observational tools and computation, something approaching Bacon's dream is increasingly possible, only the minions are replaced by modern computers (Franklin 2005).

Exploratory methods generally keep many variables in play. In this way, they are like realistic tests in ancient weapon studies. Indeed, a realistic experiment could count as exploratory and vice versa, while this can hardly be said of a polished controlled apparatus.

But different experimental approaches are not easily categorized. Exploratory methods are implicated in the initial phases of the construction of effective controlled approaches, but exploration must exhibit some degree of control if it is to reveal anything. To take an exploratory approach is not to take an "anything goes" approach to experimental archaeology (Outram and Harding 2008). Both realistic and controlled approaches can be used to test hypotheses, but finalized controlled apparatuses are not good for exploration for the following reason: The implementation of enough controls to isolate phenomena can come at the cost of "considerable loss of flexibility and openness to unexpected experimental outcomes" (Steinle 1997:S67).

According to Steinle (1997), controlled (what he calls theory-driven) approaches do not help us address the issue of equifinality. They are conducted through instrumentation designed to answer a single well-informed theoretical question. In this sense, the apparatus, and consequently the results, are highly constrained.

Franklin (2005) defines the opposite approach as employing "'wide', also known as 'high-throughput', instruments (those which allow the simultaneous measure of many features of an experimental system)" (Franklin 2005:888). A search for the term "high-throughput" on Google Scholar brings up hundreds of recent articles, many of which mention revolutionizing effects, including the ability to sequence the human genome. High-throughput instrumentation has largely replaced hypothesis testing in biology, allowing multiple (thousands) of experiments to be performed simultaneously (Franklin 2005). Powerful computation can be necessary to process the datasets. Rapidly improving computation has certainly made compiling large datasets and performing statistical procedures much easier, while powerful observational tools are also becoming more widely available, making effective exploratory studies increasingly possible.

The old “standard view” of science subsumes exploratory methods under the category of discovery, stating that the insights provided by them should not be analyzed epistemically, while priority is given to controlled approaches that can justify observations of regular behaviors (Steinle 1997). Advances in wide instrumentation make this position questionable. Even exploratory methods in the initial phase of discovery can be epistemically powerful, as they bring new phenomena into the linguistic and conceptual framework of a field (Steinle 1997).

I suspect that many of our goals in experimental archaeology would benefit from effective exploratory approaches. We would like to know what ancient people knew about their tools, how they purposefully designed them, and how they used them in the complex contexts of human realities. Archaeologists have long recognized that the laboratory is not necessarily the best place to achieving this end (Bamforth 2010). We would like to arrive at some understanding of the agency of ancient people through their tools. To do so, we need to develop familiarity with old tools by reverse-engineering them and using them in a variety of ways. These won’t be the exact ways things were in the past, but they help us redevelop something approaching ancient skill to explore possible contexts of use and test tools effectively (Milks 2019). In doing these things, we can develop experiential insights and better address equifinality. This is part of the exploratory (trial and error) process leading to theory. Such efforts might culminate in the need to design controlled apparatuses to test theoretical questions, but this should not be considered the only suitable solution to achieving the rigor necessary to understanding ancient technology.

4.3 Ongoing challenges in archaeological weapon research

In the following I present some of the prominent challenges we still face in researching old hunting and fighting weapons by way of some examples. Where I draw on problems with past studies, my aim is not to criticize those authors but to review what I think has been effective and where more work is needed. Science is a social process of trial-and-error that is not confined to individual laboratories or research programs (Chang 2004; Chapman and Wylie 2016; Gooding 1990). To approach these topics, I draw from my own experiences in making and testing old weapons.

4.3.1 Weighted atlatls, launching contraptions, and modern analogs

One of the most challenging components of ancient weapon technology to interpret has been the atlatl weight. These are stone objects purposefully shaped to be fitted to an atlatl. They occur predominately in North America and appear to date as far back as the Early Archaic. The oldest complete preserved atlatl in North America, from Nicolarsen Cave along the shores of the now dry Winnemucca Lake in Nevada (Hester 1974), has a long “boatstone” type weight attached (Figure 4.3) (see also Butler and Osborne 1959). This atlatl has been radiocarbon dated to 5650 years BP (Barnes 2000:117). A number of interpretations of atlatl weights have been put forward (see Whittaker 2010a).

To assess the effect of attaching an external weight to an atlatl, Cane and Sobel (2015) designed a controlled experiment with a single atlatl and dart fitted to a modified clay pigeon launcher. The atlatl was used with and without a removable weight. This experiment demonstrated that without the weight the dart went farther, but with less precision.

Figure 4.3. A replica of the Nicolarsen Cave atlatl by the author.

The problem with this approach is twofold: First, the launching mechanism, a modified clay pigeon launcher, does not reproduce the complex, variable and adaptable mechanics of human bodies and minds. We can grip and throw things in different ways and accentuate different muscle groups and ligaments. This has a pronounced impact on the way an individual uses an atlatl and consequently how the system is designed. This is in no small way a product of individual and cultural preference, not to mention how people in different societies learn to use their bodies from a young age (Mauss 1973). Variations in gripping methods are particularly relevant, as this is the point at which the body articulates with the weapon (Figure 4.4) (Pettigrew 2012, 2018).

Second, control was further implemented by limiting the test weapon to one dart and one atlatl with and without a weight, but the atlatl and dart is characterized by extreme variability! Ethnographic and archaeological hunting darts range from 1.5 to 4 m long and 90 to 400 g (Guernsey and Kidder 1921; Palter 1977; Pettigrew and Garnett 2015). Even without a weight attached, atlatls can have wooden or even osseous shafts that vary from thin and light to long and heavy. The best mass and balance for an atlatl depends on many factors: the length of the working lever from handle to spur, how it is gripped, the stature of the atlatlist and how they use their body to launch the dart, and all the specifications of the dart. Even within this great range of variability, multiple masses and placements of external weights can be allowable when the other factors are held constant. This is because, to an extent, the human user can learn to adapt her or his body to subtle variations in the parameters of the weapon and still deploy it effectively.

Figure 4.4. Showcasing two of the many different methods of gripping and casting darts with atlatls. Top: Justin Garnett with a 107 g weighted truncated handle Basketmaker atlatl launching a 90 g Basketmaker dart with a "flinging" technique. The weapon balances near the grip and the finger loops form the only point of articulation with the user. Bottom: Ryan Grohsmeyer with an 187 g unweighted personal hammer grip atlatl launching a 174 g replica Yukon ice patch dart with a “levering” technique. The weapon balances ~20 cm in front of the grip. Photographs by the author, Cahokia, 2015.

Modern understandings of technology tell us that variations on the essential parameters of a weapon must be aspects of technological advancement (see also Webb 1981). But essentializing variable tools does not help us understand them, let alone the cultures that used them or how they were deployed in any particular context in the past (chapter 2). Controlled experiments that hold such variability constant can produce misleading results. We need to understand variability within weapon systems, where it might be a result of the spread of populations or ideas, or where it might be due to localized adaptations.

Testing different equipment, Whittaker, a well-practiced user, achieved his slowest speeds (22.2-23.5 meters/sec) with the lightest of three atlatls (139 g). Using the same darts, he achieved faster speeds (25.3-25.7 m/s) with a heavier and significantly heavier atlatl (162 and 259 g), but speeds were not noticeably different between these latter two atlatls (Whittaker et al. 2017). This does not mean that lighter atlatls are slower! Whittaker reported being most comfortable with his personal equipment, the 162 g Basketmaker atlatl. The heaviest atlatl with a long weight, inspired by the Nicolarsen Cave atlatl, felt more familiar to him, and balanced better with his darts than the lightest atlatl. Bob Berg, the maker of the lightest and longest atlatl, is a strong person who prefers to launch heavy darts with a “hammer grip” (gripping the handle as one does a hammer, Figure 4.4).

In a simple experiment published in the World atlatl Association Newsletter, myself and a colleague (Pettigrew and Garnett 2011) performed an accuracy test at our respective residences over several weeks. Every day we each launched a single Basketmaker dart with two Basketmaker atlatls of the same proportions and construction, but one with and one without an attached weight. Five shots were made each day with each atlatl at targets 15 m distance. Each day we switched the atlatl we started with to reduce sampling bias, and after each shot the distance from the center of the target to the impact location was measured. No pattern emerged from the accuracy data. The ancient Basketmaker culture in the US Southwest has yielded well-preserved examples of complete weighted and unweighted atlatls along with complete preserved darts, allowing close reconstruction of an Indigenous North American atlatl and dart weapon technology (Garnett 2015; Guernsey 1931; Guernsey and Kidder 1921; LaRue 2010; Pettigrew and Garnett 2015). If weights made a substantial difference in accuracy, two practiced users of Basketmaker atlatl technology should have noticed a difference, but we did not. Apparently, the ancient Basketmakers with weighted versions did not have a more accurate or technologically advanced weapon. Certainly, with or without attached weights the mass of an atlatl has an effect. But what that effect entails is dependent on many variables, including the extreme variability in the human launching mechanism.

More appropriate analysis of how variable atlatl mass and balance operates will come from measuring a large sample of atlatlists and equipment, as was done by Whittaker and colleagues (2017) for velocity, as well as closely studying artifacts and ethnographic examples of use. Some might find it unfortunate that this kind of study would rely on hobbyists whose deep fascination with an old weapon possibly suggests character flaws (Reynolds 1999). But understanding the mechanical principles of a weapon designed by and for humans to use as extensions of the body requires studying real humans with real bodies, and this requires trusting that modern users of old tools can learn to use them effectively (Milks 2019). The velocity measurements have shown that practiced users of atlatls are often highly consistent (Whittaker et al. 2017). I can’t see how building a complicated throwing contraption to mimic the human body as a way to study the external ballistics of weapons used with real human bodies is really necessary.

I agree with others that modern people can develop enough skill with old weapons to serve as appropriate, if imperfect, analogs to past use (Longman et al. 2020; Milks 2019; Milks et al. 2019). The imprecision of contemporary analogs also affects the application of ethnographic analogs for interpreting archaeological materials, or for the use of any contemporary processes to understand past processes in any of the sciences. Without drawing from current or historically recent analogs there is very little archaeologists can say about the past (Wylie 1985, 2002). This is true whether we use realistic or controlled approaches. Some controlled studies have used crossbows (or mounted bows) with calibrated velocities based on the atlatl dart speeds recorded by Whittaker and colleagues to validate their experimental projectiles as analogs (Bebber and Eren 2018; Lowe et al. 2019; Werner et al. 2019). If these velocities were not available, how would experimenters calibrate their controlled firing contraptions? Milks (2019) has put forward the same argument in regards to thrusting and throwing spears.

It is certainly not out of the question to apply the concept of rigor to research involving modern analogs, such as requiring a degree of athleticism or practice (see Milks 2019). Milks and colleagues (2019) accomplished this by conscripting practiced javelinists to throw copies of the ~350,000 year old Schöningen javelins and compared their velocities with less-practiced users. The practiced javelinists were able to achieve significantly better velocity and accuracy, demonstrating possible extensions of ancient javelin hunting range from only 8 m (Churchill 1993) to 15-20 m. More practice with these javelins would likely improve the results further. Our analysis of many practiced atlatlists demonstrated that new users to the weapon who still struggled to hit a target at 15 m could, within a day or two of throwing, achieve the velocity of well-practiced individuals, including strong throwers who had practiced from a young age

(Whittaker et al. 2017). Accuracy is harder to master than speed with an atlatl, but for javelins both speed and accuracy require significant practice and athleticism. Further testing these concepts and refining our understanding of the capacities and tendencies of old, variable hunting projectiles will benefit from rigorous testing of modern users.

4.3.2 Distinguishing weapons by armature size

One of the basic assumptions modern researchers have of ancient weapons is that weapon improvements over time helped hominins better defend themselves against large predators, enemies, and to be more successful hunters of dangerous prey (Churchill and Rhodes 2009; O'Driscoll and Thompson 2018; Shea and Sisk 2010). Various challenges come with implementing these ideas, not the least of which are high success rates with javelins and thrusting spears recorded for San hunters in South Africa (Hitchcock and Bleed 1997). Over the period of study in the 1970s, young San hunters in Botswana were switching increasingly from bow and arrow to spear use, not only because spear hunting with dogs and from horseback was both effective and an attractive pursuit for younger hunters, but conservation efforts were seeing traditional hunters relabeled as poachers. While carrying bows and poison arrows could get one fined, thrown in jail, or shot on sight, San were allowed to carry spears, which were their primary means of defense against large predators (Hitchcock and Bleed 1997).

Despite the complexities of what different hunting technology really means, archaeologists would understandably like to know when and where various weapon technologies were in use. Being able to see weapon systems from the armatures alone would be highly beneficial to researching such aspects as social cognition and learning (Lombard 2015; Lombard and Haidle 2012) and adaptation to local environments. Archaeologists have attempted to use several different metrics to distinguish weapon systems from their armatures, which are usually all that survive of ancient composite and organic weapons. Fenenga (1953) measured the masses of 884 stone points from archaeological sites in the US and found a bimodal distribution above and below 4 g, suggesting two different weapon technologies. Noting the problems with relying on mass alone, others have developed ratios derived from basal and other dimensions of armatures (Ames et al. 2010; Corliss 1972; Hildebrandt and King 2012; Shott 1997; Thomas 1978). In these latter cases, relying on hafted archaeological and ethnographic darts and arrows helps ensure ratios are applied to the proper weapons. It also creates a sampling bias, since shafting and hafting elements will not preserve in most conditions.

Friis-Hansen (1990) recognized the importance of the tip cross-sectional area (TCSA) of armatures in creating drag as the armature penetrates, while the tip cross-sectional perimeter (TCSP) can be used to calculate the wound surface-area and thus the deadliness of a hunting armature. Hughes (1998) further suggested that TCSA could be used to distinguish between weapon systems. These metrics are derived from the simple measures of maximum width and thickness of armatures (for equations see Sisk and Shea 2009). As such they measure relatively robust features of ancient armatures and are easily calculated for large assemblages. Several researchers have expanded on these measures and applied them to distinguishing ancient weapon technologies (Borrell and Štefanisko 2016; Lombard 2020; Sahle et al. 2013; Shea 2006; Shea and Sisk 2010; Sisk and Shea 2009; Villa and Lenoir 2006; Villa and Soriano 2010; Wilkins et al. 2012).

Armature size is suggested to correlate with different weapon technologies because as weapons improve, the projectiles become smaller and faster, with correspondingly smaller shafts. If they have smaller shafts, they should have smaller armatures to minimize drag when they penetrate. Problems arise with internal and external ballistics as well if armatures are too large.

An arrow that is too heavy for a given bow cannot be fired with sufficient speed and energy. Increasing the tip weight will require corresponding increases in shaft thickness so the spine (stiffness) of the projectile matches the launching mechanism, resulting in further mass increase. The debate over the size of armatures attached to different types of projectiles has been going since at least the 1930s (Christenson 1986).

Some effective realistic experiments have undertaken to address this question. Evans (1957) conscripted a practiced archer to fire arrows with and without fletchings and with tips ranging up to 90 g. As tip mass increased, the flight of unfletched arrows improved until an impressive degree of accuracy was possible. Fenenga (1953) tried a variety of tip weights with light atlatl darts, including very light tips, demonstrating that highly variable point mass can be used on different types of projectiles. This should come as no surprise given that javelins (Milks 2020), atlatl darts (LaRue 2010) and arrows (Waguespack et al. 2009) were used in the past with simple wooden tips. But Fenenga (1953) also recommended that it is not the place of modern experiments that show us what is possible with a weapon to tell us how ancient people designed their weapons. I think experiments that show us what is possible with weapons give us a better sense of what to look for and when to be cautious in our interpretations.

One problem with the samples used to build databases of hafted ethnographic and archaeological spears, darts and arrows is that most of the hafted atlatl dart points came from Basketmaker deposits in the southwestern US (Thomas 1978). Replicas of these darts show them to be on the lighter end of the dart spectrum (~90 g) (Pettigrew and Garnett 2015), but they appear to have been popular as far east as Missouri and Arkansas, and were probably even more widespread in the Late Archaic given the distribution of small corner notched dart points of a similar type (Christenson 1986; Pettigrew 2018). Samples of TCSA and TCSP have been built from Thomas' (1978) and Shott's (1997) data with additional metrics of Levallois points from experimental thrusting spears (Shea 2006). Since we are allowing experimental weapons into the samples, then TCSA and TCSP for atlatl dart tips should be extended well into the larger thrusting spear category (Table 2.5). Coincidentally, very large ethnographic atlatl dart points have been measured in Australia (Newman and Moore 2013).

More recently, Lombard (2021) included TCSA samples from light southern African hunting javelins with iron tips. These cross the threshold into the category of lighter dart points from Shea's (2006) study, further demonstrating that darts and javelins are impossible to distinguish by TCSA. Ashby (2008) accompanied Indigenous hunters in Papua New Guinea (PNG) on a Rusa deer hunt and examined pre and post WWII era bows and arrows. Prior to WWII, arrow tips were expertly carved from wood with complex barbs. The latter are still made for spears, but the hunters now fashion large lanceolate arrow tips from iron rebar (Figure 4.5). Ashby measured five of these arrows and provided the following weights for the complete projectiles: 256, 135, 149, 108, and 117 g. The lightest arrow measured by Ashby is ~20 g heavier than close copies of Basketmaker darts from White Dog Cave in AZ (Pettigrew and Garnett 2015).

PNG big game arrows observed by Ashby (2008) span the atlatl dart category and cross the threshold into the spear category in terms of both their mass and the size of their tips. Exact thickness and widths of the broadheads were not taken, but widths were provided for me by estimates from the photos and other measured parameters (Ed Ashby, personal communication, 2021). Using a conservative thickness estimate of 3 mm, I used these widths to calculate TCSA estimates for the four arrows shown in Figure 4.5. This gave TCSAs of 34.5, 45, 52.5, and 36 mm^2. This places the larger PNG iron broadheads within the TCSA range of African hunting javelins (44-98 mm^2) (Lombard 2021).

Figure 4.5. Left: Papua New Guinea bowhunters with a Rusa deer that was stalked in open terrain. Right: Javelin-sized iron points on PNG arrows. From (Ashby 2008), reproduced with permission from the author.

The PNG arrows are not only heavier than many darts, they appear larger than some light African hunting javelins shown by Lombard (2021:Figure 1). As Evans (1957) noted of the fletchless arrows he tested, the heavy points help the unfletched shafts fly straight by maintaining a balance point forward of center (Ashby 2008). And as discovered by Evans (1957), the flight of these arrows is assisted by long and powerful bows. Powerful bows with longer limbs, such as the English longbow, have more leverage on the projectile and can throw a heavy arrow farther, while bows with shorter limbs are snappier and can throw a light arrow at high velocity and energy over a shorter distance (Baker 1992; Karpowicz 2008; Strickland and Hardy 2005). These represent different strategies in bow design, but clearly in certain contexts, such as stalking deer, both ends of the spectrum can be adapted to a single task. To properly match the arrow spines for the heavier tips, the modern PNG archers use larger shafts than pre-WWII PNG arrows. The average proximal (nock end) diameter is 1.3 cm. This proximal diameter matches the distal diameter of most Basketmaker atlatl darts. In other words, the shaft diameters of the PNG arrows are a little larger on average than Basketmaker darts. This clearly problematizes efforts to distinguishing weapons by armature basal dimensions as well.

The transition from pre to post-WWII equipment is apparently not a product of the degradation of PNG bow and arrow technology, as some have proposed for late historic arrow tips in North America (Hildebrandt and King 2012). The PNG hunters use these weapons to stalk Rusa deer in open terrain and to hunt pigs from platform stands. Shots are frequently taken beyond 25 m. When practicing, they can "almost effortlessly" strike the center of a 25 cm diameter tree from ~20 m (Ashby 2008). Even larger arrows with heavy detachable barbs are used to shoot alligators from canoes.

In reviewing the challenges still faced in distinguishing projectile weapons from their armatures, Hutchings (2016) found metric-based approaches to be insufficient given the unknown parameters of ancient projectile weapons. He instead prefers a use-wear approach focusing on fracturing characteristics and loading rates associated with different projectile velocities (Hutchings 2011, 2015). This has only yet proven applicable to glassy materials and the results have been challenging to reproduce (Iovita et al. 2016). In any case, the light African spears and heavy PNG arrows problematize efforts to distinguish projectile weapons by the mass, cross-section, hafting dimension, or even impact velocities, given the apparent possibility of substantial overlaps in all of these unknowable parameters in the variable hunting conditions of the past (Whittaker et al. 2017). Or put differently, any application of laws regarding the characteristics and functionality of recent to past weapon technologies requires ceteris paribus clauses that are challenging to prove or disprove. Distinguishing past delivery systems seems to be a statistical, probabilistic issue no matter how it is approached. The bimodality found in old assemblages (e.g. Corliss 1972; Fenenga 1953) seems encouraging enough! As many of these authors point out, any of these methods to distinguish armatures will benefit from multiple lines of evidence.

Realistic experiments with old weapons show us what to look for and ethnographic accounts of real hunters who rely on their weapons for their livelihoods reassure us that our experiences are applicable. In reading about PNG bows and arrows, it is fully apparent that Ashby's thorough experience in bowhunting and designing effective hunting arrows (Ashby 2015) substantially improved his ability to interpret contemporary PNG bows and arrows. This is why Frison (2004) recommended that archaeologists who study ancient hunters should hunt. It is unlikely Ashby ever read the article by Evans over 50 years earlier and it was not necessary for him to. These experiences in the practical applications of old weapons simply cannot be developed from controlled experiments alone, but they are readily available to those willing to tinker with and explore ancient technologies.

Exploratory tinkering such as Evans' (1957) is far more useful in helping us to understand the *capacities* of variable arrows to produce acceptable and accurate flight when fitted with variable tips and shot from variable bows by practiced human archers than any controlled experiment that would minimize these variables. Nevertheless, archaeologists from the late 1970s to the present have felt it necessary to criticize the "authoritative intuition" that comes with practical experience in making and using old tools. Eren and colleagues (2016) describe how this played out in flintknapping studies: "At the heart of the matter is the vexing conceit that underlies too much of contemporary lithic technology: some flintknappers behave as if the act of breaking rocks gives them an inside track to the truth" (Thomas 1986, in Eren et al. 2016). "…nearly all the experiments are empirical ones… they are—so far—not really controlled experiments" (Muller-Beck 1978, in Eren et al. 2016).

My point is not that researchers of old weapons who tinker and employ exploratory approaches never display any degree of conceit, but conceit can be attached to both types of approaches (Eren et al. 2016). All types of archaeological experiments thus far discussed appear to be useful when applied with appropriate rigor and to the proper contexts. And *none* of these approaches provide a sliver bullet to understanding old weapons (Chapman and Wylie 2016).

4.3.3 Ongoing challenges in terminal ballistics

In the following I draw from two different experimental programs: a series of exploratory realistic experiments with atlatl darts and arrows on fresh pig, goat, and bison carcasses (Chapter 2), and a controlled experiment with a calibrated crossbow, ballistics gelatin and various types of skin simulant (Chapter 3). The former deployed two high speed cameras ("wide instrumentation") to capture impacts in slow motion and record velocity and deceleration entering the carcasses. These data were then used to calculate several variables important for effective arrow and dart terminal ballistics. Further byproducts of the realistic experiments included damage to stone armatures and animal bone accompanied by detailed histories of impacts, used butchering tools, freezers of meat, and insights into weapon construction and stone tool butchering methods. In the latter controlled experiment, I discovered that it is fully possible to learn very little from a highly rigorous laboratory experiment, apart from the fact that target simulants must be scaled to the reality we wish to study. Nevertheless, the analysis of the realistic tests required a few statistical hurdles to parse out the important ballistic variables, whereas this was less the case when analyzing the controlled dataset.

4.3.3.1 Cutting armature efficiency, target scalability, and laboratory fictions

Ancient weapon researchers have deployed several different target media to simulate prey bodies. These media have been used to explore armature efficiency, hafting durability, and material durability (see supplemental materials). Several experiments have also used target simulants in a secondary role, such as to capture armatures fired through organic targets or as a means of studying impact damage by way of bone embedded in gel. Arguably, these are less problematized by the appropriateness of the simulant than those that study armature performance, although unscalable simulants still problematizes comparison with "real" impact damage from encounters with bone in real bodies or objects in the natural hunting environment. The use of any artificial target simulant requires extra effort to validate it against realistic conditions of use. Frequently, this requires delving into the material properties of both the simulant and simulated media. But this has rarely been done to any meaningful degree. Here I focus on purposeful studies of ballistic efficiency (weapon performance) explored using animal carcasses, foam, clay and ballistics gelatin targets.

Firearm terminal ballisticians have for a long time recognized the importance that a target simulant is scalable to the target (generally bodies of humans or prey animals) being studied (Jussila 2004; Maiden et al. 2015). The proper application of collagen-based ordinance ballistics gelatin for testing firearms requires that appropriate methods of manufacture are used. The finished gel must be calibrated prior to testing by a standardized penetration test. Calibration efforts were not performed much prior to the early 1980s, so research results prior to this time are suspect (Maiden et al. 2015). Archaeologists rarely report the way they manufactured ballistics gelatin (Mullen 2021) and I have yet to come across any mention of calibration efforts.

More importantly, ballistics gelatin appears not to be scalable to prey bodies for the weaponry we study. Karger and colleagues (1998) demonstrated this by firing various types of arrows into 10% (collagen to water content) ordinance ballistics gelatin, ballistic soap, and four recently killed pig carcasses. Arrows saw the lowest penetration into the dense soap, but regular field tips (target points without cutting blades) penetrated more deeply into gelatin than through the carcasses, while the opposite was the case of sharp hunting broadheads. Of the armatures and targets tested, cutting tips always penetrated the deepest and this was achieved by shooting them into the carcasses. Karger and colleagues concluded that neither ballistic gelatin nor ballistic soap are suitable for simulating the efficacy of arrows or crossbow bolts with various armatures to penetrate real bodies. The viscoelastic nature of ballistics gelatin apparently creates more drag on armatures with larger surface area, despite the nature of their cutting edges. Two armatures of the same size and shape but one with completely dull edges can penetrate the same depth into gelatin targets (chapter 3).

This places constraints on the applicability of other targets as well. Sisk and Shea (2009) tested Levallois points with varying TCSA and TCSP measured from rhomboid equations by shooting them from a bow into a foam target. The foam demonstrated that TCSA and especially TCSP are important variables in determining Levallois point terminal ballistics. The importance of TCSA and TCSP has also been shown by shooting ground chert points of various sizes into moist potter's clay (Eren, Story, et al. 2020; Mika et al. 2020a; Sitton et al. 2020). In the study by Sitton and colleagues (2020), TCSA and TCSP were able to capture ~70% of the variability in penetration depth into the clay. But here again, the target used is not scalable, since dull tips can experience less force of resistance penetrating clay than sharper tips, despite that very sharp tips dramatically reduce the force of resistance penetrating cadavers (Ankersen et al. 1998). In short, none of the controlled experiments that have used these target simulants (Table C-1) seem to have isolated the same causal mechanisms of armature penetration into hunted animals or human victims.

In the calibrated crossbow experiments I undertook, accurate TCSA and TCSP measures obtained from 3d models of 16 different stone and glass armatures both captured >85% of the variability of shots into Perma-Gel, a synthetic version of ballistics gelatin (Chapter 3). If we ignore the importance of scaling the target media to real bodies, TCSA and TCSP appear to be essential variables of armature efficacy. But a different pattern emerged when coverings of 2-3 mm thick tooling leather were placed over the Perma-Gel. Deceleration through these materials was measured with a high-speed camera and stopped after the armature's blade disappeared into the target. Only in the case of 2 mm tooling leather did TCSA provide a significant fit with deceleration, capturing ~20% of the variability, while weaker correlations occur in nitrile rubber and thin upholstery leather (Figure 3.10). But it was difficult to determine the extent to which this was due to the greater ease of the armatures in traversing these materials and interacting with the gel underneath. Neither TCSA nor TCSP were important in predicting deceleration through the more resistive 3 mm tooling leather. Instead, sharper armatures made of glass decelerated less rapidly than rougher Burlington or Mozarkite chert, despite being the largest points tested.

Clearly, the impact of various armature characteristics on their terminal ballistics depends on the nature of the target. But despite how compelling the above results are in demonstrating this, they are challenging to apply to realistic hunting scenarios. Thick vegetable tanned tooling leather is not the same as living skin with underlying bone and muscle structures. It fails (fractures) differently than living skin. This is also true of every other skin simulant yet tested in firearm terminal ballistics, stab wound traumatology, and archaeological weapon experiments

(Fenton et al. 2020). Understanding the properties of a material being worked by a cutting tool is necessary to interpret how the tool will perform (Reilly et al. 2004). Unfortunately, this means that the effective application of a target simulant requires careful study of its material properties to ensure it is scalable to the past targets of projectile weapons, namely prey bodies.

Far more easily interpreted are shots into fresh animal carcasses, despite potential inaccuracies that occur between on the hoof or recently deceased biological tissue (Fenton et al. 2020; Kneubuehl 2011). Use-wear analysts also express frustration that further breakage and micro-wear resulting from movement of a hunted animal after projectile impact does not occur in stationary carcasses. But the only way to achieve this would seem to be by hunting with stone armatures in places where it is legal (e.g. Loi and Brizzi 2011). Nevertheless, the reduced force of resistance experienced by armatures of finer-grained materials penetrating goats and bison is far more compelling than shots into processed leather or rubber over gelatin. Those results are also easier to apply to the archaeological record without having to delve into materials testing or other fields that most archaeologists have little experience in.

Researchers desire target simulants for several reasons. Some of these are not strictly associated with the imposition of controls. Some archaeologists have reported difficulties obtaining complete carcasses (e.g. Osipowicz and Nowak 2017; Smith et al. 2020). Target simulants can be easier to obtain and deployed in a more convenient lab setting. There are also safety and ethical problems associated with using fresh animal carcasses, but these can be remediated by using animals destined for slaughter and butchering them after the experiment. I found the best approach is to find a rancher willing to allow an experiment on her/his land and to put down the animal prior to the experiment. This allows the timing of the event to be controlled. After the heart has stopped pumping, hemorrhaging around wounds does not ruin large sections of meat. Surprisingly little meat is lost if the carcass is butchered in a timely fashion (within 3-5 hours), reducing much of the ethical dilemma.

TCSA and TCSP seem to remain important components of armature efficacy when properly contextualized to intra-weapon variability. This is done by considering the size of a projectile shaft, which can be performed using the ratios developed by Friis-Hansen (1990) (chapter 2). Larger shafts have the tendency to impact with higher energy and momentum. It would help validate controlled approaches if we could assume that darts of heavier weight thrown by the same atlatlist will not carry more energy *ceteris paribus*, since they are harder to throw, and thus armatures of various sizes can be attached to shafts of the same mass and shot at the same velocity in controlled tests to study their penetrating efficacy (Eren, Story, et al. 2020). Unfortunately this is an example of a convenient laboratory fiction (Rouse 2008).

Previous work has already shown that balls of the same size but different mass thrown by a number of individuals travel slower but carry more energy when they are heavier, up to a point of diminishing returns dependent on the skill and strength of the thrower (Toyoshima and Miyashita 1973). In the carcass experiment, heavier darts carried substantially more energy even when thrown by the same atlatlist (Table 4.1). For two darts that were comfortable to me and with characteristics of darts I have been using over several years, I achieved higher energy and only a marginal decrease in velocity with the heavier shaft. Two stronger throwers than myself, Carlton Gover and Donny Dust, were able to achieve substantially greater energy than my throws and even higher velocity with heavier cane and ash shafts during the carcass experiments. Unsurprisingly, these latter darts demonstrated the capacity to penetrate deeper despite carrying larger armatures. This pattern of increased energy for heavier darts occurs across a large sample of atlatlists (Whittaker et al. 2017:Table 2).

Table 4.1. A comparison of three different throwers and four different atlatl darts, showing some of the variation in mass (g) velocity (m/s) and kinetic energy ($0.5m*v^2$, in Joules) from the carcass experiments.

	Thrower DP, willow Basketmaker dart			Thrower DP, cane dart			Throwers DD & CG, cane and ash darts		
	m	***v***	***KE***	***m***	***v***	***KE***	***m***	***v***	***KE***
Mean	87.3	24.7	26.6	125.2	23.8	35.9	199.9	26.3	72.8
StDev	2.4	1.1	2.4	11	2	7.7	45.2	2	13.7
N	14			22			23		

Essentializing variable tools and representing them in controlled contexts can produce misleading results. These findings are by no means authoritative. They represent the *capacity* of larger points with larger armatures within the same weapon technology to carry more energy, penetrate deeper, and produce larger wounds. Removing these capacities in order validate laws in a laboratory setting does not necessarily produce more valid results.

Although statistical analysis from the carcass experiments indicates that TCSA and TCSP do remain important when properly contextualized to projectile variability, armature sharpness appears to be another important, if not a more important variable. After noticing only marginally better penetration of stone over wood tipped arrows in gelatin, Waguespack and colleagues (2009) suggested that stone points might serve as objects for costly signaling. Salem and Churchill (2016) have already critiqued this conclusion, but did so by devising another experiment that measured wound tracks in ballistics gelatin from wood and stone points. The latter produced larger wound tracks, indicating greater lethality. But the fundamental problem of scalability of ballistics gelatin for arrow impacts problematizes both the initial experiment and the response (Karger et al. 1998). Nevertheless, cutting armatures do have the capacity to produce larger wound surface areas (Friis-Hansen 1990).

Second, Waguespack and colleagues shot arrows with a 60 lb compound bow, claiming it to be within the draw weight of Indigenous bows, but the maximum draw weight of a bow is a poor predictor of the resultant arrow speed. This problem is commonly overlooked. Draw weight provides an easy way to roughly gauge the power of a bow, but the force-draw curve (the force of draw measured at intervals over the draw length) is more meaningful (Baker 1992). Modern compound bows with superior force-draw profiles, like the Hoyt® Helix Turbo (https://hoyt.com/compound-bows/compound-hunting-bows), can deliver arrows at well over twice the velocity (>106 m/s) of traditional bows with similar draw weights (Bergman et al. 1988). More important than the basic characteristics of the firing mechanism is the final velocity of the projectile on impact.

Third, a costly signaling interpretation is problematized by bowhunting experience. Field points are not legal for bowhunting big game for ethical reasons and most states in the US also place requirements on the size, material, and other characteristics of hunting broadheads. For example, Colorado requires broadheads for hunting big game with at least two steel cutting edges and a minimum width of 7/8 inches (Colorado Parks and Wildlife 2021). Having bow hunted big game for many years, Ashby (2006) finds armatures with razor sharp cutting edges to better ensure the retrieval of an animal. Granted, this is a distinction between sharp and razor sharp, not between armatures that cut versus those that do not. The implication is that the quality of a cut, not just the surface area of the wound, is important.

Some might be frustrated by the fact that these are empirical findings that do not stem from controlled experiments like the one by Waguespack and colleagues. In fact, Ashby claims to have tried various target simulants, but like others (Karger et al. 1998), found no simulant that reliably demonstrates the effective parameters of hunting arrows. Ashby instead prefers “outcome driven” (realistic) approaches to studying hunting arrows, testing various tips on freshly killed game animals with many of the variables found in realistic hunting left intact (Ashby 2005a). These demonstrate the capacities of various arrows to penetrate, but only hunting can demonstrate the capacities of sharper armatures to produce deadlier wounds.

Cox and Smith (1989) performed an experiment similar to Ashby’s outcome driven approach. They tested Perdiz arrow points mounted to reed arrows and shot them from two different compound bows (45 and 15 lb) into a fresh white tailed deer carcass and a stack of 10 deer hides. They also tried Perdiz arrow points as butchering tools for deer, apparently unaware of a 17th century account of Native American hunters butchering bison with stone arrow tips (Brink 2008:177). No mention is made of the hypotheses they wished to falsify. Theirs appears to have been an exploratory approach, which revealed that the sharpness of stone arrow points has a substantial impact on penetration. Perdiz points could become ineffective after being fired four or less times into the stack of hides. Perdiz points were effective for cutting meat as butchering tools, but it is difficult to resharpen a small arrow point without substantially reducing it. Dullness from shooting and butchering with arrow points could explain the numerous discarded complete points at archaeological sites in Texas.

This is not surprising to me having helped butcher a bison with stone tools. John Whittaker, the maker of many of our bifacial butchering knives, had to be tasked with the bothersome job of frequently pressure flaking the edges to bring them back to working order. Even more so than quality steel hunting knives, stone butchering tools become dull and need to be resharpened. Cox and Smith (1989) also recognized that experienced modern bowhunters ensure their broadheads are sharp, significantly increasing their odds of retrieving deer hit with arrows. Again, they did not mention being aware that this observation is also supported by ethnographic accounts of Native American hunters, who reported that steel trade points were more durable, but chipped stone and especially obsidian arrow points were sharper and more damaging to prey (Bohr 2014:74).

Stone cutting armatures are probably not only for costly signaling, but the useful tables of ethnographic wood points compiled by Waguespack and colleagues (2009) is worth further consideration, even if the results of their projectile experiment need to be discarded. It is also problematic to rely solely on the experiences of modern hunters, but it seems more problematic to go without these experiences. In this case, realistic tests with stone armatures in animal carcasses support the commonsense assumption that more efficacious armatures have sharper tips and edges.

4.3.3.2 Clovis point penetration, hafting and durability

Many old dart armatures in North America have ground basal edges. Intuition suggests to us that this reduces the possibility they will cut through their haft bindings when they penetrate a target. To test this, Werner and colleagues (2019) compiled an experimental arsenal of consistent armatures with ground and unground basal edges that were hafted with sinew. The armatures were then shot straight into clay and moose antler targets with a mounted 29 lb compound bow. No difference was observed in the longevity of the hafts between points with ground or unground bases. They concluded that basal edge grinding may be tied to knife use but has no function in projectile use.

An additional problem with hafting armatures considers the fluting found on Paleo-Indian (e.g. Clovis and Folsom) points. Thomas and colleagues (2017) attempted to explain the purpose of fluting using a controlled approach that placed unhafted ground chert test points in an Instron static pressure loading machine. For fluted versions, fracturing was found to initiate at the base, preserving more of the distal portion of the armature. This could be a tactic to increase the longevity of Paleo-Indian armatures.

Given the stark discrepancies between these experiments and actual projectile construction and use, both experiments fail to meet the requirements for external validity. In actual use, atlatl darts flex and may impact at skewed angles or glance off the edges of hard targets. Just as mass and velocity affects penetration, it also affects breakage on armatures, which can vary dependent on how an armature is hafted. None of the fluted points deployed in the bison experiment broke from the base. A point that penetrated through the scapula and impacted the spine experienced a substantial longitudinal fracture initiating from the tip. Others experienced light fracturing at the tip. Most importantly, haft failure was common with these high energy darts (Figure 4.6). Points that impacted the bison at an angle or experienced off-center impacts to bone showed the capacity to leverage sideways in the haft, often cutting through their sinew bindings. This was the case even of points with lightly ground bases. Corner notched points also demonstrated the capacity to cut through their bindings. In fact, this kind of haft failure resulting from bone impact was so common during the experiments that I strongly suspect ancient hunters noticed it and tried to mitigate it. Clovis points with long haft connections also combined with the length of the point to give the point leverage on the hafting notch and subsequently the ability to break it. This was the case even when seated in foreshafts of sturdy hardwoods: green ash (*Fraxinus pennsylvanica*) and oak (*Quercus* spp) and supported with plenty of sinew.

These results from the bison experiment are also problematized by lack of external validity, because they do not represent effective Clovis projectiles. Rather, they demonstrate that high energy projectiles for hunting large animals need to be durable, with solid hafts and shaft junctures (Frison 1989). When points destroy their hafts, penetration stops quickly. It is better for penetration to have the armature fracture rather than bending (in the case of metal broadheads, Ashby 2006), or being dislodged from the haft when bone is encountered. Ensuring perfectly straight impacts to hard targets could reduce this problem, but this is not the way that flexible atlatl darts behave (Pettigrew et al. 2015), and darts frequently glance off the edges of ribs (e.g. Bement 2018). Dart points and their hafts need to be sharp, sturdy, and capable of withstanding high energy glancing impacts to bone at the ends of heavy but flexible dart shafts. It may be that fracturing could initiate at the base with different hafting arrangements, but this remains to be seen. In short, more work is required to effectively reverse engineer Paleoindian weaponry. Here, experiments on large animal carcasses can be highly informative in ways that controlled experiments are not.

There have been numerous theories regarding Paleoindian basal point fluting (see Thomas et al. 2017). Few researchers have linked fluting on Paleoindian armatures to slimmer hafts that would improve penetration (but see Roberts 1935). This could be especially important when hunting very large animals, which requires powerful and/or optimized weapons (Ellis 1997). In the carcass experiments, deceleration noticeably increased when bulky hafts encountered the skin. While hafting the 186 armatures for the experiments, I noticed that fluted points not only had slimmer hafts, but they were also more solid in their hafts than other types. They seat deeply, which combines with the concave base and fluted channel to reduce lateral movement in the haft. But with deep hafting notches also comes the need for stronger foreshaft materials. These insights are by no means authoritative. They come from a small sample of 11 fluted and unfluted Clovis points hafted and thrown at the carcass. These are ideas to test further.

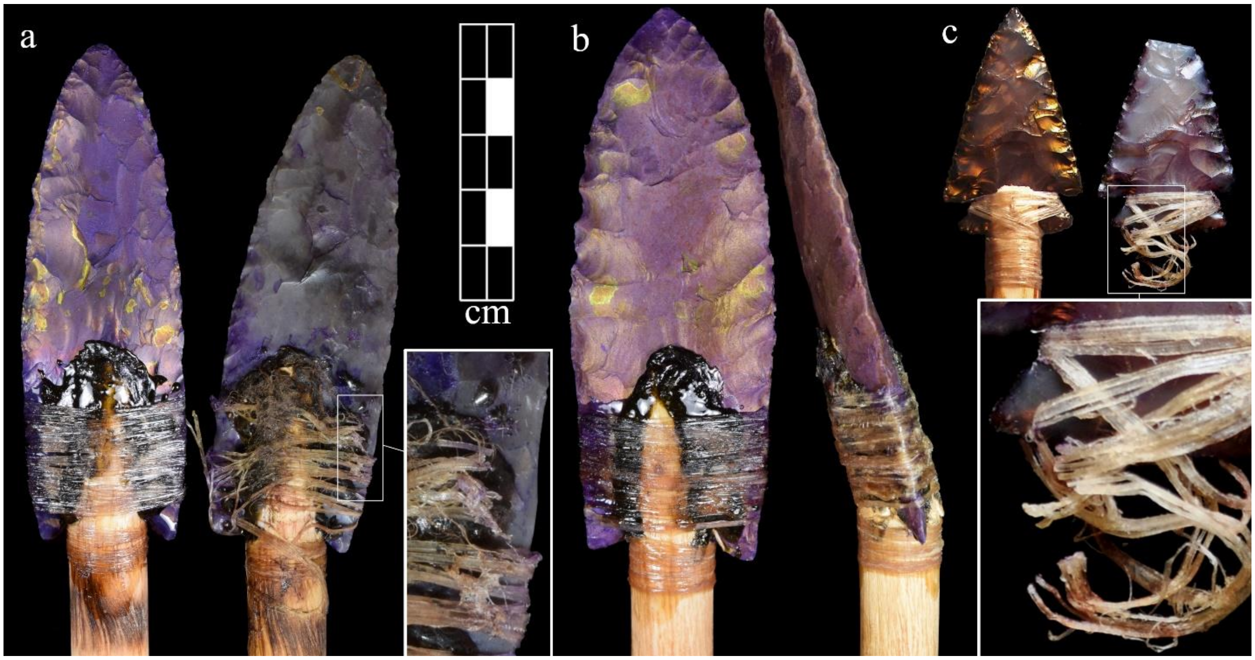


Figure 4.6. Example test armatures that experienced haft damage during the carcass experiments: a) before and after photos of an unfluted Clovis point that leveraged sideways from skewed impact to the bison and cut its bindings, b) Clovis point that broke its foreshaft notches from skewed impact to the bison, c) corner notched point that cut its bindings from striking the edge of a hog rib.

These unexpected insights suggest that an ideal dart for hunting large animals would have high energy and momentum, a sharp but robust armature, a sleek haft, a blade that does not project too far above that have that it leverages and breaks the hafting notches and/or strong hafting notches, features that ensure the armature will not be leveraged sideways in the haft, and a stiff forward shaft to reduce flexure on impact. It may also be desirable to increase the balance of the dart forward of center to maximize penetration (Ashby 2008). The necessity for a stiff forward shaft and sturdy hafting notches may help explain the presence of osseous foreshafts and hafting notches recovered from a few Paleo-Indian sites (Frison and Zeimens 1980; Galm and Gough 2008; Potter et al. 2014), although some of these items are clearly *sagaies*, pointed osseous tips like those found in Europe (e.g. Pétillon et al. 2011), and others seem to be fragmentary osseous segments of yet uncertain function.

Although many have focused on the idea that Paleo-Indians tried to preserve their armatures for reuse as much as possible (see Bamforth 2002a), the archaeological record casts doubt on this interpretation. Paleo-Indians have not been shown to recover and reuse their armatures more than hunters during later Archaic periods (Bamforth 2002a). Features of Paleo-Indian armatures should also be considered in light of optimizing terminal ballistics. Clearly more work is required to reverse engineer effective Clovis weaponry. Frison's (1989) experiments on culled African elephants demonstrated that Clovis points mounted to heavy atlatl darts have the capacity to produce lethal wounds from shots to the thorax from 17 m. However, Frison also mentions hafting issues, inability to penetrate through ribs, and most importantly his darts show large bindings at the mainshaft sockets, which impedes penetration (Chapter 2).

Using a large sample of stone point penetration depths from various projectiles impacting various targets, including both carcasses and a variety of simulants, Eren and colleagues (2021) have suggested that Clovis points were not as efficacious for hunting Pleistocene proboscideans as some have suspected. However, substantial methodological issues problematize this research. First, the lethality of a cutting armature cannot be judged solely by penetration depth. Rather, lethality as a result of hemorrhaging or organ damage is a function of the size and sharpness of the armature and the resultant surface area and quality of the wound (Ashby 2009; Friis-Hansen 1990). Second, penetration depth is a result of many variables, including the skewness of the projectile shaft on impact, the momentum and kinetic energy of the projectile, the size and sharpness of the armature, the sleekness of the armature haft, the size, shape and texture of the trailing shaft, and the composition of the prey body at the point of impact (Chapter 2). Internal organs are far less resistive than bone, skin, and muscle, so projectiles that successfully break through the thoracic or abdominal cavities of large prey can penetrate deeply through the softer interior before encountering more resistive material on the opposite side. Projectiles may therefore penetrate deeper through larger prey. Many experiments included in the analysis by Eren and colleagues were performed on simulants such as clay and gel, which have not been shown to be scalable to prey bodies (Chapter 3). In short, drawing penetration depths of stone-tipped projectiles from a great variety of experiments without attention to these variables provides no grounds to judge how well-designed Paleoindian hunting equipment would have performed.

A better assessment of Clovis hunting requires reverse engineering their weaponry. Such data will not be effectively obtained by delivering test armatures into homogonous target simulants at consistent velocities, but through tinkering with and gaining experience in the use of well-designed powerful equipment and testing it against large animal carcasses as Frison (1989) and Callahan (1994) did, albeit in a more rigorous way. The physiological differences between African elephants and extinct mammoths and mastodons requires careful consideration of the applicability of the results, but the results of such a test are more informative in light of what we do know of mammoths and mastodons than are controlled shots into non-scalable simulants. As Eren and colleagues (2021) point out, even the heaviest darts thrown by strong throwers may not be able to break through thick pachyderm ribs, but thick ribs also presented a problem for historic Plains bison hunters. Bison could come away “bristling with arrows” when shots were not skillfully placed (Bohr 2014). This did not stop Plains hunters from efficiently exploiting this resource, and perhaps even contributing to the depopulation of plains bison after the introduction of the horse (Flores 1991).

4.4 Conclusion

Archaeologists can learn quite a lot from old weapons, but this usually necessitates some practical experience building and using them. There is nothing wrong with controlled approaches that attempt to isolate laws and regularities, but we should be wary of the fictions these can produce. It is a mistake to assume that controlled experiments are the only way to be rigorous. When sufficient observational tools are deployed, realistic experiments can be rigorous and highly productive. The results can be more easily compared with each other and with the archaeological record. When designed effectively, realistic exploratory approaches can simultaneously test multiple hypotheses, reduce equifinality, provide unexpected insights about the design and function of old tools, and propose new hypotheses to test.

For realistic experiments to work properly it is essential that human participants develop the skill necessary to construct and use old tools. This is required for necessary rigor, but it is also part of the exploratory process. Similarly, skill and background knowledge are necessary in the design and implementation of controlled experiments, but the tinkering necessary to develop such skill is very different from the social processes that produced the archaeological record. Unfortunately, it is difficult to gauge what constitutes enough practice with archaeological tools. Close replicas of entire preserved weapon systems, such as the atlatls and darts from the North American Southwest, provide unique opportunities to gauge user skill. When replicated and deployed properly it is immediately apparent that the weapon has been refined over generations. When not deployed properly, the weapon can completely fail to function (Pettigrew 2009).

It is unfortunate that archaeologists sometimes shy away from opportunities to gain practical experience in the things they study. Students benefit from starting early in gaining skill with old tools and hobbies that help achieve this goal should be encouraged. Atlatl events, historic reenactments, mountain man rendezvous and flintknapping events offer unique opportunities to simultaneously learn from experienced individuals and observe unique subsets of modern culture; by all means worthy anthropological undertakings (e.g. Whittaker 2004). Better familiarity with old tools can also be gained from practical texts regarding their use and construction that are not always academic in nature (Allely et al. 2000; Garnett 2015; Hamm 1989, 2018; Whittaker 2010b). Students of experimental archaeology should not feel shy about pursuing these resources to gain practical skill in old tools. Just keep in mind the insights they put forward can be tested and critiqued.

CHAPTER 5. A FURTHER LOOK AT DEER HUNTER SUCCESS IN IOWA AFTER 40 YEARS OF COMPOUND BOW DEVELOPMENT

(Note: this chapter will be submitted with a second author, Tyler Harms of Iowa DNR, who assisted in the implementation of the survey and helped clarify important details regarding Iowa deer hunting and management)

5.1 Introduction

Archaeologists attribute advancements in hunting weaponry to higher cognition, modern behavior, safer interactions with predators and large prey, and the ability of our species to leave Africa and inhabit challenging new environments (see O'Driscoll and Thompson 2018). These ideas are partially predicated on the assumption that improvements in hunting weaponry make hunters more effective, but the extent to which this is the case requires further evidence. Archaeological understandings of hunting and hunting weapons are, of necessity, based in recent and contemporary analogs (Wylie 1985). Here, I present data from a survey of modern hunters in the US to shed light on how improvements in ranged projectile weapons make hunters more effective. As will be discussed, hunting success is highly contingent on many complex factors. To some extent, these can be tracked through statistical analyses when enough data are present.

Humans have come to fill the role of top predator of white-tailed deer (*Odocoileus virginianus*) across much of the United States. Effective management strategies require careful assessment of hunter numbers and success rates. In Iowa, seasons with various hunting weapons are used in local deer population management strategies in various parts of the state. Of seminal importance to both archaeologists and wildlife managers, then, are the impacts of changing weaponry and tactics on hunter success. This article presents an analysis of a survey taken in

2021 to gauge Iowa hunter success considering changing weaponry. The survey illuminates relative success and wounding rates across weapon categories currently legal for hunting deer in Iowa, but special focus is given to the evolution of the compound bow. Modern compound bows allow the user to hold the weapon at full draw for long periods and aim down a sight, while also dramatically increasing arrow velocity. The analysis finds that reported success rates can be markedly different between weapons, while reported wounding rates covary with success and are not statistically different between weapon categories.

To capture the relative effects of weapon evolution, we compare modern bowhunter success and wounding rates with a survey taken of Iowa bowhunters between 1976-79, which gauged the relative effects of traditional and compound bows on these variables (Gladfelter et al. 1983). The modern compound bow (Figure 5.1) was developed in 1967, but affordable compound bows only started being widely available to consumers in the later 1970s (Bear 1980). Between 1976-79 compound bow use increased from 32 to 73% among Iowa bowhunters. Currently, more than 80% of bowhunters in Iowa use compound bows.

Contemporary traditional bows tend to be longbows or recurve designs with limbs composed of wood and fiberglass (Bear 1980). The general form has not changed since the late 1970s. Although made from different material, modern traditional bows are comparable in form and application to more ancient forms. In contrast, compound bows make use of off-center pulleys (cams) attached to the limbs that simultaneously increase draw length and leverage on the limbs, and produce an effect known as “let off”, which significantly reduces the final weight at full draw and allows the hunter to hold the weapon at the ready for relatively long periods. Compound bows also incorporate attachments such as stabilizers and sights calibrated to different distances. Traditional bows lack such features or incorporate simple sights, but sighting is usually “instinctive.” Slower arrow speeds with traditional bows can result in deer “jumping the string” (hearing the shot and instinctively dodging the arrow) (Bear 1980). Gladfelter et al. (1983) found that while wounding rates were not statistically different between hunters using compound or traditional bows, compound bow users experienced 1.4 times greater odds of success than traditional bowhunters, therefore concluded that new bowhunting regulations could be necessary to sustain deer populations as compound bows saw further improvements.

Figure 5.1. Examples of a modern compound bow (left) and a “traditional” recurve bow with fiberglass limbs (right; photos in public domain).

Since the late 1970s significant improvements have been made to compound bows (Sung et al. 2018). New cam designs, improved arrow rests, improved limb and riser materials, improved sights, and lighter arrows of stronger material enable compound bows to be fired with greater velocity, consistency, and reduced noise. Laser rangefinders enable hunters to determine arrow drop and aim using the proper sighting pin when taking longer shots. All these features are currently legal in Iowa. Modern compound bows can shoot arrows at more than twice the velocity of traditional bows. The Helix Turbo by Hoyt, for example, is reported to shoot arrows at 350 feet per second (fps; https://hoyt.com/compound-bows/compound-hunting-bows) whereas arrows shot from traditional bows rarely exceed 160 fps (Bergman et al. 1988). Faster arrows produce flatter trajectory, increasing the range of modern compound bows, while simultaneously decreasing the likelihood that deer are capable of jumping the string.

Expanding on the Gladfelter et al. (1983) study, our survey also considers success rates with other weapons currently legal for hunting deer in Iowa. This allows us to situate bowhunting success within a broader range of modern hunting weapons. Since the late 1970s, modern rifles that fire tapered cartridges and bullets are no longer legal in Iowa given the open terrain and danger to bystanders, but straight-wall cartridge rifles with more limited range were legalized in Iowa in 2019 and provide a relative measure of modern rifle hunting efficacy. Straight-wall cartridges such as the historic .45-70 Government have an effective range of ~200 yards, after which the bullet begins to drop considerably. Muzzleloaders, or black powder guns, must be loaded with a powder charge and bullet from the muzzle as the name suggests. The charge is ignited with an external primer or an older flintlock mechanism. Growing interest in hunting firearms from the 18th-19th centuries eventually led to increasingly affordable replicas becoming available in the later 1950s and the creation of traditional muzzleloader hunting seasons in the US (Bridges 1972). However, as with archery, tradition has given way to modernizing efforts. Most muzzleloaders used by hunters now contain the firing pin and primer inside an enclosed bolt, are fitted with modern telescopic sights, and some are even designed to load a ready-made powder charge from the breech. Muzzleloaders have a maximum range of

~150 yards and require half a minute or more to reload depending on proficiency, although reload time is reduced in some modern forms. In Iowa, telescopic sights are legal on both muzzleloaders and straight-wall cartridge rifles. Since the restrictions placed on tapered rifle cartridges, the most popular hunting weapon in Iowa are shotguns firing slug ammunition. These weapons are effective to ~100 yards. Group drives to push deer out of timber and in range of hunters are common during shotgun seasons. However, straight-wall cartridge rifles, muzzleloaders and handguns are also legal during shotgun seasons. Disabled or elderly hunters can use crossbows during the archery season and all hunters are allowed to use crossbows during the late muzzleloader season. Like compound bows, modern crossbows feature powerful limbs fitted with cams, and frequently telescopic or optical reflector (red dot) sights are fitted to modern crossbows. The seasons during which these weapons can be used are given in Table 5.1.

Table 5.1. Iowa deer season dates and legal method of take.

Season	**Dates**	**Archery**	**Muzzle-loader**	**Handgun**	**Shotgun**	**Crossbow**	**Straight-wall**
Youth/Disabled	Sept. 19-Oct. 4	X	X	X	X		X
Archery	Oct. 1-Dec. 4, Dec. 21-Jan. 10, 2021	X					
Early Muzzleloader	Oct 12-25		X	X			
Late Muzzleloader	Dec. 21-Jan 10, 2021	X	X	X		X	
Shotgun 1	Dec. 5-9		X	X	X		X
Shotgun 2	Dec. 12-20		X	X	X		X

A deeper understanding of hunting weapons is necessary for understanding the ecology of modern hunting and its continued application for deer population management. This study illuminates elements of change and consistency since the late 1970s in Iowa hunting that will be of use for anthropologists and biologists. Following the methods of Gladfelter et al. (1983), we attempt to determine the effects of hunter years of experience and days hunted on success and wounding rates among the different weapon categories.

5.2 Methods

We selected individuals to be surveyed from the Iowa Department of Natural Resources (IDNR) licensing database. We queried all individuals who purchased 1) only an archery license in 2019-2020, 2) only a shotgun license in 2019-2020, and 3) only a muzzleloader license in 2019-2020. We stratified by these weapon types due to suspected differences in hunting tactics, success and wounding rates, and number of deer harvested. We then filtered out individuals who either 1) did not have an email address on file or 2) had an email address that was not valid (e.g., noname@dnr.com). This exercise resulted in a total of 46,711 Iowa residents who hunted in 2019-20 in our online survey sample. An online survey was built using Qualtrics XM and sent through the Qualtrics website to the entire list. The survey asked about number of days hunted, years of experience, deer retrieved, and deer wounded in each weapon category. Two email reminders were sent one and two weeks after the initial email for those who had not yet taken or completed the survey. The statistical analysis presented in this article was performed using JMP.

In the late 1970s bowhunters could not harvest more than one deer, which resulted in binary dichotomous (yes/no) success rate data. A significant increase in deer numbers since the late 70s means that hunters can now harvest two antlered deer (one with archery and one with gun) on a general license. In most counties, hunters can also purchase any number of antlerless tags in addition to a general tag until a specified county-specific quota is reached. This means that it is possible for individual hunters to harvest several deer in any weapon category.

Our survey allowed hunters to enter up to 10 harvested or wounded deer in each weapon category. We felt this number was sufficient because the average hunter harvests ~2 deer annually (IDNR, unpublished data). Subsequently, we analyze the impacts of years of experience and days hunted on success and wounding rates using an ordinal logistic regression with up to 10 categorized response variables. This allowed deer retrieved and wounded to be fitted as cumulative response probabilities (SAS Institute Inc. 2021a).

To compare odds of success with the 1970s survey and between current weapon types, an indicator column was created for weapon type, and data for deer retrieved, deer wounded, days hunted, and years of experience were placed in single columns. Filtering by weapon type allowed entries to be pooled or isolated by weapon type and cross-compared. Additionally, since most hunters (81%) retrieved or wounded 0-1 deer with any given weapon, a more general comparison with success and wounding can be performed by retabulating deer retrieved and wounded as additional binary categories. This allows use of a binary nominal logistic regression for which JMP provides odds ratios of success and wounding, for comparison with the 1970's data.

What leads to hunter success with any given weapon is highly complex. We explore the underlying structure of this complexity using a K-means cluster analysis (SAS Institute Inc. 2021b). This analysis uses an iterative fitting algorithm to find clusters based on distances from central means. When a range of clusters are explored, the analysis suggests an optimal number of clusters for the dataset.

Screening was applied during the analysis to reduce the effect of outliers, especially in the category of deer wounded, which has the strongest potential to introduce bias in the sample. In the shotgun and straight-wall rifle categories 23 and 10 respondents respectively reported wounding the maximum number of 10 deer in only a few days of hunting, while entries steadily decline to well below these numbers for 7-9 deer wounded. This is most likely a protest of the survey question. Entries beyond 10 deer wounded are therefore excluded from the following analysis across weapon categories. Understandably, hunters were less truthful about wounding deer, but these extreme outliers are the exception. Less than 25% of hunters reported wounding one or more deer with any weapon.

We can be less certain how many respondents did not report wounding, or how many non-respondents wounded deer. Non-response has the potential to bias both success and wounding. McPhillips et al. (1985) found that 28% of respondents to a bowhunting report card reported success, while 19% of non-respondents (who were later forced to respond) did. In other words, non-response can bias results towards higher percentages of success, and likely, lower percentages of wounding. Hunters occasionally made mistakes in other categories, such as entering more days hunted than allotted during the season for a particular weapon. Where such mistakes were noticed they were screened from the analysis. Removing outliers had the most noticeable impacts on the traditional bow and handgun averages, both of which are small samples, but there were also few outliers in these samples.

5.3 Results

5.3.1 Survey response and weapon use

Response rates to the Gladfelter et al. (1983) mailed survey ranged from a high of 81.7% in 1977 to a low 74.8% in 1979. In contrast, 27% of recipients responded to the emailed survey in spring of 2021. Of the total 12,661 responses, 1,270 were excluded due to ballot box stuffing, incompletion, or because the respondent did not hunt.

Of the total 11,391 responses analyzed, 324 (2.8%) reported hunting at least one day with a traditional bow and 2,032 (18%) with a compound bow. Within the bowhunter sample, 13.7% hunted with a traditional bow and 86% with a compound, including 24 respondents who hunted with both weapons. Through the late 1970’s, 32.2%, 51.7%, 65.3% and 72.9% of hunters switched to compound bows over the four respective years from 1976-79. This suggests that since the late 1970s compound bow use has either plateaued around 85% usage among hunters or traditional bows have recently increased in popularity.

Of the 11,391 responses, 23% hunted with muzzleloaders, 52% with shotguns, 2.4% with handguns, 20.5% with straight-wall cartridge rifles and 4% with crossbows. These percentages include hunters who used multiple weapons. With weaponry tabulated into signifier categories, the database consists of 14,007 entries for use in the statistical analysis.

5.3.2 Odds of success

Through the late 1970s, compound bow success rates fluctuated around 27.2% while traditional bow rates climbed from 17.4% to 23.9% over the four years from 1976-1979. In 2020-21 compound bow users reported significantly higher overall success (67.1%) and traditional bow hunters also reported better success (33%) than in the late 1970s. Table 5.2 gives percentage of success in each weapon category as both binary (yes/no) and cumulative (total deer retrieved). The success percentages with archery equipment from 1976-79 (Gladfelter et al. 1983:Table 1) are included for comparison.

One expects that success rates are influenced by the number of days hunted. A measure of this is provided by the ratio of average days hunted to deer retrieved in Table 5.3. According to this ratio, compound bowhunters hunted ~15 more days than muzzleloader hunters per deer retrieved, but 35 less days per deer retrieved than in the late 970s (Gladfelter et al. 1983:Table 2). This does not account for variation in individual hunter success, or the fact that our survey did not capture the specific time spent hunting per deer retrieved. As also reported by our predecessors, a Wilcoxon test indicates that average days hunted are statistically different between compound and traditional bowhunters (P-value <.0001). In fact, average days hunted for both bow types have not changed since the late 1970s. Traditional bowhunters still tend to hunt about 13 days a year, four less on average than compound users. Gladfelter et al. (1983) do not give significance to this difference for success rates due to a poor fit between days hunted and success in both bow categories. Depending on many variables, some hunters could achieve success in only a few days while others hunted a whole season and were unsuccessful.

Table 5.2. Percent success across weapon categories, including results from 1976-79 for comparison (Gladfelter et al. 1983).

Year	Tradbow	Compound	Muzzle-loader	Shotgun	Handgun	Straight-wall	Crossbow
1976	17.4%	27.4%					
1977	18.1%	24.8%					
1978	23.1%	28.8%					
1979	23.9%	27.8%					
2020-21 (binary)	30.6%	47%	47.7%	54.2%	21.9%	64.5%	47.1%
2020-21 (cum.)	33.0%	67.1%	62.4%	74.9%	28.6%	102.9%	69.3%

Table 5.3. Average experience and days spent hunting in each weapon category. The ratio Days:Retrieved is calculated as total days hunted/total deer retrieved.

		Tradbow	Compound	Muzzle-loader	Shotgun	Handgun	Straight-wall	Crossbow
Days hunted	**mean**	12.6	16.4	5.8	3.9	4.5	4.2	14.1
	st dev	10	12.3	4.1	2.15	3.5	2.4	12.7
	sum	4063	33390	15107	22808	1257	9807	6776
Years exp.	**mean**	13.6	16.8	14	21.7	9.6	4	5.5
	st dev	13.1	12.8	10.7	14.6	9.5	7.3	7
	sum	4392	34192	36682	127934	2696	9360	2661
N hunters		324	2032	2617	5929	281	2332	482
Days:Retrieved		35	24	9	5	16	4	20

In contrast with the Gladfelter et al. (1983) study, logistic regressions performed on our data of both cumulative deer retrieved and binary success rates finds days hunted to provide a significant fit across weapon categories. To start the analysis, an ordinal logistic regression is fitted to assess the cumulative probability of retrieving multiple deer given predictor variables. Since relatively few hunters across weapon categories (<2%) and no traditional bowhunters retrieved more than three deer, entries above that figure are screened. The model fits the bow categories, years of experience and days hunted as predictors of deer retrieved. This model has good fit (χ^2 =86, df =3, P-value <.0001) and years of experience and days hunted in their raw form are both significant (Table 5.4). The small parameter estimates ($\hat{\beta}$) demonstrate that the effect of a unit increase in days hunted on cumulative deer retrieved is not substantial but can have an impact over an extended range. Each day hunted increases the cumulative probability of success by 3%, each year of experience by 1.3%, and compound bow use by 30%.

Table 5.4. An ordinal logistic regression comparing compound vs traditional bow cumulative success. Entries beyond 3 deer retrieved are screened.

Term	$\hat{\boldsymbol{\beta}}$	**DF**	**SE**	$\boldsymbol{\chi^2}$	**P-value**
Intercept[3]	-4.60427	1	0.169101	741.36	<.0001
Intercept[2]	-2.95546	1	0.11366	676.14	<.0001
Intercept[1]	-0.97828	1	0.093493	109.49	<.0001
Weapon[Compound]	0.2997	1	0.064497	21.59	<.0001
Days	0.019969	1	0.003388	34.74	<.0001
Years	0.012911	1	0.00318	16.48	<.0001
Goodness-fit		2577		1944	1

In firearm categories all models that include days hunted as a predictor of cumulative deer retrieved fail goodness-of-fit tests. Why the models should lack fit or have small effect is visually demonstrated in Figure 5.2 and 5.3. The fit between days hunted and deer retrieved is not linear. Some hunters retrieved multiple deer in a few days of hunting (especially with firearms) while others hunted the whole season and came up empty. Hunters who retrieve the most deer tend to have 10 to 40 years of experience with bows, or 5 to 40 years of experience with muzzleloaders. This is consistent with our predecessor's finding that success plateaus

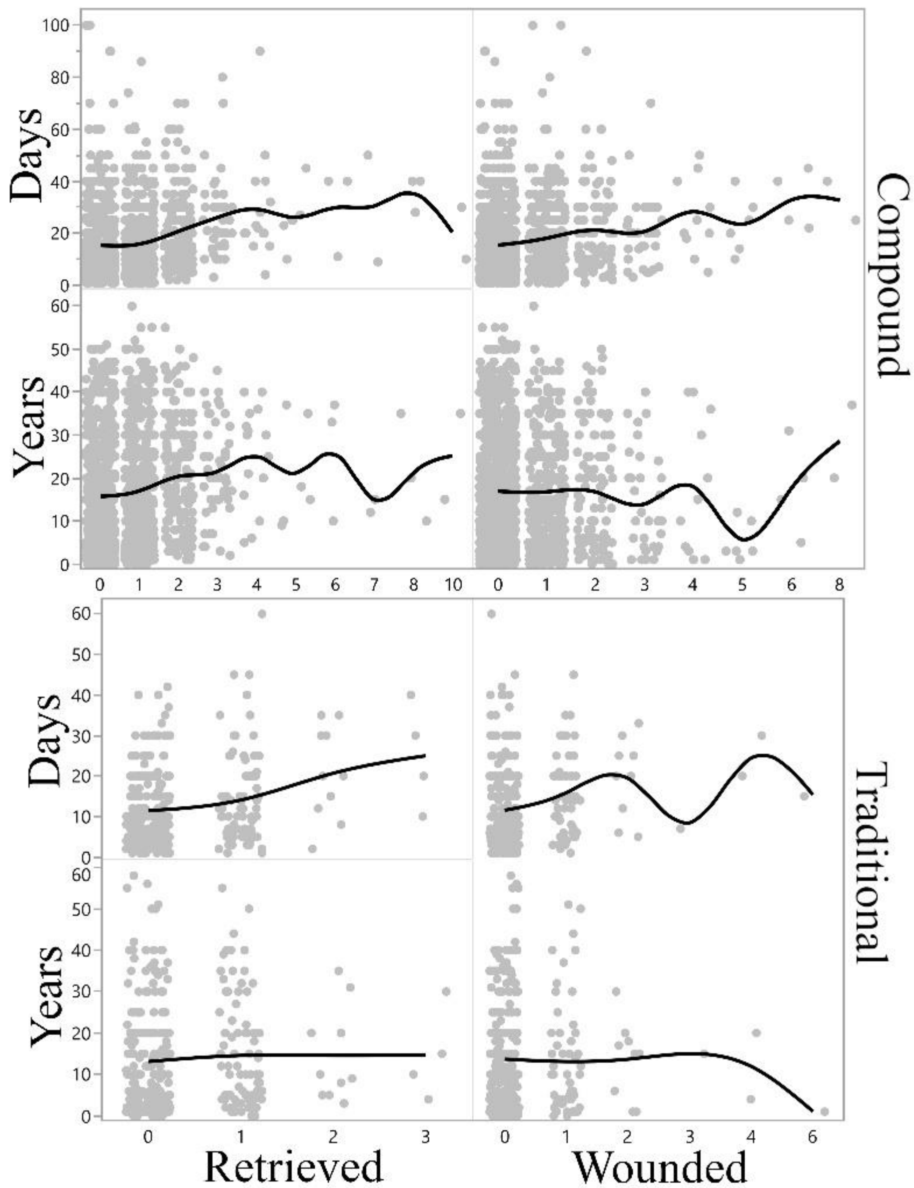


Figure 5.2. A scatterplot of raw data for the bow categories.

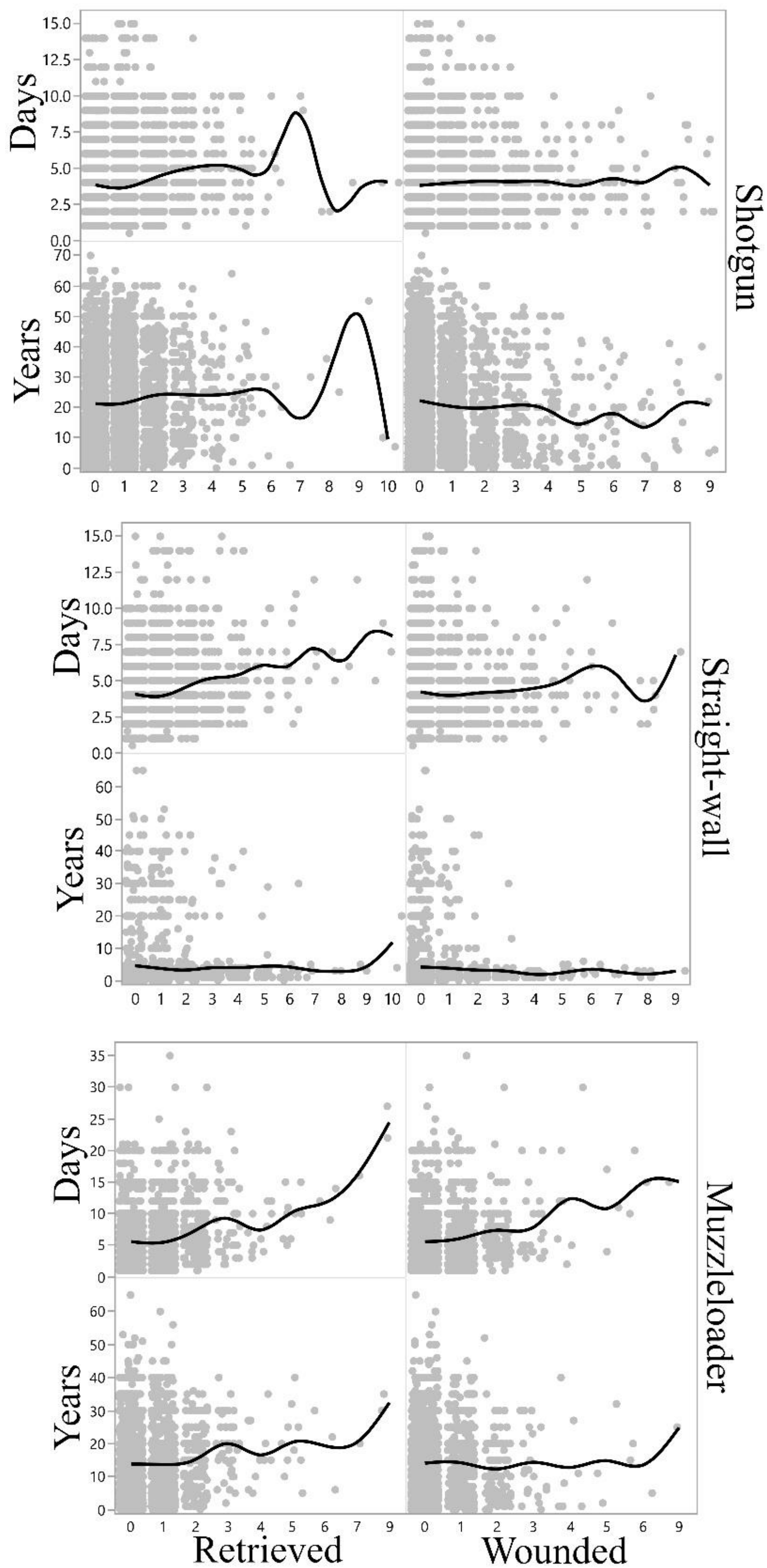


Figure 5.3. A scatterplot of raw data for three of the firearm categories.

around 10 years for traditional bows or 7 for compounds (Gladfelter et al. 1983:Figure 1). Understandably, few hunters have much experience with straight-wall rifles given that the weapon was recently legalized, although hunters are achieved the highest success with this weapon. This clearly does not account for the effect that overall hunting experience has on success with this weapon, but some hunters using another modern firearm with a longer history of legal use in Iowa, the shotgun, could achieve substantial cumulative success with <5 years of experience.

Taking the $\log_e$ of years of experience, which is positively skewed, better captures the transition to greater experience. This can improve our comparison in the following models, especially for bow categories since these weapons are the most impacted by experience and traditional bowhunters had lower average experience than compound bowhunters (57% of traditional bowhunters had <10 years of experience while 42% of compound bowhunters did). But the parameter estimates for Log_e(years of experience) cannot be readily interpreted.

An effective approach that gives a simplified model of weapon efficacy employs a nominal logistic regression with binary weapon categories and success rates to produce odds ratios of success. Here, we assess the odds of retrieving at least one deer with a given weapon versus another. Gladfelter et al. used such a model comprised of bow type, survey year, and $\log_e$(years of experience) to demonstrate that compound bowhunters had 1.4 times greater odds of success than traditional bowhunters. Since our survey only includes one year of data, our analogous model considers only bow type, $\log_e$(years of experience), and binary success. This produces a model with good fit suggesting that modern compound bowhunters experience 1.93 times greater odds of retrieving at least one deer than traditional bowhunters (χ^2 =53, df =2, P-value <.0001) (Table 5.5).

Table 5.5. Nominal logistic regression models of binary success.

	Term	$\hat{\beta}$	DF	SE	χ^2	P-value
Compound vs Tradbow	Intercept	-0.86965	1	0.11266	59.59	<.0001
	Weapon	0.330457	1	0.065758	25.25	<.0001
	Log[Years]	0.180921	1	0.03952	20.96	<.0001
	Goodness-fit		92		102	0.22
Muzzleloader vs Straight-wall	Intercept	0.246474	1	0.029517	69.72	<.0001
	Weapon	-0.35082	1	0.029517	141.26	<.0001
Muzzleloader vs Shotgun	Intercept	0.033523	1	0.023714	2	0.1575
	Weapon	-0.13384	1	0.023714	31.97	<.0001

When the same model considers compound bows and muzzleloaders, $\log_e$(years) remains significant (P=0.003) but the model fails goodness-of-fit (P<.0001). Removing $\log_e$(years) and only fitting these weapons with binary success produces a model in which the difference in success rates between these weapons remains insignificant (χ^2 =0.229, df =1, P-value =0.633). A better measure uses an ordinal logistic regression in which entries above 6 deer are screened. Days hunted and years of experience in raw form are again significant and the model has good fit, suggesting that compound bows reduce the probability of cumulative success by 13% relative to muzzleloaders (χ^2 =77, DF =3, P<.0001) (Table 5.6).

We can also consider the odds of retrieving at least one deer between firearm categories. Muzzleloader hunters are given separate seasons due in part to presumed lower odds of success. To test this, we can compare muzzleloader success with that of shotgun hunters as well as straight-wall rifle hunters. Because straight-wall rifle and shotgun hunters could only hunt 14 days, muzzleloader hunters who hunted over that mark are screened. The resulting model excludes years of experience and days hunted due to lack of fit. These models indicate that straight-wall rifle hunters had 2.02 times greater odds of retrieving at least one deer than muzzleloader hunters within 14 days (χ^2 =144, DF =1, P-value <.0001), while shotgun hunters had 1.31 times greater odds than muzzleloader hunters (χ^2 =32, DF =1, P-value <.0001) (Table 5.5).

Table 5.6. An ordinal logistic regression comparing compound bow vs muzzleloader cumulative success.

Term	$\hat{\beta}$	**DF**	**SE**	χ^2	**P-value**
Intercept[6]	-7.11964	1	0.412008	298.61	<.0001
Intercept[5]	-5.81596	1	0.220727	694.27	<.0001
Intercept[4]	-5.02818	1	0.155295	1048.4	<.0001
Intercept[3]	-3.95345	1	0.10278	1479.6	<.0001
Intercept[2]	-2.56417	1	0.071973	1269.3	<.0001
Intercept[1]	-0.53111	1	0.058177	83.34	<.0001
Weapon[Compound]	-0.13087	1	0.033851	14.95	0.0001
Days	0.024437	1	0.003246	56.69	<.0001
Years	0.010647	1	0.002444	18.99	<.0001
Goodness-fit		6471		3070	1

5.3.3 Wounding rates

Various terms have been used in reference to non-retrieval. We use “wounding” to refer to deer hit with a projectile but not retrieved in contrast to “crippling” in the previous study. Failing to retrieve wounded prey is not peculiar to our species (e.g. Wikenros et al. 2009), but understandably it carries negative connotations for modern hunters. As Gladfelter et al. (1983) noted and as our data will also demonstrate, some percentage of prey animals can be expected to escape after being hit with a projectile despite improvements in weaponry. Animals are not always “crippled” by wounds from predators, including hunters, but different projectile weapons can lead to different outcomes in wounding. Firearms carry more energy and are generally more damaging, while bows require closer range and greater precision to ensure retrieval. Compound bows firing arrows with more energy have also been shown to be capable of inflicting more damage to bone than traditional bows (Karger et al. 1998). Better data on non-retrieval is achieved when deer movements can be tracked after the event or incentives are used to improve reporting. Ditchkoff and Welch (1998) found that out of 11 radio collared deer hit but not retrieved with arrows from traditional bows only 3 died of their wounds. Those that lived and were harvest later generally carried scars on the shoulder area. The shoulder, containing bone and dense muscle, is a greater obstacle to traditional bows than firearms. These differences in terminal ballistics have implications both for wounding outcomes and retrieval rates.

Gladfelter et al. (1983) noted a slight increase in wounding rates from 12.9 to 16.8% of compound bowhunters and 9.6 to 14.8% of traditional bowhunters between 1976 and 1979. Along with success, percentages of wounding have further increased since the late 1970s. A total of 27.2% of compound bowhunters in our sample reported wounding at least one deer while 21% of traditional bowhunters did. A range of percentages of wounded to retrieved deer from bowhunting have been described in the literature, ranging from over 50% to under 20% of deer hit but not retrieved (Ditchkoff and Welch 1998; Pedersen et al. 2008; Stormer et al. 1979). Table 5.7 provides the percentages from our study when more than 9 deer reported wounded are screened.

Presumably, wounding rates are influenced by days hunted and years of experience. Although both had significance, the latter was excluded by Gladfelter et al. to improve the fit of their model, which fit binary success, $\log_e$(days hunted), and weapon type to binary wounding data. This model revealed that success and days hunted were correlated with wounding, but weapon type was not. In other words, wounding was not statistically different between compound and traditional bows when the disparate success rates were also accounted for.

Table 5.7. A comparison of retrieval and non-retrieval across weapon categories. Outliers above 9 deer wounded are screened.

	Compound	Crossbow	Handgun	Muzzle-loader	Shotgun	Straight-Wall	Tradbow
N Deer	1364	334	81	1636	4414	2382	117
N Wound	807	185	65	758	2460	1018	91
N Hit	2171	519	146	2394	6874	3400	208
%Retrieved	63	64	55	68	64	70	56
%Wounded	37	36	45	32	36	30	44
Wound/100 days hunting	2	3	5	5	11	10	2

Importantly, wounding was negatively correlated with success in our predecessors' data. Unsuccessful hunters were found to be 1.37 times more likely to wound deer than successful hunters. Wounding and success are also correlated in our data both within and across all weapon categories, but wounding is positively correlated with success. We suspect this is due to the cumulative aspect of our data, which captures the results of more opportunities to hunt and engage deer during a hunting season than in the 1970s.

A simple nominal regression fitting binary success to binary wounding across weapon categories provides an odds ratio suggesting that successful hunters are 3.23 times more likely to also report wounding deer than unsuccessful hunters (95% CI = 3-3.52, χ^2 =798, DF =1, P-value <.0001). This indicates that among contemporary Iowa deer hunters, higher percentages of retrieval also implicate higher percentages of non-retrieval across weapon categories. This corroborates prior evidence of positive correlations between both bow and firearm success and wounding (McPhillips et al. 1985; Stormer et al. 1979). Stormer et al. (1979) suspected that a partial cause of this correlation was that unsuccessful hunters who wounded deer were less likely to report it. We cannot know the degree to which this bias is affecting our sample, but we assume this bias is evenly distributed across weapons and the correlation between success and wounding is strong enough to lead us to suspect it is real.

To repeat the nominal logistic regression used by Gladfelter et al. (1983), binary success, $\log_e$(days hunted), and bow categories are fitted as predictors of binary wounding. This produces a good fit, but as was the case of our predecessor's model, bow categories are insignificant (P-value = 0.769). The P-value is even higher than in the late 1970's, suggesting that differences in reported wounding rates between the two bow categories are insignificant, while success and $\log_e$(days hunted) both correlate with wounding ($\chi 2$ =196, DF =3 P-value<.0001) (Table 5.8). Intuitively, years of experience should correlate negatively with wounding, but this variable is insignificant in either raw or log form.

Table 5.8. The effect of binary success, days hunted, and bow types on binary wounding among compound and traditional bowhunters.

Term	$\hat{\boldsymbol{\beta}}$	**DF**	**SE**	$\boldsymbol{\chi^2}$	**P-value**
Intercept	-1.94664	1	0.168448	133.55	<.0001
Weapon[Compound]	0.022331	1	0.076021	0.09	0.769
Success[Yes]	0.57767	1	0.0498	134.56	<.0001
Log[Days]	0.350877	1	0.060445	33.7	<.0001
Goodness-fit		141		169	0.054

When the model is extended to include all weapon types, $\log_e$(days hunted) and success remain highly significant (P-value <.0001) while weapon type is not (P-value=0.153) and the model fails goodness-of-fit (χ^2 =410, DF =340 P-value=0.005). The lack of significance between weapon types continues when the model compares entries between firearm categories or between firearms and bows (when traditional bows and straight-wall rifles are considered, P-value=0.311).

To further assess the relationship between wounding and weapon type, we fit an ordinal logistic regression in which entries above 6 deer wounded or retrieved are screened. Weapon type, days hunted, years of experience and deer retrieved are fitted as predictors of cumulative wounding. This model has good fit, but many of the parameter estimates for weapon categories are insignificant (χ^2 =951, DF =14 P-value<.0001) (Table 5.9). Unsurprisingly, years of experience and days hunted have a similar limited effect on wounding as they do on success. Each day hunted increases the probability of wounding by 2.2% while each year of experience decreases it by 1.2%. The largest contributions to the wounding probability come from the ranges of 3-4 and 5-6 deer retrieved in the shotgun and compound bow categories, which are large groups of hunters with effective weapons.

To summarize, when only weapon categories are regressed against wounding the fit is of course significant, as it is when weapon categories are regressed against success, and weapons that are more likely to yield success subsequently have larger positive parameter estimates indicating they are also more likely to produce wounding. Gladfelter et al. (1983) explained this by suggesting that compound bowhunters were willing to take longer shots given greater confidence in their weapon.

We should extend this assumption to the other weapon categories as well. To understand relative wounding between weapons it is necessary to include success in the models. This does not prove that success and wounding remain perfectly proportional as weapons improve. The wounding percentages in Table 5.7 suggest this is not the case. Hunters with traditional bows and handguns reported lower overall percentages of both success and wounding than other weapon categories, but within these categories larger percentages of hunters failed to retrieve deer. Logistic regression models fail to find a statistical significance for this relationship due to the variance in wounding that occurs within all weapon categories. When a fit can be found between weapon types and the variance in wounding, logistic regression models tend to favor the increased rates of wounding among weapons with improved range and energy, rather than the ratio of non-retrieval to total deer hit.

Table 5.9. An ordinal logistic regression to assess the contributions of weapon categories, days and years to cumulative probabilities of wounding.

Term	$\hat{\beta}$	**DF**	**SE**	χ^2	**P-value**
Intercept[6]	-6.01538	1	0.470317	163.59	<.0001
Intercept[5]	-5.10279	1	0.453367	126.68	<.0001
Intercept[4]	-4.3617	1	0.447254	95.11	<.0001
Intercept[3]	-3.55901	1	0.444131	64.22	<.0001
Intercept[2]	-2.61138	1	0.442536	34.82	<.0001
Intercept[1]	-1.19874	1	0.441718	7.36	0.0067
Weapon[Compound]	0.102632	1	0.063884	2.58	0.1082
Weapon[Handgun]	-0.28197	1	0.158435	3.17	0.0751
Weapon[Muzzleloader]	-0.00794	1	0.057813	0.02	0.8907
Weapon[Shotgun]	0.220452	1	0.052679	17.51	<.0001
Weapon[StraightWall]	-0.02675	1	0.061136	0.19	0.6617
Weapon[Tradbow]	0.002378	1	0.126288	0	0.985
Days	0.024307	1	0.003077	62.41	<.0001
Deer[5-6]	1.178097	1	0.497322	5.61	0.0178
Deer[4-5]	-0.73385	1	0.298771	6.03	0.014
Deer[3-4]	0.174117	1	0.212413	0.67	0.4124
Deer[2-3]	-0.18422	1	0.121843	2.29	0.1306
Deer[1-2]	-0.05375	1	0.064978	0.68	0.4081
Deer[0-1]	-1.1569	1	0.046729	612.95	<.0001
Years	-0.01152	1	0.001716	45.09	<.0001
Goodness-fit		24928		8906	1

We should also reiterate that reported success rates are higher than wounding rates with any given weapon. While hunters in our data across weapon categories reported a roughly 50% chance of retrieving at least one deer, they reported a 24% chance of wounding one.

The wounding and success rates presented here are by no means atypical when compared with wounding and success among other predators. Wolves hunting roe deer (*Capreolus capreolus*) and moose (*Alces alces*) in Scandinavia had a 22 and 26% success rate per respective species of animals they began to chase. Of 22 moose physically engaged, 13 were injured and 8 (36%) escaped with injuries, whereas one of 14 roe deer initially escaped with injuries but was later killed (Wikenros et al. 2009). Different constraints affect various predator success and wounding rates, but prey can sustain non-fatal injuries and escape predators of all kinds.

5.3.4 A multivariate approach to hunter demographics

Hunting success is clearly impacted by a complex range of factors. Adequately capturing these variables as raw data would require a complex survey that could further reduce response rates and increase the potential for bias. We can reveal some of the underlying structure in the available data by using a K-means cluster analysis. Much of the underlying structure can be thought of as hunter demographics, including differences in knowledge, age, skill, experience, dedication, and preference for numbers and types of deer harvested.

A K-means cluster analysis was performed across weapon categories, screening entries for more than 6 deer wounded and retrieved to reduce the effects of outliers. The analysis considered the four variables of days hunted, deer retrieved, deer wounded and years of experience. Based on the cubic cluster criterion (CCC) provided by the JMP output, the most optimal model results in eight clusters (Figure 5.4 and Table 5.10). How these eight clusters fit across weapon categories is revealed by the within-weapon frequencies presented in Table 5.11.

- **Cluster 1**: hunters who retrieved 1-3 deer over only a few days, while wounding very few. These hunters have a range of experience levels. Cluster 1 has its strongest representation in the firearm categories.
- **Cluster 2**: hunters who hunted very few days with a weapon and experienced low to moderate success but did not report wounding deer. These hunters have the least experience. This cluster dominates all weapon categories.

- **Cluster 3**: hunters who were typically successful but reported wounding more deer than they retrieved. They hunted relatively few days and have a range of experience. This is the second smallest cluster in the sample, comprised of only 411 entries. It is poorly represented across weapon categories but is most prominent in the shotgun and straight-wall categories.
- **Cluster 4**: hunters who hunted only a few days and experienced moderate to low success, but all reported wounding 1-2 deer. These hunters also report low to moderate experience and can be found across weapon categories but are most prominent in the straight-wall cartridge category.
- **Cluster 5**: hunters who typically hunted 30 days in a season and experienced a range of success, some retrieving several deer, while wounding fewer than they retrieved. These are committed hunters with a range of experience but most report several years. These hunters are best represented in the archery categories.
- **Cluster 6**: dedicated hunters who reported hunting a significant number of days with a weapon and had a high degree of success, while wounding fewer than they retrieved. These hunters are only found in the archery categories, since firearm seasons were shorter. This is the smallest cluster in the sample.
- **Cluster 7**: the most experienced hunters in the sample and probably also the oldest. They hunted relatively few days and reported a ~50% success rate at retrieving deer, while wounding fewer than they retrieved. These hunters are common in the archery, muzzleloader and shotgun categories. They do not appear in the straight-wall rifle category most likely because the weapon was only recently legalized.

- **Cluster 8**: hunters who hunted several days and reported a ~50% success rate, while wounding fewer than they retrieved. They report low to moderate experience and comprise the second largest percentage of hunters in the archery categories.

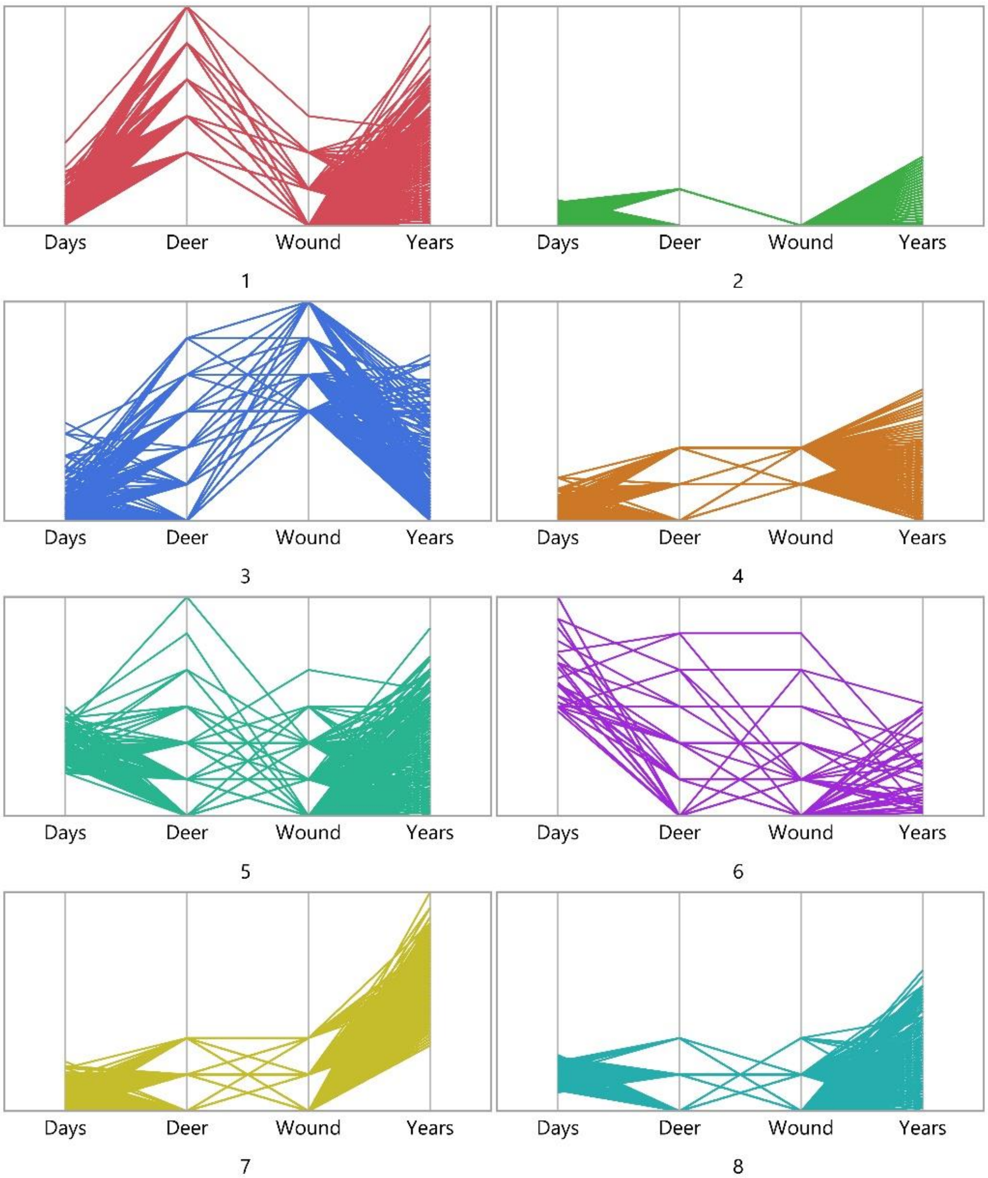


Figure 5.4. A parallel coordinates plot of K-means clusters across weapon categories.

Table 5.10. The composition of clusters from K-means analysis.

Cluster	Days mean	Days st dev	Retrieved mean	Retrieved st dev	Wounded mean	Wounded st dev	Years mean	Years st dev	*N*
1	5.9	4.0	2.6	0.9	0.2	0.4	14.7	12.3	1277
2	4.2	2.4	0.4	0.5	0	0	7.7	6.7	5759
3	6.6	6.8	1.4	1.2	3.8	1.0	14.0	13.5	411
4	4.7	3.1	0.8	0.6	1.3	0.4	9.3	8.7	1852
5	31.9	6.0	0.8	0.9	0.5	0.8	19.1	13.6	483
6	64.9	14.3	1.4	1.4	0.8	1.2	12.6	10.5	49
7	4.5	2.9	0.5	0.6	0.1	0.4	35.2	8.7	3033
8	16.8	4.0	0.5	0.6	0.2	0.4	14.0	10.0	1037

Table 5.11. Frequencies of K-means cluster representations within each weapon category.

Cluster	Compound Column%	Crossbow Column%	Handgun Column%	Muzzle-loader Column%	Shotgun Column%	Straight-Wall Column%	Tradbow Column%
1	4.45%	4.79%	2.85%	7.73%	9.68%	16.51%	1.54%
2	22.44%	40.21%	74.38%	52.26%	35.90%	56.37%	40.12%
3	2.08%	2.08%	1.42%	1.38%	3.86%	3.82%	1.23%
4	8.40%	11.67%	9.96%	15.53%	12.39%	19.04%	8.02%
5	18.59%	11.67%	0.36%	0.27%	0.00%	0.00%	12.65%
6	1.88%	2.08%	0.00%	0.00%	0.00%	0.00%	0.31%
7	12.31%	2.71%	7.83%	16.11%	37.50%	3.82%	11.11%
8	29.86%	24.79%	3.20%	6.73%	0.65%	0.43%	25.00%

The K-means analysis helps capture some of the fundamental differences and similarities in hunter behaviors and demographics. Most Iowa hunters in any given weapon category are relatively new to hunting and do not spend many days in the field (cluster 2). The short time spent hunting may reflect lack of drive to hunt or simply lack of available time to hunt. The high percentage of hunters with few years of experience may also be a product of the Covid pandemic providing more opportunities of Iowans to try a new hobby. The lack of wounding in cluster 2 may be in part a result of response bias but may also reflect a lower encounter rate with deer and perhaps a conservatism against risk taking. If this is the case, it could help explain why years of experience does not necessarily correlate with more wounding.

Cluster 3 captures a relatively small number of individuals who were usually successful but had a hard time retrieving deer. Although this cluster is most common in the modern firearm categories, individuals with similar bad luck or lack of skill occur in clusters 5 and 6, which are most common in the archery categories. Hunters using the newly introduced straight-wall cartridge rifles occasionally failed to retrieve deer (cluster 4) but a near equal percentage had very good success and retrieved the majority of deer they fired at (cluster 1). Archery hunters with the highest success (clusters 5 and 6) tend to hunt 30 days or more out of a year. Those who hunt 60 days or more are rare. This level of dedication is slightly less prevalent in the traditional bow than compound bow categories, which likely has some impact on the disparate success rates between those weapons.

With all weapon categories, wounding still occurs among hunters with many years of experience, a fact noted in the 1970s survey, but the oldest hunters in our sample with 30 or more years of experience (cluster 7) were usually content to hunt only a few days, during which they had a ~50% success rate and the second lowest wounding rate among the clusters. The reduction in wounding with increased patience of highly experienced hunters is particularly well demonstrated in the traditional bow sample in Figure 5.5.

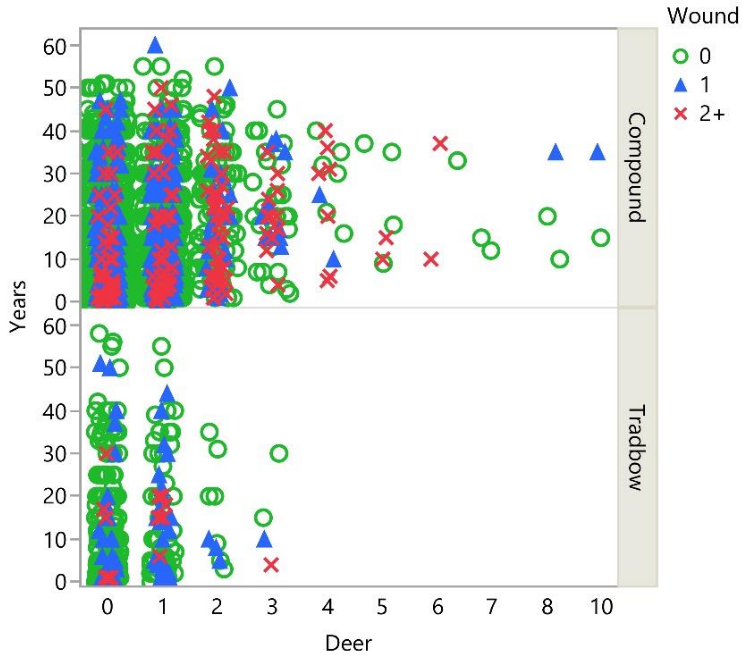


Figure 5.5. Skill among bowhunters as a function of years of experience and deer retrieved.

5.4 Discussion

Improved bowhunter success since the late 1970s may be partly attributed to a larger deer population in 2020-21. White-tailed deer numbers have risen steadily in Iowa since the early 1900s, topping out in 2005 with a total harvest across all weapon types of 211,451 (Lyon 2021). The current goal of IDNR is to maintain total harvest levels at 100,000-120,000 annually, which it has achieved since 2013. During the 2019-20 season, bowhunters harvested 22,142 deer, whereas in 1979 the total archery harvest was estimated at 3,305. However, archery hunters were also more numerous in 2019-20: 85,217 archery licenses were sold in 2019 compared with <13,000 in 1979.

A ~570% increase in white-tailed deer coinciding with a ~555% increase in bowhunters suggests that the effects of a larger deer population on archery success rates are either not substantial or a result of more complex hunter-prey interactions. Larger numbers of both human predators and their prey should increase the rate of encounters and subsequently success rates. If we may draw on studies of other predator-prey relations, this may be better predicted by hunter numbers, or the ratio of hunter densities to deer densities (Vucetich et al. 2002). But it is also noteworthy that compound and traditional bowhunter success rates have not risen proportionally: compound bow users experienced 141% and traditional bow users 51% greater success than in 1979. It is unlikely that a larger deer herd alone resulted in the substantial increase in compound bowhunter success.

Assuming an increased deer population increases success proportionally across weapon categories, the increasing disparity in bowhunting odds of success is most likely a result of the significant improvements made to compound bow technology. A consolidation of skill in the traditional bowhunter group may also have driven up success in that category. With some exceptions, bowhunters not dedicated to developing skill with traditional bows would likely use compounds instead (Gladfelter et al. 1983:10). This trend could also explain the rising success rates among traditional bowhunters through the late 1970s. Although oddly, traditional bowhunters in our sample on average have fewer years of experience than compound bowhunters, which may represent a resurgence in interest in traditional bowhunting.

Gladfelter et al. (1983) reasoned that improvements to compound bows made users more confident in their ability to take longer shots. They also discovered a lack of correlation between years of experience and wounding. Put differently, weapon improvements and experience do not necessarily decrease the willingness or necessity of hunters to take risks in attempting to achieve success. Experienced hunters may even be inclined to take more risks given greater confidence in their abilities. Some risk of non-retrieval is inherent in hunting because prey animals employ anti-predator strategies, such as remaining close to cover, remaining highly vigilant, and swiftly avoiding predator attacks, including dodging arrows. In this sense, non-retrieval correlates with the challenging nature of predation. Contrary to some suspicions (e.g. Pedersen et al. 2008), these data suggest that compound bow developments do not automatically reduce rates of wounding among bowhunters. Rather, each improvement in ranged weapons presents more opportunities for both retrieval and wounding.

The correlation between success and wounding appears across weapon categories, although the degree to which it manifests is dependent on many variables and may be controlled by extraneous circumstances, such as proficiency exams and mandatory reporting (Pedersen et al. 2008). Survey data are problematized by certain types of bias, but bias is also inherent in more controlled settings, such as described by Pedersen and colleagues (2008). Years of experience is not necessarily a good way to quantify skill, but skill usually entails sufficient experience. This is especially the case in the traditional bow categories, and less so as weapon ranges increase. No hunter who retrieved 2 or more deer with a traditional bow and had above 10 years of experience reported wounding deer, while those with fewer than 10 years occasionally did. Those who hunted with a compound bow and retrieved several deer also reported low wounding rates. This propensity to achieve success without losing deer can be found in any weapon category Figure 5.5 and 5.6. But general wounding rates with any weapon in this sample are higher than those found in more controlled settings such as described by Pedersen et al. (2008). This suggests that if reduced non-retrieval is desired, the answer is not necessarily to improve weapons but to improve proficiency. As with any analysis of survey data, these findings suffer from unknown response bias and should be confirmed through field studies (e.g. Ditchkoff and Welch 1998).

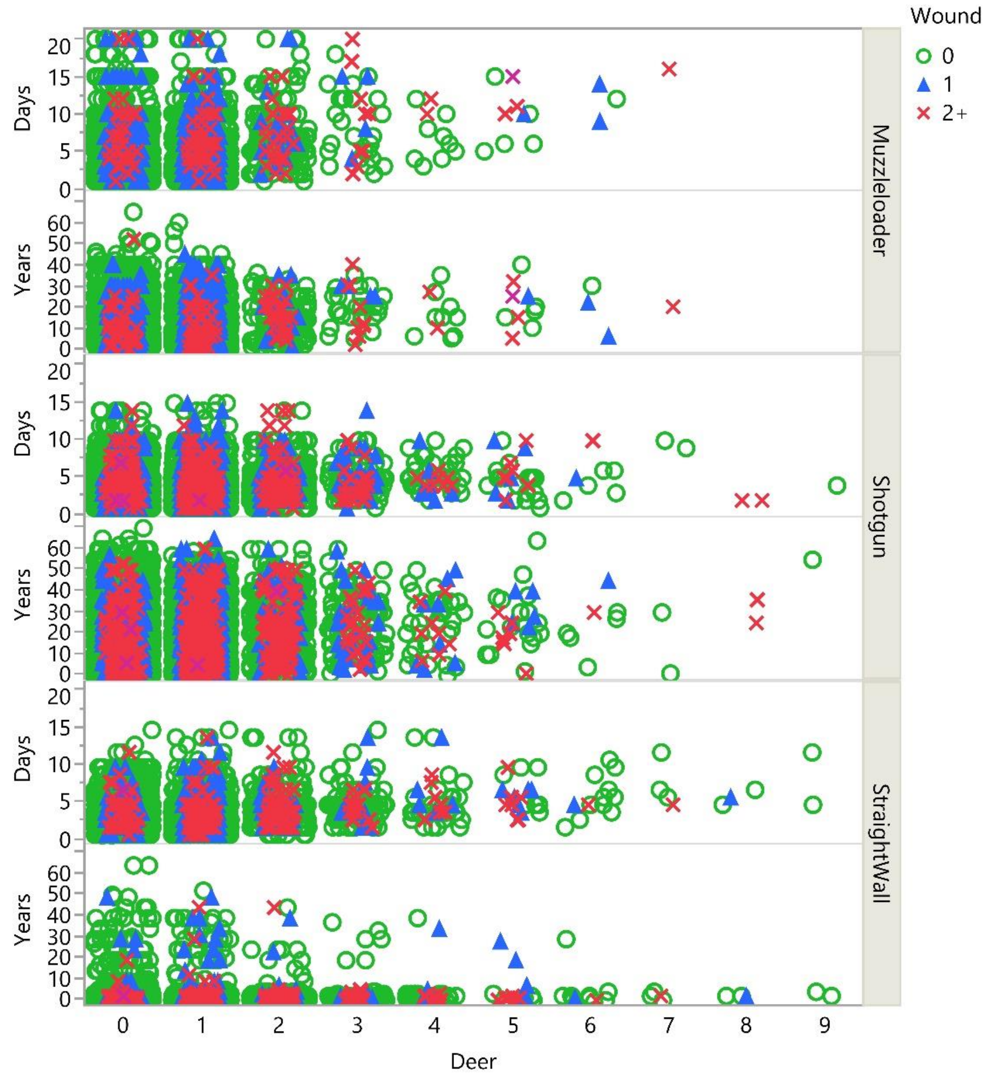


Figure 5.6. Skill among gun hunters as a function of years of experience and deer retrieved.

The comparison of relative success rates between weapons is complicated by an additional factor not included in the statistical analysis, prey responses to predator tactics and increasing predator densities. Modern hunters observe yearly that white tailed deer quickly modify their behavior as the season progresses, becoming warier, switching to nocturnal patterns, and decreasing movement on the landscape. These behaviors are more pronounced in areas with denser hunter numbers (Little et al. 2016). In western states mule deer (*Odocoileus* *hemionus*) alter their behavior in response to hunting pressure by relocating to areas farther away from roads (Rodgers et al. 2021). Seasons that allow hunters to deploy more challenging weapons, namely bows, occur prior to more popular firearm seasons for this reason. To improve these models, it may be advisable to consider the effects of tactics and hunter densities on deer antipredator behavior in future analyses.

Some implications for archaeologists can be drawn from these data. Hunting success is a result of a complex range of factors relating to prey species, weapon technology, hunter demographics, and more. Success rates can be improved by increasing technical skill and experience, especially with traditional weaponry. However, improvements in weapon technology can also drive success while reducing the necessary technical skill and duration of hunts. This suggests that in certain conditions, such as when hunters enter new, unfamiliar environments, a reduced social emphasis is placed on developing hunting skill, or a reduced social emphasis is placed on spending significant time hunting, hunters would especially benefit from improvements in ranged weaponry. Developments in ranged weaponry through time likely parallel social changes and may be driven by environmental factors as well as prey response. As hunter densities increase, prey deploy antipredator tactics, presumably increasing the benefits of ranged weapons. Some appearances of improved weaponry in the archaeological record may coincide with increasing human populations. Hunters using traditional weaponry were likely to occasionally wound prey, but given the lower power of ancient hunting weapons, such as the bow and arrow or atlatl and dart, many prey animals may have survived these attacks. When early firearms were introduced success rates could have more than doubled in certain conditions (but see Bohr 2014), while improved cartridge rifles may have quadrupled success rates. However, social conditions leading to hunter skill and dedication, as well as prey becoming edgier and more challenging to hunt with traditional weapons when firearms are introduced (Bohr 2014; Hitchcock et al. 2020), both reduce the applicability of these analogs to past hunting with traditional tools. This will remain an ongoing problem for archaeologists who use modern and recent ethnographic analogs to study ancient hunting societies. Hunting success is dependent on a complex range of factors.

5.5 Conclusion

Gladfelter et al. (1983:11) feared that, “The primitive status of bow hunting is being threatened as archery success rates begin to match success rates of firearms hunters.” They also suspected that deer populations could become threatened and new management practices would be necessary. As a result of good management practices, compound bow use does not appear to threaten the status of white-tailed deer in Iowa, although further improvements have certainly affected the former issue. Like modern rifle evolution from early muzzle loading guns, modern compound bows have evolved into something distinct from the older form, where success is only marginally lower than muzzleloader success in Iowa. Both compound bows and modern muzzleloaders were introduced as traditional weapon categories but have undergone significant modernization. And while compound bows and straight-wall cartridge rifles approximately double the odds of hunter success over the older weaponry, muzzleloaders are given a special season in Iowa and many other states, whereas this is not yet the case of traditional bows.

CHAPTER 6. MODERN WEAPONS, HUNTER SUCCESS, AND THE IMPACTS OF TECHNOLOGICAL DETERMINISM

6.1 Introduction

Hunting success rates have important implications for interpretating human behavior and human evolution, as well as establishing wildlife conservation policies that mitigate impacts to traditional hunting societies. Several authors who research past human adaptation and evolution have written about the supposed advantages that newer weaponry must have given our lineage (see O'Driscoll and Thompson 2014). Each new development in weapon delivery is thought to have extended the distance between ourselves and our prey, making large animals safer to hunt (Churchill and Rhodes 2009). Advancements in projectile weapons are theorized as allowing us to exploit the full range of large terrestrial fauna (Churchill 1993). Weapon advancements are also thought to have allowed us to fend off deadly predators. It is suggested that advancements in weapon technology assisted our species in migrating outside of Africa (Shea and Sisk 2010).

However, hunting success is dependent on a complex range of factors, such as hunter-prey relations, hunter demographics, weapon technology, and environmental factors. This paper discusses the topic of hunter success with various weapons relative to these extraneous variables, with a particular focus on the success rates of San hunters in southern Africa and modern hunters in the US. Weapon technology will be shown to be only one (and not always the most important) variable leading to hunter success. Furthermore, the San case is important not only from an ethnoarchaeological perspective, but from a humanitarian perspective. The livelihoods and hunting traditions of Indigenous San are being threatened by wildlife conservation policies.

Western understandings of pre-industrial hunting tools and livelihoods have influenced the establishment of such policies and the specific forms they take, while overlooking key evidence regarding hunting efficacy.

Archaeologists will also benefit from further considerations of hunting weapon efficacy. In the last decade, researchers have begun pointing to problems with some of the most prominent interpretations of ancient weapon advances and hunting methods. Based on skeletal evidence and the size of armatures (stone weapon tips), Neanderthals were previously thought to have relied only on group ambush strategies and deploying thrusting spears (lances) to hunt large animals, while more sophisticated ranged weapons were only developed by our species (Rhodes and Churchill 2009; Shea and Sisk 2010; Trinkaus 2012).

However, evidence from impact damage to Levallois flakes in Africa suggests that throwing spears (javelins) may have been invented as early as 500 kya (Wilkins et al. 2012). Experiments with replica Neanderthal armatures from the Iberian Peninsula suggests they are lighter than expected, perform well as javelin tips, and carry evidence of impact damage consistent with being thrown (Rios-Garaizar 2016). Other researchers have also analyzed the stone armatures crafted by Neanderthals and found favor with a javelin interpretation (Lazuén 2012). Wooden artifacts found preserved at a coal mine near Schöningen, Germany are properly weighted for throwing, being tapered like modern javelins, and date to >300kya. These artifacts were found with primarily horse remains in what was interpreted as a natural cul-de-sac at the time of deposition, indicating a coordinated group drive by pre-Neanderthal Archaic Humans (Milks et al. 2019; Thieme 1997). Although skeletal evidence was used to demonstrate a lack of throwing in Neanderthals, more recent analysis of Neanderthal skeletons also demonstrates a lack of spear thrusting (Shaw et al. 2012b). Evidence from costal sites demonstrates that

Neanderthals were capable swimmers who exploited a wide range of resources, including diving multiple meters under the surface to harvest aquatic resources (Trinkaus et al. 2019). Wider niche exploitation by Neanderthals is not limited to marine settings. Recent work suggests that Neanderthals exploited a wide range of small game and aquatic resources at inland sites as well (Hardy et al. 2013).

I review the Neanderthal problem simply to highlight the current challenges in our interpretations of past behaviors and adaptations based on prior assumptions of technological advancement. Given our current relationship with technology, modern researchers are predisposed to look for technological advances in the archaeological record (Macola 2016). But the recent evidence regarding Neanderthals suggests that prior interpretations have been biased by the assumption that modernity begins with our species (Villa and Roebroeks 2014). Weapon advances have been included in the characteristics archaeologists have devised to recognize the "Upper Paleolithic Behavioral Revolution," leading to "behavioral modernity" (Bar-Yosef 2002; Shea 2009), but many of these characteristics, including advanced projectile weaponry, can be recognized much earlier in the archaeological record and increase gradually through time (Mcbrearty and Brooks 2000). As our field progresses, it seems possible that the assumed material differences between Neanderthals and *H. sapiens* during the initial stages of their interaction could fail to materialize.

There are also indications that, based on the size of small armatures, the bow may have been in use in Europe by the Middle Solutrean period ~20ka (Márquez and Muñoz 2008) well in advance of the prior date for its initial appearance at 11kya based on the finds at Stellmoor in Germany (Rust 1943). In Southeast Asia, new evidence suggests that bow and arrow technology may have appeared as early as 48ka (Langley et al. 2020), while in southern Africa evidence suggests the initial appearance of the bow occurred before 60 to 70ka (Lombard 2021; Lombard and Phillipson 2010). If the bow offered a distinct advantage, as many have assumed, and even appeared before the most substantial push of humans out of Africa, why did less "advanced" weapons like javelins and atlatls (spearthrowers) persist for so long in Europe, the New World, the Pacific, and Australia, in some cases even completely independent of the newer and "better" weaponry (Davidson 1936; Milks 2020; Tregear 1892)?

If we are to understand ancient weapons and the implications of their introduction, we need better data on what makes hunters successful with their weapons. This is impactful not only to our ability to interpret the archaeological record, it also affects decisions made regarding wildlife conservation that can have powerful implications for Indigenous lives and livelihoods.

In the following I focus on hunting success, although a discussion of the application of weapon technology for combat will be found in section 6.4.1 of this article. Most discussions of weapon advances among archaic and early modern humans center around hunting and defense against predators, so it is logical to focus attention there. Of course, since the development of the earliest ranged weapons, significant improvements have been made to hunting weapon technologies. If weapon improvements give hunters a significant advantage, then the differences between these and more ancient forms should be discernible. This study draws on ethnographic accounts of hunters in southern Africa, South America, and the United States to build a picture of what leads to hunter success with different weapons. The findings will demonstrate that hunting success is complex and highly context dependent, but hunter and prey densities can have a more substantial impact on success than the weapon used. Future interpretations of ancient weapons should consider the cultural, demographic, and environmental contexts in which those weapons occurred in the past.

6.2 Methods

Before assessing the relative differences in success rates, I present a background of the context of hunting weapons and tactics in the respective areas. Given that the prominent comparisons in this research occur between modern Americans and the San, I forgo a description of the South American context in this section (see Bleed 1991). For modern weapons and tactics, I assess data from surveys of Iowa bow and gun hunters that provides comparative data regarding modern American hunting weapons. These data offer examples for discussing the relative differences between San and contemporary American hunting weapons.

6.2.1 San hunting weapons and tactics

The San comprise a common cultural group of three language families who inhabit substantial portions of central southern Africa. The San, or Bushmen, share a common history as hunter-foragers whose way of life may stretch as far back as 75ka (d'Errico et al. 2012). San hunting kits are minimalistic and developed by many generations of use (Hitchcock et al. 1996; Hitchcock and Bleed 1997; Liebenberg 1990). Spears include both a heavy thrusting variety and a lighter throwing variety, both with steel points fashioned from truck leaf springs. San bows and arrows are small and of light draw, shooting arrows with small, barbed points that incapacitate prey by delivering a lethal dose of poison. Arrow mainshafts are designed to fall away to ensure the foreshaft remains in the wound and the mainshaft can be recovered (Archer et al. 2020). Once prey is struck, a hunter will return after several hours to track.

San hunters use multiple sources of hunting poison but the most common is obtained from the larva of the *Diamphidia* beetle (Chaboo et al. 2016, 2019). San bow hunters attack the cardiac systems of prey not by damaging internal organs and causing substantial hemorrhaging, but by introducing a toxic protein that leads to cardiac failure (de la Harpe et al. 1983).

Anywhere between 30-70% of prey shot by San bowhunters is lost to predators such as lions and hyenas. Therefore, some groups of San living in areas with higher frequencies of large predators, such as the Tyua, tend to prefer spears for large game. Unlike San poison arrows, spears do kill through hemorrhaging in vital organs. Frequently prey struck with thrown spears drop on the spot or close by the hunter (Hitchcock and Bleed 1997). San spear hunting can be performed with the aid of dogs, from horseback and from platform stands or ambush locations near water sources at night. These hunts can be highly successful (Hitchcock et al. 2019). San spear hunting has its own drawbacks, such as close encounters with large and dangerous prey (Chaboo et al. 2019). San also use clubs and thrown sticks for dispatching small game, as well as setting traps and snares.

San hunters recognize the need for skill and practice at hunting (Hitchcock et al. 1996). Stalking with bow and poison arrow is considered by San hunters to be an arduous task (Hitchcock and Bleed 1997), but clearly one that some of them take pride in. Aside from pursuing prey with dogs and spears, the most successful of San hunting practices is long-distance pursuit hunting, or running prey to hyperthermia (overheating) (Bramble and Lieberman 2004; Carrier et al. 1984; Liebenberg 2006). These hunts are usually just under marathon distances, and are highly taxing, as well as potentially dangerous when hunters themselves become hyperthermic and dehydrated (Liebenberg 2013). However, hunters are frequently rewarded with a large animal. San hunters are flexible and can choose a variety of tactics dependent on season and other circumstances (Hitchcock et al. 1996).

6.2.2 American hunting weapons and tactics

A survey taken of Iowa hunters in the late 1970s gauged the relative impact of the introduction of compound bows on bowhunting success rates (Gladfelter et al. 1983). In spring of 2021 a follow-up survey was carried out to allow the impacts from 40 years of compound bow development to be studied (Chapter 5). In addition, the new survey asked about success and wounding rates with other weaponry currently legal for hunting deer in Iowa.

Deer hunters in Iowa are allowed to use a variety of hunting weapons throughout the fall season, however, these are employed at different times. Traditional bows and compound bows can be used starting in early October. In mid-October muzzleloaders take the field. These are followed by shotgun and straight-wall cartridge rifles in December. Although crossbows and handguns can also be used, few hunters use these weapons so I will not discuss them here. For a comparison with Colorado hunters, our primary concerns are the data relating to bow and straight-wall cartridge rifle hunting in Iowa.

In the mid-1970s compound bows became increasingly available to hunters. Prior traditional bows did not have drastically different operation from bows around the world and through time. Most modern traditional bows used by American hunters have a core of wood with a fiberglass exterior that offers superior longevity over a simple wood bow (Bear 1980). These bows generally come with wide, flat limbs and recurve tips, although simple D-shaped bows with longer limbs (longbows) are also popular. In contrast, the compound bow utilizes specially shaped pulleys (cams) at the ends of the limbs. These create an effect known as let-off, in which the draw weight climbs throughout the draw length and is suddenly drastically reduced at full draw, allowing the hunter to hold the weapon at the ready for long periods. The cam system also improves leverage on powerful fiberglass limbs and greatly increases arrow velocity (Sung et al. 2018). Modern compound bows, such as the Helix Turbo by Hoyt, can fire arrows at over twice the velocity (>100 m/s) of traditional bows (https://hoyt.com/compound-bows/compound-hunting-bows). Arrows fired from traditional bows rarely travel faster than 50 m/s (Bergman et al. 1988). Modern compound bows are also fitted with attachments such as stabilizers and complex sights with pins calibrated to different distances, features missing from traditional bows. Laser range finders allow compound bow users to aim using the proper sighting pin when taking longer shots.

The data from the Iowa surveys indicate that in the late 1970s, hunters experienced 1.4 times greater odds of success with compound bows. Few hunters still hunt with traditional bows in Iowa, but a large enough sample took the 2021 survey (324) to allow a comparison. Hunters with modern compound bows in Iowa, which have been significantly improved since the late 1970s (Sung et al. 2018), now experience ~2 times greater odds of success (Chapter 5). However, in both surveys the difference in wounding rates were not statistically significant once success rates were factored into the statistical models. In other words, wounding (hitting but not retrieving an animal) is correlated with success in these data. If the models do not include success, then there is a strong correlation with more wounding among more advanced weapon categories. Gladfelter and colleagues (1983) suspected this was because users of the newer weapon technology still take risks in hunting and are willing to shoot farther given more confidence in their weaponry. Although hunters generally try to avoid wounding animals, one might argue that a degree of risk that prey will escape and heal or succumb later to wounds is an inherent aspect of predation.

In contrast to bows, straight-wall cartridge rifles offer hunters significantly greater odds of success in just a few days of hunting. These rifles are like those used in the late 19th and early 20th centuries in America. Unfamiliar readers can imagine the lever action cowboy rifles in Old West movies, although improvements such as rifle scopes and better gun powder are now available. These guns have a range of ~180 m before the bullet begins to drop significantly.

Modern tapered cartridge rifles are available to Colorado rifle hunters. These have better ballistics and can shoot >500 m. They are no longer legal hunting weapons in Iowa due to the open terrain and danger to bystanders. The resultant comparison between rifle and bow success in Colorado is therefore not perfect, but close.

The following statistical comparisons were not performed in Chapter 5. See Chapter 5 for details about the data and statistical methods. First, I tried a nominal logistic regression that fits the days each hunter spent in the field (log_e[days]) and whether they reported retrieving at least one deer with any given weapon (binary success) against weapon categories. However, these models suffer from lack of fit (P-value<.0001). The days spent in the field seems significant given that bowhunters had more time to hunt over the season than rifle hunters, however, the analysis also demonstrated that a simple correlation between the number of days hunted and success does not exist. Hunting and hunters are more complex than can be captured with a few simple variables. In any weapon category, some hunters were able to retrieve multiple deer in just a few days while others hunted an entire season and were not successful. This may reflect skill level, selection for large bucks or hunting for meat, access to land holding deer, weather, the presence of absence of travel corridors and food sources, and many other factors.

A simple nominal regression of binary success fitted against binary weapon categories may be more useful. These models indicate that straight-wall rifle hunters reported 2 times greater odds of retrieving at least one deer than compound bow users and 4.1 times better odds than traditional bow users. This simple test tells us that, based on survey data, modern compound bows are roughly twice as effective as traditional bows, and rifles are roughly twice as effective as compound bows. In Colorado where hunters can take longer shots with rifles, the disparity between compound bows and rifles may be even greater.

6.2.3 Compiling the data

Effectively modeling success with pre-industrial hunting technologies is challenging to impossible for most ethnographic cultures due to a lack of adequate data and variability in how the data were obtained. Successful hunting depends on many factors. Archaeologists who study ancient hunters but have even fewer data to work from should be especially wary of this. For post-industrial hunting in the United States, most states provide data on numbers of harvested species, but not hunter numbers or days spent in the field. Detailed hunting statistics for multiple species that provide both overall success in a season and total recreational days is provided by Colorado Parks and Wildlife (https://cpw.state.co.us/thingstodo/Pages/Statistics.aspx). Information on harvest and hunter numbers is obtained through tag purchases and check-in of harvested prey, whereas hunter-days in the field is estimated from surveys completed by hunters at the end of a season. This allows hunting success to be modeled for Colorado hunters as *success per hunter-day*.

For pre-industrial hunting, the San hunters of southern Africa are among the most studied societies on earth (Hitchcock 2019). Data from San hunting comes from Hitchcock's studies (Hitchcock et al. 1996; Hitchcock and Bleed 1997), as well as Liebenberg's (2006). Most anthropologists who study hunting societies have not been in the habit of recording the detailed success rate data provided by Hitchcock, which is a time-consuming and challenging endeavor that requires significant cooperation from informants. Some additional data are provided by Bleed (1991) and are included. These data are presented in Table 6.1.

Table 6.1. Data used in the analysis of hunter success.

Loc.	Period	Weapon	Method	Prey	*N* Prey	*N* Hunters	*T* Hunters	Hunter-days	*N* Take	% Succ-H/day	% Succ-*T*	Hunter /km2	Hunter /km2 (PL)	*T* Hunter /km2 (PL)	Prey /km2	Prey: predator	Prey:*T* predator
CO	2020	rifle		Elk	293590	148615	215,075	668434	31754	5	21.4	0.82	1.50	2.17	1.62	1.98	1.37
CO	2019	rifle		Elk	292760	156509	227,136	714693	29073	4	18.6	0.86	1.58	2.29	1.62	1.87	1.29
CO	2018	rifle		Elk	286680	162,031	228,943	728,954	35,505	5	21.9	0.89	1.64	2.31	1.58	1.77	1.25
CO	2017	rifle		Elk	281700	163,781	227,343	767,061	30,986	4	18.9	0.90	1.65	2.30	1.56	1.72	1.24
CO	2016	rifle		Elk	277750	163,598	225,270	772,344	32,113	4	19.6	0.90	1.65	2.27	1.53	1.70	1.23
CO	2015	rifle		Elk	275880	162,275	217,680	762,587	36,874	5	22.7	0.90	1.64	2.20	1.52	1.70	1.27
CO	2014	rifle		Elk	279490	161,076	218,114	766,059	33,181	4	20.6	0.89	1.63	2.20	1.54	1.74	1.28
CO	2013	rifle		Elk	264025	165,284	221,114	749,870	35,626	5	21.6	0.91	1.67	2.23	1.46	1.60	1.19
CO	2012	rifle		Elk	266300	163,110	217,971	760,005	36,012	5	22.1	0.90	1.65	2.20	1.47	1.63	1.22
CO	2011	rifle		Elk	264170	159,987	218,080	743,079	36,669	5	22.9	0.88	1.62	2.20	1.46	1.65	1.21
CO	2010	rifle		Elk	283430	162,363	222,259	738,125	40,820	6	25.1	0.90	1.64	2.24	1.57	1.75	1.28
CO	2009	rifle		Elk	286510	160,320	220,574	723,208	40,636	6	25.3	0.89	1.62	2.23	1.58	1.79	1.30
CO	2008	rifle		Elk	283210	170,517	238,479	791,868	37,877	5	22.2	0.94	1.72	2.41	1.56	1.66	1.19
CO	2007	rifle		Elk	291960	176,397	255,868	795,609	41,243	5	23.4	0.97	1.78	2.58	1.61	1.66	1.14
CO	2006	rifle		Elk	271840	183,077	261,879	825,183	49,402	6	27.0	1.01	1.85	2.64	1.50	1.48	1.04
CO	2005	rifle		Elk	258370	197,089	271,354	880,366	48,891	6	24.8	1.09	1.99	2.74	1.43	1.31	0.95
CO	2020	archery		Elk	293590	53,426	65,409	381,825	5,366	1	10.0	0.30	0.54	0.66	1.62	5.50	4.49
CO	2019	archery		Elk	292760	51,485	63,857	356,902	5,915	2	11.5	0.28	0.52	0.64	1.62	5.69	4.58
CO	2018	archery		Elk	286680	50,750	63,160	351,600	5,730	2	11.3	0.28	0.51	0.64	1.58	5.65	4.54
CO	2017	archery		Elk	281700	47,727	59,732	333,729	5,507	2	11.5	0.26	0.48	0.60	1.56	5.90	4.72
CO	2016	archery		Elk	277750	47,721	59,083	342,074	5,116	1	10.7	0.26	0.48	0.60	1.53	5.82	4.70
CO	2015	archery		Elk	275880	46,854	57,425	335,894	5,746	2	12.3	0.26	0.47	0.58	1.52	5.89	4.80
CO	2014	archery		Elk	279490	44,536	55,262	328,680	6,434	2	14.4	0.25	0.45	0.56	1.54	6.28	5.06
CO	2013	archery		Elk	264025	41,967	52,569	297,737	5,634	2	13.4	0.23	0.42	0.53	1.46	6.29	5.02
CO	2012	archery		Elk	266300	39,883	50,891	284,580	5,028	2	12.6	0.22	0.40	0.51	1.47	6.68	5.23
CO	2011	archery		Elk	264170	39,589	50,440	278,894	4,901	2	12.4	0.22	0.40	0.51	1.46	6.67	5.24
CO	2010	archery		Elk	283430	40,568	52,294	294,073	4,935	2	12.2	0.22	0.41	0.53	1.57	6.99	5.42
CO	2009	archery		Elk	286510	36,654	48,010	269,079	4,729	2	12.9	0.20	0.37	0.48	1.58	7.82	5.97
CO	2008	archery		Elk	283210	40,954	52,461	296,357	5,119	2	12.5	0.23	0.41	0.53	1.56	6.92	5.40
CO	2007	archery		Elk	291960	37,186	48,768	270,068	5,092	2	13.7	0.21	0.38	0.49	1.61	7.85	5.99
CO	2006	archery		Elk	271840	38,634	50,470	287,212	4,775	2	12.4	0.21	0.39	0.51	1.50	7.04	5.39
CO	2005	archery		Elk	258370	35,628	46,792	271,920	5,112	2	14.3	0.20	0.36	0.47	1.43	7.25	5.52
CO	2020	rifle		Deer	427570	66,460	215,075	268,596	32,842	12	49.4	0.25	0.67	2.17	1.58	6.43	1.99
CO	2019	rifle		Deer	418310	70,627	227,136	292,209	30,521	10	43.2	0.26	0.71	2.29	1.55	5.92	1.84
CO	2018	rifle		Deer	433140	66,912	228,943	269,302	32,311	12	48.3	0.25	0.68	2.31	1.61	6.47	1.89
CO	2017	rifle		Deer	418800	63,562	227,343	258,205	31,835	12	50.1	0.24	0.64	2.30	1.55	6.59	1.84
CO	2016	rifle		Deer	418560	61,672	225,270	257,102	31,170	12	50.5	0.23	0.62	2.27	1.55	6.79	1.86
CO	2015	rifle		Deer	435660	55,405	217,680	227,491	29,025	13	52.4	0.21	0.56	2.20	1.61	7.86	2.00
CO	2014	rifle		Deer	424190	57,038	218,114	242,219	27,499	11	48.2	0.21	0.58	2.20	1.57	7.44	1.94
CO	2013	rifle		Deer	390660	55,830	221,114	221,936	27,538	12	49.3	0.21	0.56	2.23	1.45	7.00	1.77
CO	2012	rifle		Deer	408010	54,861	217,971	214,958	27,358	13	49.9	0.20	0.55	2.20	1.51	7.44	1.87
CO	2011	rifle		Deer	417950	58,093	218,080	224,928	28,354	13	48.8	0.22	0.59	2.20	1.55	7.19	1.92
CO	2010	rifle		Deer	430390	59,896	222,259	239,873	30,002	13	50.1	0.22	0.60	2.24	1.59	7.19	1.94
CO	2009	rifle		Deer	460520	60,254	220,574	242,827	29,136	12	48.4	0.22	0.61	2.23	1.71	7.64	2.09

CO	2008	rifle		Deer	466760	67,962	238,479	275,189	31,120	11	45.8	0.25	0.69	2.41	1.73	6.87	1.96
CO	2007	rifle		Deer	538770	79,471	255,868	311,829	40,118	13	50.5	0.29	0.80	2.58	2.00	6.78	2.11
CO	2006	rifle		Deer	612760	78,802	261,879	317,113	39,903	13	50.6	0.29	0.80	2.64	2.27	7.78	2.34
CO	2005	rifle		Deer	613450	74,265	271,354	282,552	37,380	13	50.3	0.28	0.75	2.74	2.27	8.26	2.26
CO	2020	archery		Deer	427570	11,983	65,409	97,461	3,181	3	26.5	0.04	0.12	0.66	1.58	35.68	6.54
CO	2019	archery		Deer	418310	12,372	63,857	96,139	3,183	3	25.7	0.05	0.12	0.64	1.55	33.81	6.55
CO	2018	archery		Deer	433140	12,410	63,160	94,814	3,110	3	25.1	0.05	0.13	0.64	1.61	34.90	6.86
CO	2017	archery		Deer	418800	12,005	59,732	91,112	3,086	3	25.7	0.04	0.12	0.60	1.55	34.89	7.01
CO	2016	archery		Deer	418560	11,362	59,083	87,581	2,913	3	25.6	0.04	0.11	0.60	1.55	36.84	7.08
CO	2015	archery		Deer	435660	10,571	57,425	81,619	2,570	3	24.3	0.04	0.11	0.58	1.61	41.21	7.59
CO	2014	archery		Deer	424190	10,726	55,262	83,106	2,881	3	26.9	0.04	0.11	0.56	1.57	39.55	7.68
CO	2013	archery		Deer	390660	10,602	52,569	81,350	2,781	3	26.2	0.04	0.11	0.53	1.45	36.85	7.43
CO	2012	archery		Deer	408010	11,008	50,891	83,608	2,956	4	26.9	0.04	0.11	0.51	1.51	37.06	8.02
CO	2011	archery		Deer	417950	10,851	50,440	80,902	2,447	3	22.6	0.04	0.11	0.51	1.55	38.52	8.29
CO	2010	archery		Deer	430390	11,726	52,294	91,299	2,803	3	23.9	0.04	0.12	0.53	1.59	36.70	8.23
CO	2009	archery		Deer	460520	11,356	48,010	91,876	2,617	3	23.0	0.04	0.11	0.48	1.71	40.55	9.59
CO	2008	archery		Deer	466760	11,507	52,461	91,599	2,421	3	21.0	0.04	0.12	0.53	1.73	40.56	8.90
CO	2007	archery		Deer	538770	11,582	48,768	92,583	2,655	3	22.9	0.04	0.12	0.49	2.00	46.52	11.05
CO	2006	archery		Deer	612760	11,836	50,470	92,208	2,577	3	21.8	0.04	0.12	0.51	2.27	51.77	12.14
CO	2005	archery		Deer	613450	11,164	46,792	84,502	2,278	3	20.4	0.04	0.11	0.47	2.27	54.95	13.11
Africa		archery	Stalk		557665	2		60	11	18	42	0.06			0.96	16.00	
Africa		spear	Pursuit		557665	2		6	3	50	100	0.06			0.96	16.00	
Africa		spear	Ambush		557665	1		19	16	84	88	0.06			0.96	16.00	
Africa		spear	Dog		557665	6		60	8	13	88	0.06			0.96	16.00	
Africa		spear	Horse		557665	2		16	7	44	88	0.06			0.96	16.00	
Africa		spear	Stalk		557665	2		12	4	33	66	0.06			0.96	16.00	
Africa		archery	Stalk		557665	5		205	2	1	5	0.06			0.96	16.00	
Africa		spear	tracking		557665	5		55	5	9	45	0.06			0.96	16.00	
Africa		spear	Pursuit		557665	3		15	4	27	80	0.06			0.96	16.00	
Africa			Dog		557665	3		15	3	20	60	0.06			0.96	16.00	
Africa					557665	4		264	84	32	62	0.06			0.96	16.00	
Africa		spear	dog		557665	7		546	18	3	23	0.06			0.96	16.00	
Africa		archery	Ambush		557665				29	59	77	0.06			0.96	16.00	

Problems still occur in the analysis given disparities in the way these data were obtained. In the ethnographic data, hunters often went out together and the analyst recorded days spent hunting and numbers of captured game, whereas in the survey data of American hunters each hunter took a separate survey independent of how a hunt was performed (e.g. individually or as group effort). To make the data comparable, the number of days hunters went out can simply be multiplied by the number in the group to arrive at *success per hunter-day*. Furthermore, San hunters often hunt in groups and group numbers are not always reported, skewing hunter-days. The average size of San hunting groups is two (Hitchcock et al. 1996), so when data on group size is missing, *N* hunters is entered as two in Table 6.1. There are further challenges with the comparison that will be addressed below.

6.3 Interpretation

6.3.1 Success as a function of weapons and tactics

The success rates of San hunters using bows and spears appear remarkably higher than Colorado hunters using modern bows and rifles Figure 6.1. But this simple comparison is problematic for several reasons. Hunters travel to Colorado from other states to hunt big game animals that are inaccessible in their state. Many hunters may not be able to stay a full season. They also come with varying degrees of experience and familiarity with the local setting and fauna. If only data from highly experienced hunters were included, success rates of Colorado hunters would be higher. In contrast, Indigenous San hunters are no doubt highly skilled and familiar with the local environment and prey.

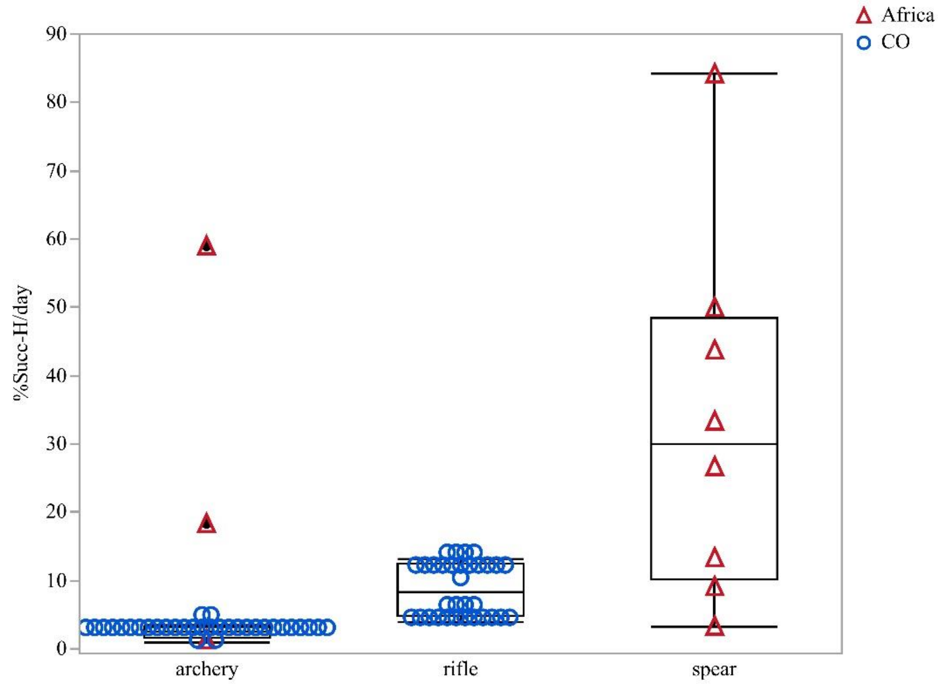


Figure 6.1. San and Colorado daily hunter success by weapon type.

However, in the survey of Iowa hunters, years of experience generally fails to predict success rates with modern firearms. Since straight-wall cartridge rifles were only introduced into Iowa in 2019, hunters reported having very little experience with these weapons yet were able to achieve substantial success relative to the other weapon categories. Shotguns shooting slug ammunition have a longer history in Iowa hunting. They are frequently used in group drives and many hunters reported >20 years of experience. But years of hunting also fails to predict user success with these weapons (Chapter 5). For archery hunters the picture is a little different. Users with 10 years or more experience with traditional bows were more likely to retrieve multiple deer and not report wounding deer. The survey by Gladfelter and colleagues (1983) found that success with traditional bows climbed steadily and plateaued after 9-10 years of experience, or 7 years of experience for compound bows. In our survey, we also noticed a decline in the numbers of deer retrieved in any weapon category after ~40 years of hunting. These findings fit with ethnographic evidence (Chaboo et al. 2019; Gurven and Hill 2009). Successful users of traditional hunting equipment benefit from experience and tend to be 30-40 years of age, but hunters in our data using modern rifles or compound bows were able to achieve a high degree of success without much experience. Modern weapons with drastically increased range, such as tapered cartridge rifles, should reduce the skill discrepancy.

Colorado hunters are also limited by species and often by sex of the animal they are hunting. However, the statistics represent individual hunting tags per species. Individual hunters may have multiple tags on a single hunting trip and their success rates are included in the statistics for each species. In other words, a hunter could have gone after both deer and elk, retrieved one, but came away “unsuccessful” in hunting the other species.

Most readers will point out that San hunters have a good reason to take hunting very seriously. If they are not successful over an extended period, they will be without an important component of their diet. Colorado hunters will not starve if they are unsuccessful so they can be pickier about what they shoot (waiting for a trophy animal for example). This important difference is allowable due to the agro-industrial economy that supports Colorado hunters. However, San hunters are also supported by foraged vegetable foods that are plentiful over much of the year (Hitchcock et al. 1996). They are opportunistic and will change course to pursue small game, or stop to collect honey. This is part of the reason for the low success rate in Liebenberg’s data of archery stalking hunts by the group from Lone Tree. These figures are closer to the success rates of Colorado archery hunters, but the Lone Tree hunters sometimes set out tracking gemsbok or kudu and instead decided to dig a springhare out of its burrow. In other data, such as retrieved by Hitchcock and colleagues (1996) from Yellen’s work, any prey brought back from a hunt was counted as a success.

Ambush hunts by the Ju/'hoansi are often performed in pairs (Hitchcock et al. 2019), whereas Tyua hunters in the northeastern Kalahari often hunt from ambush alone (Hitchcock, personal communication, 2019). Colorado hunters may hunt in small groups or with guides, where other members of the party may not have a hunting tag and are therefore not included in the number of hunter-days. Despite some gaps in the data, success per-hunter-day/night is therefore probably relatively comparable.

Colorado hunters are not allowed to use some of the methods available to San hunters. Hunting at night or with dogs is illegal in Colorado. Ju/'hoansi archery and Tyua javelin hunts of large game from ambush at night were highly effective. The success rates from two studies *per-hunter-night* for Ju/'hoansi and Tuya hunters using javelins from ambush are 59% and 84% respectively (Hitchcock et al. 1996). Prey retrieved using this method consists of large-bodied ungulates such as zebra and wildebeest.

6.3.2 Success as a function of prey and hunter densities

Part of what has resulted in lower success rates for Colorado hunters may be higher human populations relative to prey animals, as prey may respond to both hunting and non-hunting human activities with adaptive antipredator behaviors (Frid and Dill 2002). Total land in Botswana covers 581,730 km^2 relative to 269,837 km^2 in Colorado. However, human densities are higher in Colorado. Currently, Colorado has a density of 21 persons/km^2 compared with 3.7 persons/km^2 in Botswana.

Deer and elk populations are estimated by Colorado Parks and Wildlife per *Data Analysis Unit* (DAU). Deer can be found across the state including on the eastern plains where they may be hunted. Therefore, deer DAUs encompass the whole state. But elk are primarily limited to the western Plains and mountain region and consequently elk DAUs cover an area of 181,080 km^2.

Taking population estimates for 2020 gives densities for these respective areas and species at 1.58 deer/km^2 and 1.62 elk/km^2. Conservative hunter densities from total elk and deer hunters are also made for these respective areas and are presented in Table 6.1. However, most deer and elk hunters are confined to hunt on public lands with hunting access. In Colorado, approximately 99,034 km^2 of public lands are available to hunters. Using this figure gives the following estimates of Colorado hunter densities in 2020: 1.5 elk rifle hunters/km^2, 0.55 elk bowhunters/km^2, 0.67 deer rifle hunters/km^2, and 0.12 deer bow hunters/km^2.

Unlike the constraints on Colorado hunters, San during the study years did not generally seem to favor one species over another. We can thus simplify the comparison by calculating the densities of all prey hunted by San over the study period (buffalo, duiker, eland, gemsbok, hartebeest, impala, kudu, roan antelope, sable antelope, steenbok, warthog, wildebeest and zebra). Population estimates for these animals are provided through the Central Statistics Office (2004), with the earliest data starting in 1989. Population estimates for 1989-1991, a period that begins just after the study period represented in Table 6.1, give a total estimated population density of 0.96 prey/km^2 for these combined species in Botswana. Unfortunately, it is difficult to uncover reliable densities of San hunters in the respective study locations for these periods. To arrive at a general assessment, I averaged San population densities provided by Hitchcock (1982:Table 9) and subtracted half to arrive at a very rough estimate of the densities of San males during the study periods. This gives a figure of 0.06 hunters/km^2, which is probably a little high.

These estimates remain oversimplifications. Deer and elk frequently seek refuge during hunting season on land with limited access to hunters, such as in difficult mountain terrain away from roads, on private land, or on public land with no public access. Some areas of Colorado have seen significant urban sprawl or other development that has replaced wildlife habitat and blocked migration routes. Hunters face a variety of access problems and many hunters hunt nearby trails and backcountry roads. The mountainous regions of Colorado contain terrain that makes travel for hunters extremely challenging and does not include the types of habitats favored by deer and elk. Therefore, deer and elk are likely to encounter relatively hunter-dense landscapes where public land is accessible and favorable habitat exists for prey. Similar caveats occur for San and prey animals in Botswana.

Prey densities alone do not help us understand the higher success rates among San hunters, since deer and elk appear to be denser on the landscape than species hunted by San. This topic has greater coverage in wildlife biology and management. Vucetich and colleagues (2002) found that while prey densities are commonly assumed to correlate with predator success rates, predator densities and ratios of prey:predators outperformed prey density models in modeling wolf hunting success. Prey animals are also capable of adapting behaviors to avoid predation. Models of risk assessment among prey animals demonstrate that many prey species respond to predation by altering their behavior to balance predator avoidance with considerations such as nutrition intake and finding mates (Lima et al. 1999; Ydenberg and Dill 1986).

In the US, radio collared deer are found to deploy antipredator tactics in response to hunting pressure by restricting overall movement, increasing nocturnal movement, making greater use of local refuges, and relocating to areas farther from roads (Little et al. 2016; Little 2011; Rodgers et al. 2021). Similarly, elk learn to avoid motorized routes, avoid hunter vocalizations, and relocate to areas with lower hunter density such as areas with dense vegetation, private lands, or public lands with reduced hunter access (e.g. Conner et al. 2001; Millspaugh et al. 2000; Ranglack et al. 2017). Although not all elk will migrate out of public lands away from hunters (Conner et al. 2001; Proffitt et al. 2016) and during rifle season greater hunter densities can result in greater disturbance of elk, resulting in increased movement that exposes elk to hunters (Cleveland et al. 2012). Calling elk is a common tactic used by Colorado bowhunters, but elk have been shown to learn to avoid hunters who simulate bugling calls after multiple encounters (Walsh et al. 1991). Elk may be less disturbed by early archery hunters than later rifle hunters, but elk increasingly avoid hunters with either rifle or bow as the season progresses (Millspaugh et al. 2000). These antipredator behaviors can result in stable elk populations despite increased tag sales (Conner et al. 2001). In other words, despite complexities due to inter and intra species behaviors, weather, the availability of refuges, and other factors, higher hunter densities can reduce overall hunter success due to antipredator behaviors in prey.

The conservative population estimates suggest that San hunters had a comparable population density to Colorado deer bowhunters, or half the density of those hunters if the public land figure is used for Colorado densities. San are probably less dense on most landscapes than Colorado deer archery hunters. Deer hunters in Colorado must also contend with the many elk hunters in the woods. Mule deer response to hunting pressure is sex specific, with males who are pursued more by hunters relocating to marginal areas away from roads, while females tend to remain in locations with more browse despite hunter presence (Rodgers et al. 2021). Mule deer may be able to assess risk to some extent and worry less about encounters with elk hunters who do not pursue them, but in general hunters are denser on these landscapes.

Figure 6.2 compares success between Colorado elk and deer hunters using both rifles and bows. The simple linear regression suggests highly significant correlations between hunter densities and success rates. Replacing hunter/km^2 with prey/km^2 demonstrates that prey densities play no role here (archery P-value=0.99, rifle P-value=0.76), since little difference occurs between estimated elk and deer densities. Although deer may feel pressured by encounters with elk hunters, they are not pursued by those hunters. Colorado deer hunters have less competition with other hunters resulting in greater success with both rifle and bow.

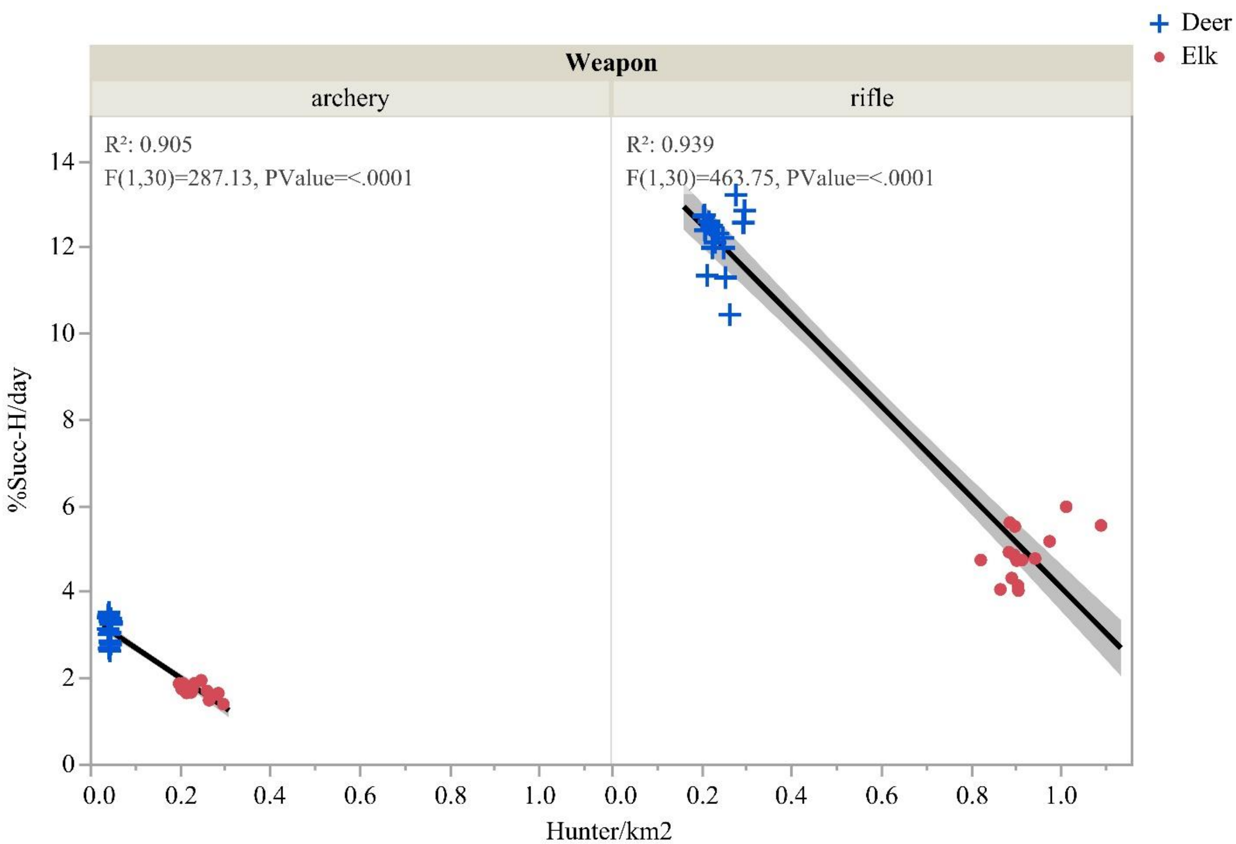
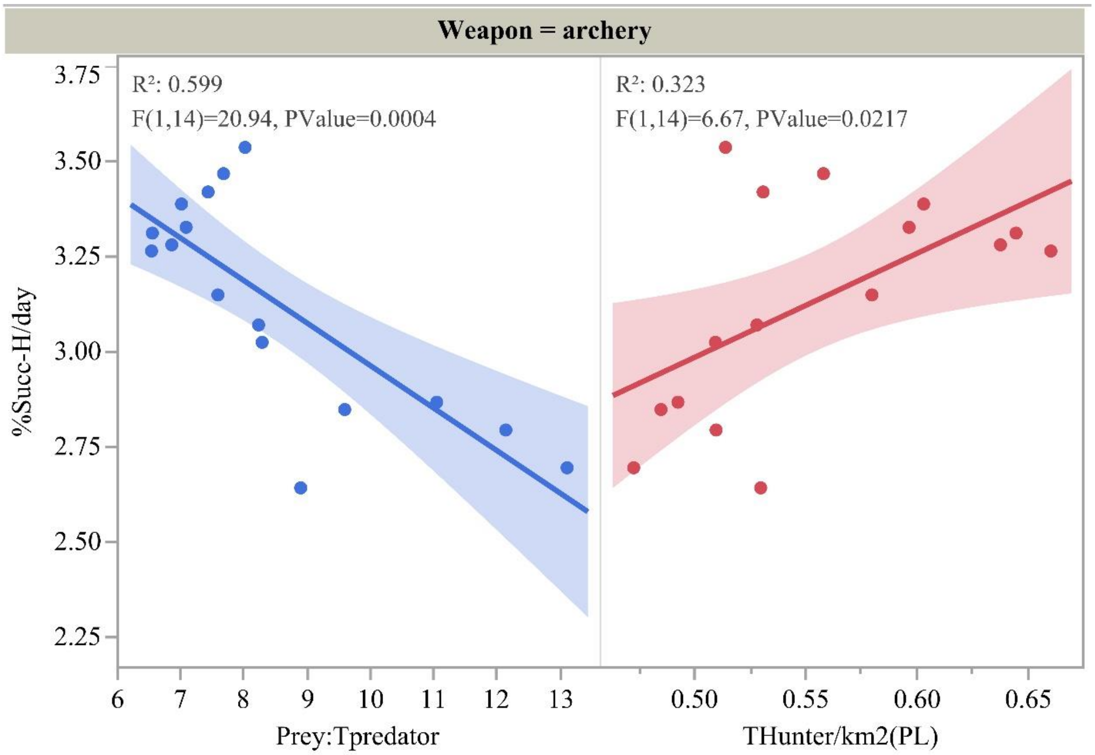


Figure 6.2. Colorado deer and elk archery and rifle hunter daily success as a function of hunter density.

However, the patterning within deer and elk success rates in Figure 6.2 suggests other variables are affecting deer and elk hunter success. It is therefore productive to look within the samples of both deer and elk hunters. Within the deer hunter sample (Figure 6.3) hunter success across both weapon types correlates best with the ratio of deer to total elk and deer hunters during the respective rifle and archery seasons (prey:*T*predator). A correlation also occurs with total hunter densities on public land during these seasons. But the simple linear regression fails to capture the complexity of these data. A negative correlation obtains with more deer per hunter in



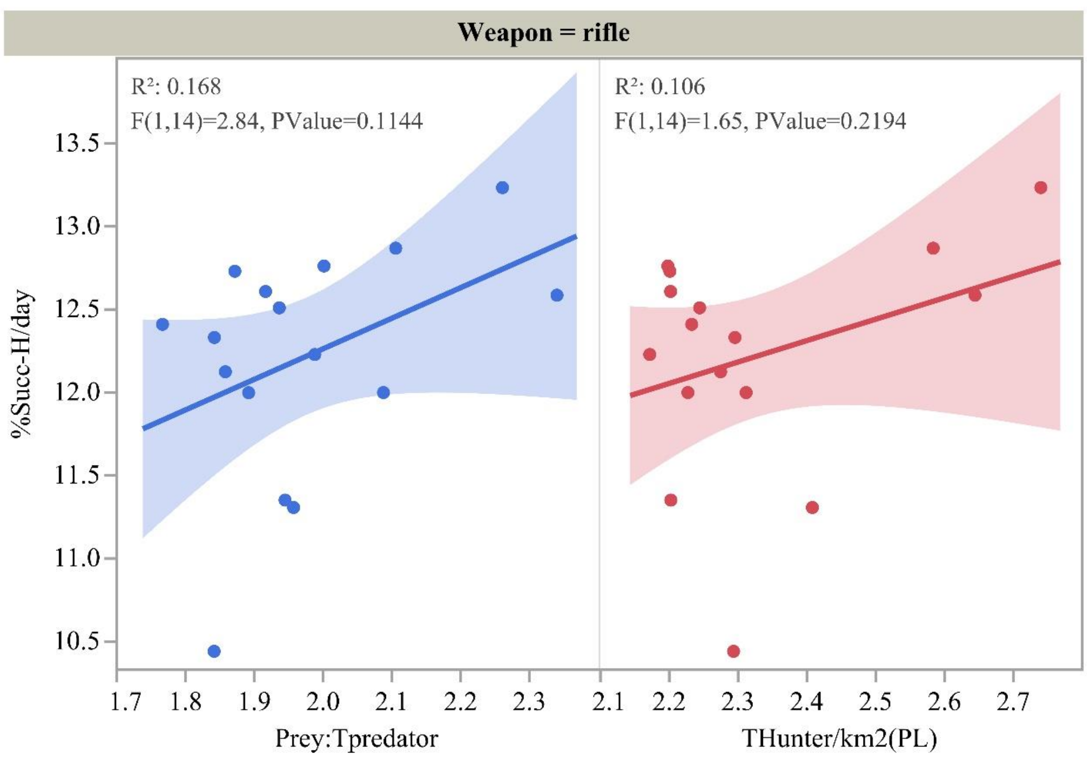


Figure 6.3. Colorado deer hunter daily success as a function of numbers of deer per total deer and elk hunters, and total deer and elk hunter densities on public land.

the archery category, but a sampling of hunting seasons on the upper left demonstrates a positive correlation. Similarly, positive correlations occur with greater hunter density, but individual groupings within the sample suggests negative correlations.

Within the elk hunter sample similar problems arise (Figure 6.4). Elk densities struggle to provide a pattern to the rifle hunter data through the ratio of elk to total deer and elk hunters, perhaps in part because over the survey years elk populations did not fluctuate as much as deer populations. Rather, elk hunter success is better captured in both weapon categories by total hunter density. This analysis captures the challenging nature of archery hunting, since higher hunter numbers have a significant negative impact on elk bowhunting success in most survey years. In contrast, rifle hunting success positively correlates with more hunters, although not strongly, and two small clusters on the left of the graph suggest negative correlations with higher hunter densities for elk rifle hunters.

In summary, among both elk and deer hunters, densities of hunters and prey capture some of the variability, however, hunting seasons are highly complex and hunter success is dependent on a range of variables that fluctuate between seasons. The science of game management involves specific management goals that target species populations across diverse regions of states through complex sets of hunting regulations (Cooper et al. 2002). This science can be as much about game species as the sociology of hunters. The result is that in dissimilar hunting seasons statistical models of hunter success loose predictive power (Cooper et al. 2002). This is clearly demonstrated in the analysis of Colorado hunters as well. Changing management strategies between seasons results in patterning in the data that is not captured by a few simple variables. However, the negative impacts of higher hunter densities are implicated in these data for both deer and elk hunters within otherwise similar hunting seasons.

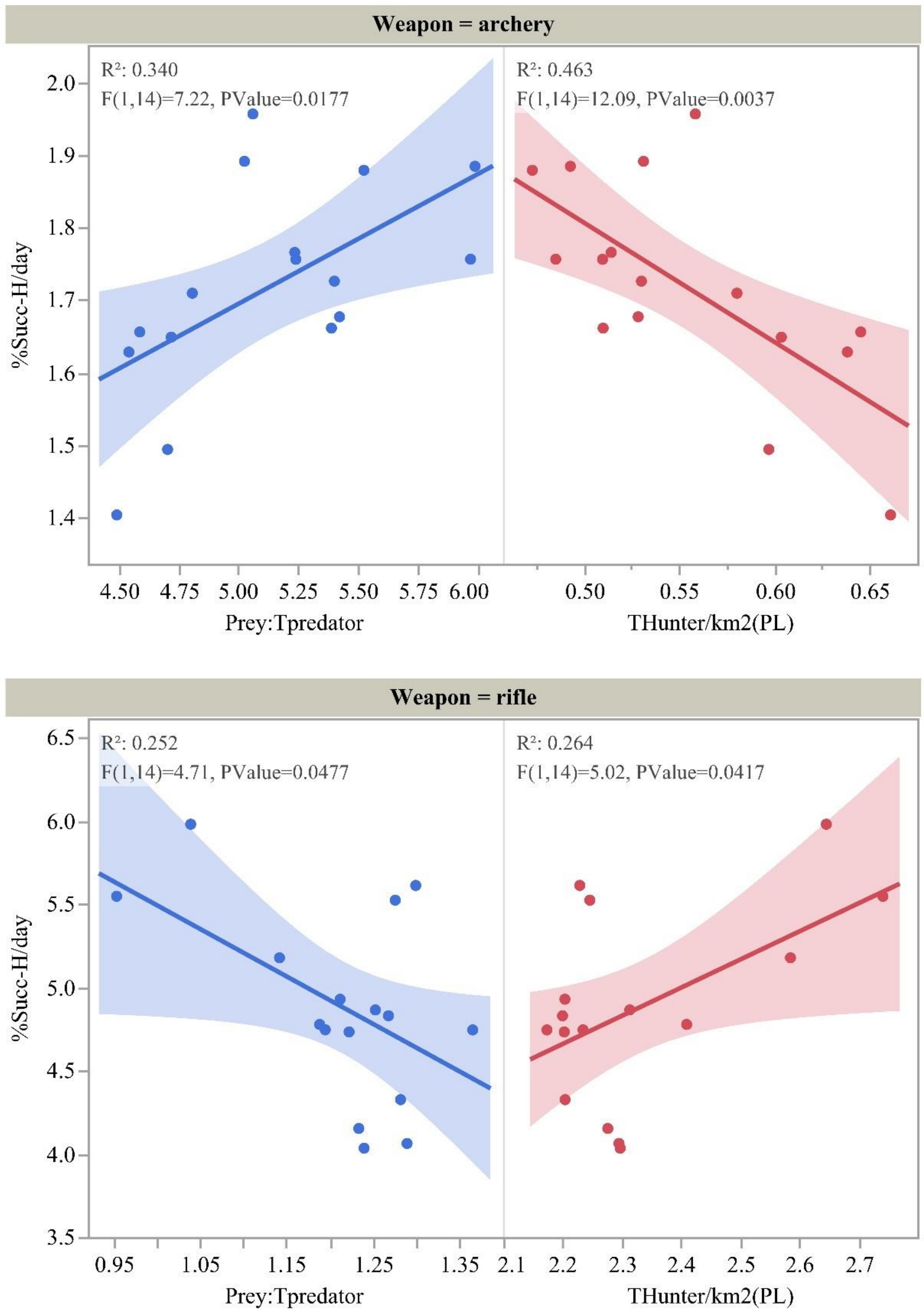


Figure 6.4. Colorado elk hunter daily success as a function of numbers of elk per total elk and deer hunters, and total elk and deer hunter densities on public land.

Little (2011) performed an analysis of white-tailed deer behavioral changes in response to rifle hunter densities in Oklahoma. A "no-risk" control group was not pressured by hunters, while a "low-risk" group was pressured by a density of 1 hunter/km^2, and a "high-risk" group was pressured by 3.33 hunters/km^2. The most significant behavioral changes occurred in the high-risk group, with deer moving significantly less during the day and shifting movement patterns to night. While a significant difference in movement patterns did not occur between the low-risk and control groups, both latter groups demonstrated a comparable reduction in movement, suggesting that deer in the control group were traveling outside the study area, encountering hunters, and perceiving a threat. Deer also gradually relocated into the control area from the other two areas over the season, made use of small refuges within their areas, and moved with greater speed when they did travel. This suggests that a hunter density of 1 hunter/km^2 is enough to elicit antipredator responses in white-tailed deer in and around hunting areas that result in noticeably altered movement patterns, while higher hunter densities cause deer to alter their behaviors more radically.

Unfortunately for Colorado bowhunters, not only are elk and deer bowhunters in the woods at the same time over the same period (the month of September), during one week in the middle of September there are also hunters in the woods using muzzleloaders. These hunters were not included in the above analysis but must have an impact on archery hunter success. For 2020, a combined 83,468 deer and elk hunters using bows and muzzleloaders hunted during September. Not all these hunters were in the woods at the same time, but the following simple comparison will help clarify the disparity between San and Colorado hunters further. If we assume most of these September Colorado hunters were confined to the 99,034 km^2 of public land, this gives a density of 0.84 hunters/km^2. If 0.06 km^2 represents a conservative estimate of

San hunter density during the study period, this would suggest that during September alone Colorado deer and elk hunters were 1300% more numerous on the landscape than San hunters. During the later rifle seasons, Colorado deer and elk rifle hunters had a combined density of ~2.2 km^2 on public land and were >3500% more numerous than San hunters.

Again, there are inaccuracies to consider in these figures. Colorado hunters are not all in the woods over the same periods, although they are more limited in land they can access and use than these numbers probably indicate. As such, there are periods when Colorado hunters become quite crowded on certain landscapes. Figure 6.1 would suggest that higher hunter densities can be more important than improvements in hunting weapon technology on hunter success. The stark contrast in hunter densities may be primarily responsible for the 500% greater average success among San spear hunters than Colorado rifle hunters. Unfortunately, the ~4 times greater odds of success that rifles provide over traditional bows cannot alleviate this situation for Colorado rifle hunters.

6.4 Discussion

6.4.1 Past hunter success and weapon transitions

The above analysis suggests that hunters living in sparsely populated groups in the past could achieve a high degree of success with simple weapons. Sharp and Sharp (2015) have discussed this in the context of Denésuliné caribou hunting in the far north. Caribou may live multiple years without ever seeing a human during their migration patterns. Denésuliné hunters now use modern rifles to great effect, but in the past simple willow bows were commonly used. One method discussed by Sharp and Sharp (2015) was to approach the caribou on open ground at a slight angle and in a relaxed fashion in order not to arouse suspicion. When the hunter had closed to a short range he shot his bow from the waist, since raising it would spook the prey. Caribou fell prey to their curiosity, having never, or rarely, encountered human predators.

Overall, the San tend to have significantly higher success than Colorado hunters, who are mostly hunting with modern weapons, and a significantly lower density on the landscape. Historically San hunter density was well below what has been considered a “low-risk” situation for deer with 1 hunter/km^2. Although there are several incompatibilities that require further consideration, what is clear from comparing Colorado and San hunters is that understanding hunting success cannot rely on the attributes of different hunting weapons alone, but requires consideration of many factors, including environment, prey species, hunting cultures and ideologies, and prey and hunter densities. Aside from weapon technology, hunter density is an important factor that may be more easily within reach of archaeological research than other factors such as hunter demographics. As hunters become denser on the landscape, there should be a larger impetus to adopt new weapons and tactics that improve the odds of successfully hunting warier prey.

These implications regarding the complex realities in which hunting weapons are fielded can also be extended to the complex social domain of warfare. In North America the earliest evidence of the bow occurs prior to 2kya, yet armature sizes suggest that in places such as the southern Great Plains and the Great Basin, the older atlatl and dart weaponry persisted for 1,000 or more years alongside the new technology (Chatters et al. 1995). Some claim that as soon as the bow appeared it was immediately adopted given its clear superiority (Hildebrandt and King 2012). Others have suggested that the appearance of the bow had such a profound impact on social coercion given its effectiveness among a police caste that it may have led to the development of complex social hierarchies (Bingham et al. 2013). When Europeans first arrived in Mesoamerica this was certainly not the case. If the bow had such a clear advantage in social coercion and warfare, one expects its use among the elite warrior and police caste of the Aztec Empire, but the atlatl was the weapon of the Eagle and Jaguar Knights (Hassig 1988).

Two processes may have caused this. First, arrows cannot be shown to give armies a clear advantage in ancient warfare against armored and shielded opponents. Hand cast spears continued to be effective well after the appearance of the bow. Powerful military societies such as the Spartans and Zulus found projectile weapons, including the bow and arrow, to be weapons of cowards (Cartledge 2003; Macola 2016). Instead, both military societies demonstrated the capacity to advance under fire to within striking distances of armies wielding projectiles. Second, upward social mobility in warrior societies is typically attained through achievements in battle, which can breed a form of military technological conservatism (Macola 2016). When guns were first introduced into central Africa the Zulus initially resisted adopting them for precisely this reason (Macola 2016). Among the warrior castes in Aztec society, upward mobility was also achieved through warfare. The bow and arrow did not offset this conservatism.

Arrows are deadly instruments when delivered with precision, but in warfare ethnographic accounts suggest that Native American warriors could be shot multiple times during combat and continue to fight (Bohr 2014). In contrast, guns had much greater range and were more damaging. Despite the military conservatism of the Zulus, guns deployed by well-trained European forces eventually broke their ranks. Guns replaced older hunting and fighting weapons in Africa and North America relatively quickly. Even early guns were effective hunting tools, being more damaging and having greater range than the bow, and were desired trade items (Bohr 2014).

An 18-19th c. firearm could deliver its projectile at >580 m/s and shoot accurately to 50 to 180 m depending on whether or not the bore was rifled (Russell 2010). Even if Native American hunters wanted to resist adopting this weapon, its presence in the woods and fields may have made traditional hunting challenging. Bohr (2014) cites multiple ethnographic accounts of Indigenous hunters complaining that the loud noises of trappers' and explorers' firearms were making their prey challenging to hunt. Research into antipredator responses in prey to human stimuli such as loud noises corroborates this (Frid and Dill 2002). The presence of firearms in the woods during archery season can elicit antipredator behaviors that make prey warier towards humans and more challenging to hunt with bows.

In terms of their ballistics, the differences between javelins, atlatls, and bows appears not to be so stark as the differences between early bows and firearms. Both javelins and atlatl darts can be launched with similar velocity and accuracy to 15 m or better, although atlatls generally appear to be easier to learn to use and field than the former weapon (Milks et al. 2019; Whittaker et al. 2017). Atlatl darts tend to travel ~25 m/s while arrows shot from traditional wood bows can travel 40-50 m/s with acceptable hunting accuracy to 20-30 m. In contrast, modern compound bows can shoot arrows at >100m/s. This suggests that the ballistic profiles of contemporary compound bows and traditional bows are more different than traditional bows are to atlatls.

There are other differences setting atlatls and bows apart other than speed, such as the reduced motion necessary to draw and fire an arrow. Bows are stealthier than atlatls. Researchers frequently cite the greater speed at which multiple arrows could be launched (Farmer 1994), but this has little bearing on hunting and is unsupported. I am unaware of any accounts of extremely well-trained warriors such as the Aztec knights testing the speed at which they could launch multiple darts. Like javelins, atlatls could have remained viable weapons alongside the bow, not only for combat but for hunting in certain contexts. This could be especially the case for hunting large ungulates in open terrain (Tomka 2013).

However, the increased stealth, range, and speed of the bow must have improved hunting success in certain contexts. This analysis suggests that increasing human populations and higher hunter densities can present such contexts, where a greater impetus to adopt new hunting weaponry may occur. Early evidence of the bow has now been pushed back to >60ka in southern Africa (Lombard and Phillipson 2010). The weapon apparently did not swiftly replace earlier hunting technologies, but came and went, being replaced again by earlier spear technology at some southern African sites (Lombard 2021). Although advances in weapon technology are often listed among the material and behavioral traits that allowed our species to thrive and expand, new technologies may also appear in later contexts due to population expansion and a resultant need for resource intensification (Mcbrearty and Brooks 2000).

Archaeologists who research transitions in ancient hunting technologies would also do well to consider the tools that rarely preserve, such as nets and traps (Oswalt 1973). These problematize our interpretations of human hunting adaptations that rely only on larger, piercing projectiles.

6.4.2 The future of traditional hunting

Several challenges face the future of traditional San hunting and affect their weapon choices. Among the San in the eastern and southeastern Kalahari, younger hunters during the period of study were switching more from hunting with bows to spears (Hitchcock and Bleed 1997). This was taking place for several reasons.

First, with increasing human presence, agriculture, livestock watering points, mechanized transport, equestrian hunting, and rifle hunting, prey animals are becoming more scarce and warier in the Kalahari. As Bohr (2014) found mention of among Native American hunters, and as has been backed by studies of wildlife responses to various human stimuli (Frid and Dill 2002), the San report that prey that has been hunted with rifles are warier of humans and run farther after being spooked, significantly reducing the chances for a follow-up hunt. This situation makes hunting with traditional weapons extremely challenging.

Along with these changes, traditional San hunters are less effective when hunting near settlements and are having to engage in costly long-distance expedition hunts (Hitchcock et al. 1996:187). Third, younger San hunters want to hunt from horseback with thrusting spears because it is more fashionable—a change that is upsetting to some older hunters who see the bow as a traditional weapon of southern San hunters (Hitchcock and Bleed 1997). Fourth and perhaps most impactful, changing game laws in Botswana and other African countries have gradually stamped out subsistence hunting. In a substantial way, these laws have resulted from discussions between conservationists and African officials.

Conservationists, holding to a “Deep Ecology” perspective that would see vast tracks of land devoid of human involvement, have deployed a “Green Militarization” approach that forcefully evicts and prosecutes traditional indigenous landscape users (Duffy 2010). Ironically, this process has only been partially effective in conserving wild animals and landscapes. African wildlife migrates seasonally over large tracts of land that cannot feasibly be combined into large parks (protected areas) designed to protect wildlife and cater to ecotourists from wealthy nations.

Conservationists historically attempted to convert traditional African hunters and herders to agriculture as a way of conserving landscape and wildlife, but recent increases in industrialized agriculture is seeing a collapse in the populations of large African fauna (Duffy 2010). Traditional subsistence hunting relies on wild animals and a landscape to support them, but conservation policies are forcing these traditionalists into the lower rungs of an agro-industrial economy that is a far greater threat to wildlife. San suffering under these oppressive practices find spears to be versatile weapons used for defense from predators as well as hunting. Game scouts are less likely to prosecute hunters carrying spears, while bow and arrow weaponry are seen as hunting tools. More San would probably hunt with rifles, but these are hard for them to acquire, let alone expensive hunting tags. In the past special subsistence hunting tags were issued, but this is no longer the case in Botswana.

In 2014 with the new presidency of Ian Khama in Botswana, a country-wide hunting ban was introduced. This ban was instated due to projections that wildlife numbers in Botswana were dropping because of overhunting (Hitchcock et al. 2020). The ban did not cover trophy hunting on private ranches run by Botswana elites, who benefited from the ban. After reconsidering Botswana census data for wildlife, however, wildlife numbers had risen steadily since the 1990s, and actually plateaued or dropped slightly during the years of the ban. After citizen pressure and reconsidering wildlife numbers, the hunting ban was dropped in 2019, but only for trophy hunting tags on public lands, not for subsistence hunters. Dropping the hunting ban produced an outcry from conservationists, some of whom suggested Botswana be punished with a ban on ecotourism (Hitchcock et al. 2020).

The situation in Botswana is not unique. Bans on hunting have turned traditional subsistence hunters into poachers. Green Militarization results in heavy fines, jail time, and subsistence hunters being shot on sight (Duffy 2010). Careful analysis of San subsistence hunting demonstrates that it has been sustainable (Hitchcock et al. 1996), but wildlife numbers are declining for more complex reasons. Most wildlife still lives in, or ranges to resource areas outside of protected areas. These traditional migration routes are being blocked by boundaries and agricultural development (Fynn and Bonyongo 2011). Pastoralists such as the Masai try to cut their losses when substantial lands are taken for conservation by turning more to agricultural development (McCabe et al. 2010). More San are turning to agriculture as well (Hitchcock et al. 1996). North-Griffiths (2008) has demonstrated a strong correlation between agriculture and wildlife declines in Kenya. The hunting ban has the ironic effect of forcing people who once included wildlife in a human ecological niche to turn towards agriculture, raising livestock, and taking part in a market economy.

6.5 Conclusion

Assumptions that weapons such as the atlatl and dart or bow and arrow would immediately replace older technology when they appeared (Churchill and Rhodes 2009; Hildebrandt and King 2012; Shea and Sisk 2010) are highly problematized by modern biases. Modern Westerners tend to think about old hunting technology through a lens of technological determinism, but societies adopt or decline to adopt new hunting and fighting weapons for a variety of reasons. When new weapon technologies are adopted, they take on new usage and new meaning as they are domesticated into the adopting culture (Macola 2016). Although advances in weapon technology have been implicated in the rise of modern behavior, the present analysis suggests that weapon advances do not always lead to more successful hunting. Modern hunting weapons have developed out of an agro-industrial apparatus that has resulted in dramatic reductions in wild habitat and significant increases in human population densities, resulting in a substantial negative impact on hunter success.

This paper also demonstrates the complexity and context-dependency of hunting success. The success rates of human hunters and other predators is exceedingly challenging to model even when many variables can be included in the analysis. This presents significant challenges for archaeologists who study ancient hunters. However, among the important variables leading to hunter success are ranged projectile weapons and hunter densities. Rather than increasing human adaptability and niche expansion leading to higher human populations, in some contexts more complex ranged weaponry that was more expensive to produce and maintain may have been adopted due to increasing human populations that made hunting more challenging.

CHAPTER 7. CONCLUSION

In the preceding chapters, I have reviewed the challenges archaeological weapon researchers continue to face, with a special focus on the terminal ballistics of ancient hunting weapons. Terminal ballistics, the ballistics of target impact and penetration, is an important focus for archaeologists because much of what we see in the archaeological record comprise stone armatures that were discarded due to impact damage or edge attrition. However, understanding these residues requires the production of experimental samples with known histories of impact.

Developing skill in constructing and using old tools is essential in this endeavor, as is an understanding of the internal and external ballistics (the ballistics of launch and flight) of ancient weapons. Furthermore, archaeologists seek to understand how weapons performed, and how they improved the lives of ancient people. These topics can be approached through experimental archaeology.

Weapon experiments generally fall along a spectrum from increasing realism to increasing control, corresponding to a spectrum from external to internal validity. This was the topic of focus in Chapters 2-4. Each end of the spectrum comes with certain advantages and disadvantages. Controlled experiments appear to be held up as what Chapman and Wiley (2016) call a silver bullet by some ancient weapon investigators. In the "old standard view of science" (Steinle 1997), controlled experiments are essential undertakings allowing causal mechanisms leading to a phenomenon of interest to be isolated and studied. However, isolating causal mechanisms can lead to different behaviors when the variability found in the "real world" comes into play. Modern computation and "wide instrumentation" is allowing scientists to conduct exploratory experiments that preserve more the variability found in realistic contexts. Applying similar protocols, exploratory realistic weapon studies have the ability to address multiple hypotheses, tackle equifinality, produce samples of impacted bone and stone armatures, and reveal avenues for future research. Additionally, students of a realistic exploratory approach have the benefit of gaining experiential insights that are more applicable to the past lives they study than those gained through more abstracted, controlled laboratory experiments.

Controlled experiments remain important approaches for addressing specific questions regarding ancient tools, but controlled approaches in ancient weapon studies are problematized by a lack of an appropriate target simulant that is scalable to prey bodies for low-velocity piercing and cutting projectiles. The use of non-scalable target simulants has led archaeologists to focus on cross-sectional metrics of armatures in determining their penetrating efficacy, while overlooking the important variable of armature sharpness. Despite ethical concerns and other challenges, freshly deceased animals currently provide far better analogs to living prey than target simulants. Using animals bred for meat and butchering them afterwards reduces much of the ethical concern, since more is obtained from such research than if the animal were simply butchered.

Hunting weapons get perhaps too much attention relative to the residues of other important human activities in the past, but weapons for hunting and defense do seem to have been important for the success of our species. Perhaps more importantly, Western anthropologists who interpret old hunting and fighting weapons are prone to search the record for technological advances. We should be wary of these biases. Ancient weapons were adapted to specific environmental conditions and social contexts of use. When new weapons were acquired, they were domesticated into new cultural settings, taking on new meaning and usage (Macola 2016). Simple tools can be highly effective in the right contexts. San bushmen in southern Africa in the late 20th century still demonstrate the effectiveness of simple thrusting and throwing spears, preferring them over bows for hunting in some settings, and frequently achieving impressive rates of hunting success (Hitchcock and Bleed 1997).

This helps explain some of the confusion surfacing around when complex projectile weapons first appeared. Previously, Neanderthals were understood to use simple thrusting spears, while ranged weapons of increasing complexity denoted modern behavior associated with our species (Churchill and Rhodes 2009). Archaeologists are beginning to question this in light of new evidence that Neanderthals too, had simple throwing weapons and exploited broad ecological niches. Archaeological interpretations are biased by what we expect to see, in this case, by the concept that modernity is a fundamental characteristic of our species. Rather there is a paucity of evidence that early modern humans had a more advanced weapon kit than archaic populations when they first left Africa (Mcbrearty and Brooks 2000; Villa and Roebroeks 2014).

Identifying weapon systems from armatures requires a statistical probabilistic approach, which is problematized in a significant way by substantial overlaps in the size, velocity, energy and momentum of ancient spears, darts, and arrows. Previously, size overlaps in darts and light javelins were recognized, but a more thorough review of the ethnographic evidence accounting for hunting bows and arrows from Papua New Guinea demonstrates that darts are completely bracketed between large arrows and light javelins. Nevertheless, armature size ranges at the extreme ends of the spectrum remain convincing to me as *probable* indicators of arrows and spears. This is less problematic when we consider that, like other social sciences, archaeologists generally deal in statistical probabilities (Rosenberg 2012). As many have pointed out, distinguishing weapon technologies from the armatures they leave behind is improved when multiple lines of evidence are used, including not only size metrics, but residue analysis and macro and microscopic signs of hafting and impact.

While javelins and atlatls have remained important weapons throughout history, there is increasing evidence to suggest that a similar bow and arrow technology to that of the contemporary San existed in southern Africa >60,000 years ago (Lombard 2021; Lombard and Phillipson 2010). In the Middle Solutrean of Spain, very small armatures have been recovered that seem likely to have been arrow points (Márquez and Muñoz 2008). If so, the bow could be >7,000 years older in Europe than previously thought, but the atlatl remained a preferred weapon there in some settings for a long time. Early evidence for the bow is also emerging from SE Asia, where the weapon could be >48,000 years old (Langley et al. 2020). This may seem unlikely to some given that "simpler" hunting weapons were not replaced sooner in nearby locations. Polynesians historically knew of the bow but considered it a toy, preferring instead javelins and slings for projectiles (Tregear 1892). Australians were in contact with bow-wielding groups on the north of the continent historically, but maintained preference for atlatls and javelins (Davidson 1936; Milks 2020).

The conditions by which new weapon technologies emerge and are adopted is more complex than a technological deterministic paradigm assumes (Macola 2016). In warfare prior to the gun, darts and spears were fielded effectively by large armies, while others avoided the use of projectile weapons altogether, relying instead on shields and armor to close the distance with enemies. Hunting success in any setting is highly complex, involving factors such as projectile weaponry, predator and prey densities, hunter demographics, hunter ideologies, and aspects of the environment. Simpler weapons can remain effective, especially when hunter densities remain low and an emphasis is placed on hunting skill. As hunter densities increase, prey animals are demonstrated to increasingly employ antipredator behaviors, making hunting more challenging. Increasing human populations may provide one grounds by which more sophisticated hunting weaponry would be adopted.

In this dissertation, I hope I have demonstrated the importance of careful, rigorous experiments for studying ancient hunting weapons. Controlled and realistic approaches can both be viable if deployed in the right context. No one type of experiment offers a silver bullet. However, exploratory methods can be highly useful for a field that constantly struggles under the problem of equifinality. I hope it is also clear that archaeologists need to develop practical experiences with old tools to better understand them. One of the drawbacks of the terminology I have used throughout this dissertation is that these weapons are only ancient because of their long usage. They continue to be viable instruments for recreation and even hunting in the right contexts. A better understanding of these tools and the hunters who deploy them effectively by modern Western society would benefit not only anthropologists, wildlife biologists, and conservationists, but traditional hunters who struggle under oppressive and misguided conservation policies.

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Appendix A. Chapter 2 Supplementary Materials

Supplementary tables of shots and details of mainshafts, armatures and foreshafts exclude shots and armatures that are not pertinent to the terminal ballistics analysis performed in this article, such as misses or direct impacts to bone that failed to penetrate deeply. Length measures are in mm and mass measures in g unless otherwise noted.

Table A-1. Details of atlatls used in the experiments. Original references are provided for artifact replicas.

ID	**Type**	**Overall Length**	**Lever Length** (spur to top of grip)	**Mass (g)**	**Balance Point** (back from spur)	**Reference**
Mag	Magdalenian inspired	647	440	122.1	327	
GBI1	Great Basin inspired	613	480	156.7	335	
WDC	White Dog Cave, AZ	604	440	100.9	280	(Guernsey and Kidder 1921)
BRC	Broken Roof Cave, AZ	538	405	121	202	(Guernsey 1931)
Clovis	Hypothetical Clovis	615	440	182	270	
Kinboko	Kinboko, AZ	655	470	111	295	(Kidder and Guernsey 1919)
SDC	Sand Dune Cave, AZ	655	480	100	340	(Lindsay et al. 1968)

Bows used in the experiments include ~20 kg (Catabwa 1 & 2) and 23 kg (Cherokee) draw weight flatbows of black locust (Robinia pseudoacacia) heartwood (see Allely and Hamm 1999:80–91).

Table A-2. Details of experimenters as of September 2021. ISAC is the International Standard Accuracy Competition of the World Atlatl Association (https://worldatlatl.org/).

Name	**Age**	**Height (cm)**	**Weight (kg)**	**Years of experience**	**ISAC Personal best**
Carlton Gover	29	185	111	6	NA
Devin Pettigrew	38	188	72	22	80
Donny Dust	42	188	107	15	NA
John Whittaker	68	168	66	25	92
Justin Garnett	38	180	68	18	76
Patrick Hashman	66	175	72	16	70

Table A-3. Details of projectile mainshafts.

MS	Type	Material	ProxDiam	DistDiam	Length	Mass	DistCirc	CM
1	Basketmaker	willow	8.8	13.7	1400	74.2	43	780
2	Basketmaker	willow	8.9	13.7	1400	74.3	43	790
3	Heavy	ash	11.1	14.2	1882	181.5	44.6	1082
4	CaneL	cane	8.4	12.6	1571	76.7	39.6	901
5	CaneM	cane	8.6	13.8	1750	93.8	43.3	990
6	Basketmaker	willow	8.5	14	1400	76.5	44	790
7	CaneH	cane	10.2	15.9	1960	150.1	50	1100
8	Basketmaker	willow	8.9	14	1530	85	44	850
9	Basketmaker	willow	8.4	13.6	1530	76.9	42.7	870
A1	Arrow	cane	7.1	7.9	750	21	24.8	
A2	Arrow	cane	6.95	9.3	753	20.9	29.2	
A3	Arrow	cane	8.3	9.2	811	26.9	28.9	
A4	Arrow	cane	6.7	10.2	615	19.1	32	345
A5	Arrow	cane	6.3	8.4	740	18.9	26.4	400
A6	Arrow	cane	6.3	8.8	745	20.2	27.6	405
A7	Arrow	cane	6.9	7.9	725	20.1	24.8	395

Figure A-1. Dart mainshafts used in the carcass experiments. From left to right: heavy ash dart 3, heavy cane dart 7, light cane dart 4, medium cane dart 5 (alongside a backup clone), and Basketmaker darts 1, 2, 9, 8, and 6. Photo by Autumn Cool.


Figure A-2. Examples of atlatls used in the carcass experiments. Photo by John Whittaker.

Figure A-3. “Cherokee” (left) and “Catabwa 2” (right) bows alongside cane arrow shafts used in the carcass experiments. Photo by John Whittaker.

Table A-4. Details of armatures and foreshafts.

Arm.	Type1	Type2	Material	1	2	3	4	5	6	7	8	9	10	11
5	Dart	Lanceolate	ReedsSpring	64	9.5	21	7.9	10.4	11.4	205	23.3	32.656	84.9056	4
7	Dart	Lanceolate	ReedsSpring	44	5.8	24	6.9	13	10.8	183	19.8	40.82	132.665	3
8	Dart	Lanceolate	ReedsSpring	38	3.9	29	6.6	9.6	10	118	19.7	30.144	72.3456	2
9	Dart	CornerNotch	Siltstone	39	5.4	19	7.6	8.6	9.7	141	8.6	27.004	58.0586	A2
14	Arrow	CornerNotch	ReedsSpring	39	5.1	23	8.1	9.8	11.4	95	8.1	30.772	75.3914	A4
19	Dart	CornerNotch	ReedsSpring	53	5.2	16	6.5	9.1	8.7	200	12.6	28.574	65.00585	A2
24	Dart	Stemmed	ReedsSpring	45	4.7	25	5.4	10	9.2	275	20.6	31.4	78.5	3
25	Dart	Stemmed	ReedsSpring	55	10.9	29	7.4	12.4	12.3	141	21.5	38.936	120.7016	3
27	Dart	Stemmed	ReedsSpring		6.2	24	6.5	9.9	6.4	172	15.1	31.086	76.93785	4
28	Dart	CornerNotch	BrazilianAgate	50	7.1	25	6	9	10	130	12	28.26	63.585	2
30	Dart	CornerNotch	BrazilianAgate	45	7.1	26	5.4	10.4	11.3	145	14.7	32.656	84.9056	1
31	Dart	CornerNotch	BrazilianAgate	43	4.9	21	4.3	9.7	10.7	255	14.2	30.458	73.86065	1
33	Dart	CornerNotch	BrazilianAgate	49	6.8	24	6	10.9	11.7	180	16.2	34.226	93.26585	1
34	Dart	CornerNotch	BrazilianAgate	40	5.5	26	5	10.3	10	112	10.7	32.342	83.28065	1
36	Dart	CornerNotch	BrazilianAgate		7.5	25	5.3	10.5	10.8	143	14.4	32.97	86.54625	1
40	Dart	CornerNotch	BrazilianAgate	45	6.6	28	4.8	10.2	11.4	262	17.1	32.028	81.6714	2
42	Dart	CornerNotch	BrazilianAgate		7	23	5.8	9.6	10.8	152	12.7	30.144	72.3456	2
45	Dart	CornerNotch	Novaculite	63	9.5	22	6.5	10	11.3	161	15.6	31.4	78.5	2
46	Dart	CornerNotch	Novaculite	60	11.2	28	7.8	12	11.6	144	20.1	37.68	113.04	4
48	Dart	CornerNotch	ReedsSpring		11.3	38	6	14.5	10.1	194	23.3	45.53	165.0463	5
51	Dart	Stemmed	ReedsSpring	66	15.4	30	7	11.8	13.4	153	24.5	37.052	109.3034	5
53	Dart	CornerNotch	IndianAgate	48	7.9	27	6.2	11.8	11.6	140	16	37.052	109.3034	1
55	Dart	CornerNotch	IndianAgate	44	6.7	25	6	10.3	11.3	135	13	32.342	83.28065	1
56	Dart	SideNotch	Basalt	58	7.2	23	5.7	11.2	11.3	140	14.3	35.168	98.4704	3
59	Dart	Lanceolate	Porcelain		15.6	26	8.4	12.3	12.7	262	35.3	38.622	118.7627	5
61	Dart	Lanceolate	ReedsSpring			22	7.5	12.8	11.5	262	28.9	40.192	128.6144	4
64	Dart	CornerNotch	ReedsSpring	57	9	26	6.1	12.2	12.2	246	29.2	38.308	116.8394	4
75	Arrow	Stemmed	Chert	29	1.5	19	3.8	6.6	6.1	187	6.9	20.724	34.1946	A7
76	Dart	Lanceolate	Burlington	87	15.7	25	8	12.7	13.2	270	39.1	39.878	126.6127	5
77	Dart	Lanceolate	Burlington	74	12.7	23	7.4	12.7	12.2	262	35.5	39.878	126.6127	4
78	Dart	Lanceolate	Burlington	82	14.9	26	7.6	12.7	12.9	265	37.2	39.878	126.6127	5
79	Dart	Lanceolate	Burlington	52	7.2	21	6.3	12.7	11.2	242	29.9	39.878	126.6127	4
81	Dart	Lanceolate	Porcelain	62	8.1	28	4.9	12.2	12.2	125	20.5	38.308	116.8394	5
83	Dart	SideNotch	Burlington	71	27.8	47	8.4	12.8	12.6	263	51.1	40.192	128.6144	5
84	Dart	SideNotch	Burlington	64	16.1	39	8.3	12.7	12.4	255	39.1	39.878	126.6127	5
85	Dart	CornerNotch	Burlington	59	11.5	23	7.8	9.5	9.8	70	18.8	29.83	70.84625	2
87	Dart	CornerNotch	TXChert	60	9.5	28	5.3	9.6	9.4	122	14.9	30.144	72.3456	1
89	Arrow	CornerNotch	Burlington	55	5.6	24	5.6	8.8	10.6	130	10.6	27.632	60.7904	A5
90	Dart	CornerNotch	Jasper	43	4.6	24	5.4	9.1	9.2	125	9.9	28.574	65.00585	2
91	Arrow	Triangular	Obsidian	39	4	21	6		10	138	8.3			A6
92	Arrow	SideNotch	Chert	34	2	19	3.7	7.1	7.5	111	5.5	22.294	39.57185	A1
94	Arrow	BasalNotch	BrazilianAgate	35.5	2.4	21	3.5	7.9	8.3	90	5.4	24.806	48.99185	A6

95	Dart	CornerNotch	Novaculite	65	16.5	38.9	7.9	13.5	14.4	227	29.3	42.39	143.0663	7
96	Arrow	Triangular	Burlington	20		15.6	3.6	7.4	6.9	100	4.6	23.236	42.9866	A5
97	Arrow	CornerNotch	Burlington	30		13.6	4		8.4	116	5.5			A5
106	Dart	CornerNotch	Novaculite	68.2	12.6	28	6.2	11.1	12.9	208	19.9	34.854	96.71985	4
108	Dart	CornerNotch	Burlington	52	8.9	26.6	6.6	9.3	11.4	17	15.4	29.202	67.89465	1
110	Arrow	SideNotch	Burlington	38.1	2.9	18.9	4.5	8.9	10.2	113	6.7	27.946	62.17985	A6
120	Dart	SideNotch	Burlington	47	10.3	33	7.5	11.6	14.4	155	22.1	36.424	105.6296	4
122	Dart	CornerNotch	Novaculite	55	15.1	45	7.2	13.8	15.9	186	26.5	43.332	149.4954	7
124	Dart	CornerNotch	Novaculite	47	11.4	41	6.9	14.7	16.4	215	26.2	46.158	169.6307	5
125	Dart	CornerNotch	Dacite	51	8.5	29.3	7.7	11.4	13.9	195	21.2	35.796	102.0186	4
127	Dart	Lanceolate	TXChert	64	12.5	25.3	7.3	12	14	248	30.2	37.68	113.04	5
136	Dart	Lanceolate	Burlington	98	24.7	26.1	8.9	14	15.7	286	54.2	43.96	153.86	7
152	Dart	CornerNotch	Dacite	62	8.5	29.4	6.3	12	12.5	245	22.3	37.68	113.04	8
157	Arrow	SideNotch	Chert	38	3	16.7	4.8	8	9.4	134	7.4	25.12	50.24	A5
161	Arrow	SideNotch	Chert	27	1.1	14.9	3.3	8.7	9.1	192	8.2	27.318	59.41665	A5
170	Dart	Lanceolate	Obsidian	139	52.6	32.4	10	16	18.5	250	77.7	50.24	200.96	7
172	Dart	Lanceolate	TXChert	99	11.4	25.1	7.8	12	14.5	270	34	37.68	113.04	5
174	Dart	Lanceolate	TXChert	74	13.9	27.2	6.3	13	15	285	31.3	40.82	132.665	7
186	Arrow	Broadhead	Steel	61.6	8.1	28.7	9.3	9.4	9.4	78.7	10.5	29.516	69.3626	A5

Column heading key: 1. unhafted armature length, 2. unhafted armature mass, 3. unhafted armature width, 4. unhafted armature thickness, 5. foreshaft diameter, 6. foreshaft width, 7. foreshaft length in when seated in mainshaft socket, 8. foreshaft mass, 9. foreshaft circumference, 10. foreshaft cross-sectional area, 11. mainshaft identifier

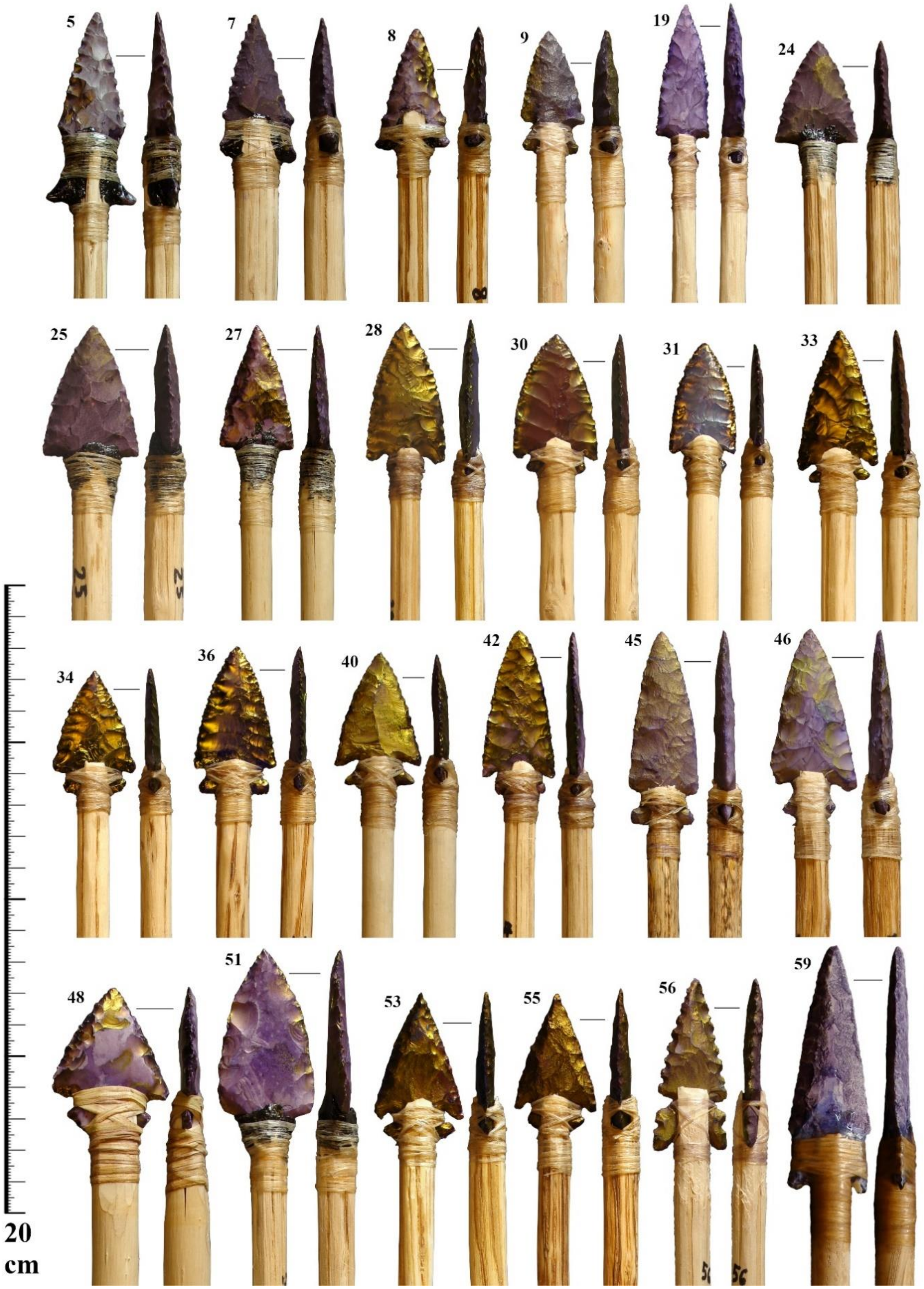

Figure A-4. Hafted dart armatures included in the analysis of terminal ballistics.

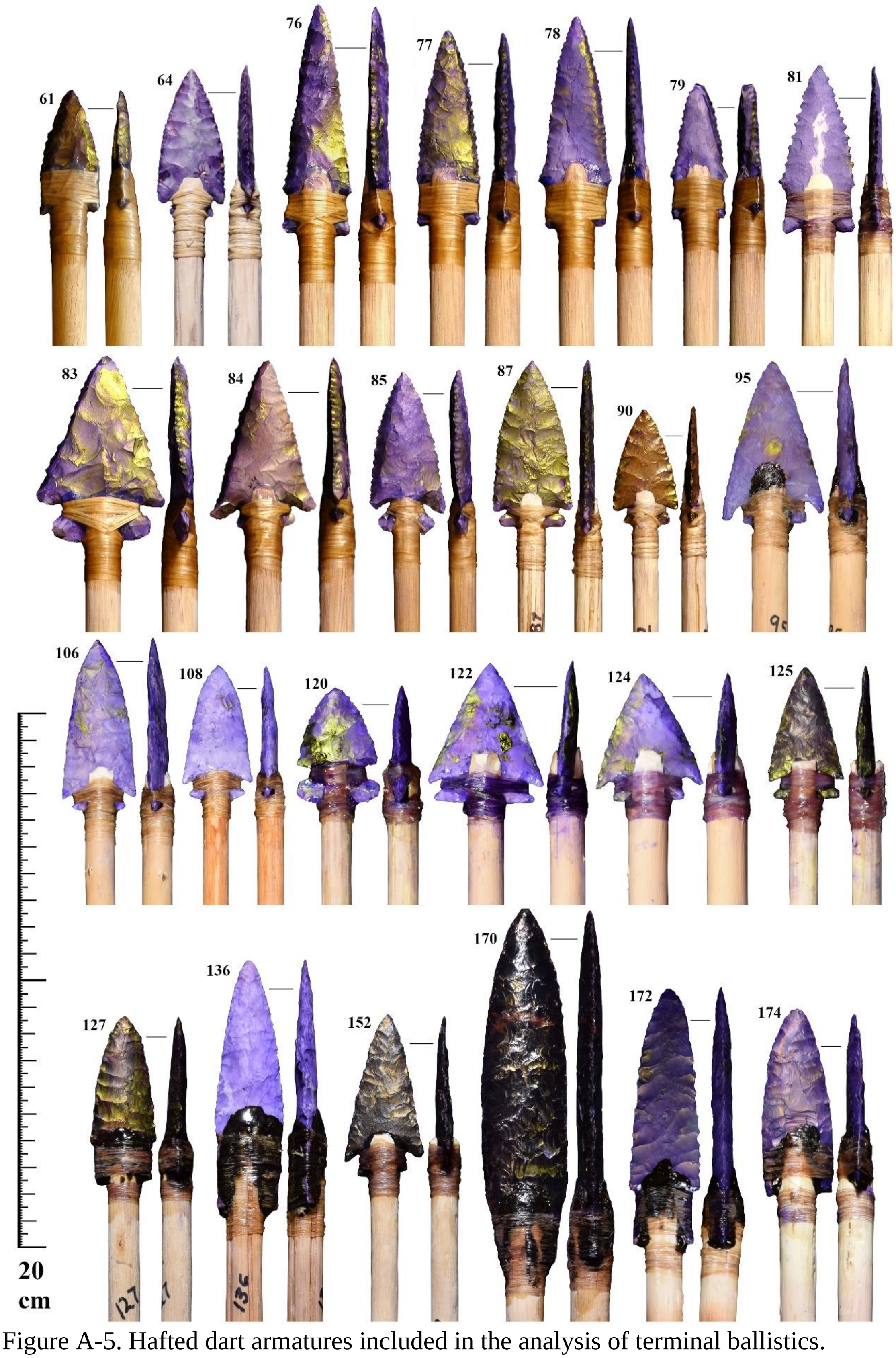

Figure A-5. Hafted dart armatures included in the analysis of terminal ballistics.

Figure A-6. Hafted arrow armatures included in the analysis of terminal ballistics.

Table A-5. Shot record.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
2	36	1	JG	BRC	Hog	hit		back	0.0886	24.4	26.37	2.16				138	138
4	90	2	JG	BRC	Hog	hit		thorax	0.0842	23.2	22.66	1.95				177	177
6	42	2	JG	BRC	Hog	hit		thorax	0.087	21	19.18	1.83				138	138
7	42	2	JG	BRC	Hog	hit		thorax	0.087	23.2	23.41	2.02				162	162
16	87	1	JG	BRC	Hog	hit		thorax	0.0891	22.3	22.15	1.99				110	110
17	87	1	JG	BRC	Hog	hit		back	0.0891	21.7	20.98	1.93				115	115
21	85	2	JG	BRC	Hog	hit		belly	0.0931							185	185
23	77	4	DP	GBI1	Hog	hit	BevelRotate	back	0.1122	24.1	32.58	2.7				180	178
24	77	4	DP	GBI1	Hog	hit	BevelRotate	thorax	0.1122	27.4	42.12	3.07				324	324
25	77	4	DP	GBI1	Hog	hit	BevelRotate	shoulder	0.1122	27.1	41.2	3.04				216	216
26	77	4	DP	GBI1	Hog	hit		thorax	0.1122	26.1	38.22	2.93				195	195
27	76	5	DP	GBI1	Hog	hit	BevelRotate	thorax	0.1329	25.5	43.21	3.39				209	209
28	76	5	DP	GBI1	Hog	hit	BevelRotate	back	0.1329	26.5	46.66	3.52				200	200
29	76	5	DP	GBI1	Hog	hit		thorax	0.1329	25	41.53	3.32				237	237
31	78	5	DP	GBI1	Hog	hit		belly	0.131	26.4	45.65	3.46				168	168
34	79	4	JG	GBI1	Hog	hit	BevelRotate	back	0.1066	24.7	32.52	2.63				113	113
35	79	4	JG	GBI1	Hog	hit	BevelRotate	shoulder	0.1066	25.1	33.58	2.68				153	153
36	79	4	JG	GBI1	Hog	hit		thorax	0.1066	23.1	28.44	2.46				196	196
37	79	4	JG	GBI1	Hog	hit	BevelRotate	thorax	0.1066	26.1	36.31	2.78				200	200
38	79	4	JG	GBI1	Hog	hit		shoulder	0.1066	23.7	29.94	2.53				182	182
41	84	5	JG	GBI1	Hog	hit		belly	0.1329	22.3	33.04	2.96				243	243
43	83	5	DP	GBI1	Hog	hit		thorax	0.1449	26.1	49.35	3.78				272	272
49	48	5	DP	GBI1	Hog	hit		neck	0.1171	26.6	41.43	3.11				120	120
51	27	4	PH	Mag	Hog	hit		neck	0.0918	26.1	31.27	2.4				207	207
57	19	A2	DP	Catawba1	Hog	hit		thorax	0.0335							194	194
58	9	A2	DP	Catawba1	Hog	hit		thorax	0.0295							176	176
59	92	A1	DP	Catawba1	Hog	hit	SkewedImpact	thorax	0.0265							160	160
61	79	4	DP	GBI1	Hog	hit		back	0.1066	23.7	29.94	2.53				282	282
62	79	4	DP	GBI1	Hog	hit		thorax	0.1066							245	245
63	79	4	DP	GBI1	Hog	hit		thorax	0.1066							195	195
65	59	5	DP	GBI1	Hog	hit		thorax	0.1291	18.3	21.62	2.36				152	152
94	75	A4	DP	Catawba2	Goat1	hit		thorax	0.027	41	22.69	1.11	-2179	59	7.2	250	250
108	7	3	DP	GBI2	Goat1	hit		shoulder	0.2013	19	36.33	3.82	-1410	284	25.2	135	135
144	97	A5	DP	Catawba2	Goat1	hit		thorax	0.0244	41	20.51	1	-2512	61	5.9	437	217
152	45	9	DP	Kinboko	Goat1	hit		shoulder	0.0899	25	28.09	2.25	-2264	204	11.5	216	216
153	97	A5	DP	Catawba2	Goat1	hit		thorax	0.0244	40	19.52	0.98	-2056	50	8.8	246	216
154	61	4	DP	GBI1	Goat1	bounce		shoulder	0.1056	22	25.56	2.32					
156	91	A6	DP	Catawba2	Goat1	hit		thorax	0.0285	42	25.14	1.2	-2345	67	12	310	190
160	89	A5	DP	Catawba2	Goat1	hit		back	0.0295	37	20.19	1.09	-1832	54	5.8	490	240
168	28	9	DP	Kinboko	Goat1	hit		thorax	0.0863	20	17.26	1.73	-576	50	4.2	119	119
174	46	4	DP	GBI1	Goat1	bounce		thorax	0.0968	23	25.6	2.23					
177	124	5	DP	GBI1	Goat2	hit		belly	0.12	21.8	28.51	2.62	-805	97	9.2	275	275

179	81	5	DP	GBI1	Goat2	hit		thorax	0.1143	23.4	31.29	2.67	-1609	184	18.6	330	330
185	8	9	DP	GBI1	Goat2	hit		thorax	0.094	23.6	26.18	2.22	-1384	130	9.5	210	210
187	53	1	DP	Kinboko	Goat2	hit		belly	0.0902	24.5	27.07	2.21	-1137	103	8.4	380	380
190	30	1	DP	Kinboko	Goat2	hit		belly	0.0889	24.8	27.34	2.2	-938	83	8.67	410	410
195	25	3	DD		Goat2	hit		belly	0.203	24	58.46	4.87	-592	120	11.5	1070	230
202	56	3	DD		Goat2	hit		belly	0.1958	25.1	61.68	4.91	-749	147	11	2022	230
208	122	7	DP	GBI1	Goat2	hit		thorax	0.1766	23.1	47.12	4.08	-1365	241	23.3	275	275
209	95	7	DP	GBI1	Goat2	hit		belly	0.1794	24.5	53.84	4.4	-742	133	12.6	820	380
217	55	1	DP	Kinboko	Goat2	hit		thorax	0.0872	24	25.11	2.09	-1552	135	8.7	290	290
219	55	1	DP	Kinboko	Goat2	hit		thorax	0.0872	24.4	25.96	2.13	-1607	140	13.6	360	360
227	14	A4	DP	Catawba2	Goat2	hit		belly	0.0272	39.4	21.11	1.07	-3378	92	10.8	350	350
232	106	4	DP	GBI1	Goat2	hit		thorax	0.0966	24.8	29.71	2.4	-1586	153	14	236	236
247	125	4	DP	GBI1	Goat2	hit	SkewedImpact	thorax	0.0979	24.4	29.14	2.39	-1143	112	9.1	330	330
250	120	4	DP	GBI1	Goat2	hit		belly	0.0988	22.2	24.35	2.19	-1679	166	10.7	135	135
258	120	4	DP	GBI1	Goat2	bounce		thorax	0.0988	21.8	23.48	2.15					
262	152	8	DP	GBI1	Bison	hit		shoulder	0.1073	25.1	33.8	2.69	-1360	146	13.4	245	245
264	152	8	DP	GBI1	Bison	hit		belly	0.1073	23.6	29.88	2.53	-1272	136	13.3	434	434
267	40	8	DP	Kinboko	Bison	hit	FSLoose	thorax	0.0914	23.5	25.24	2.15	-1089	100	9.1	350	350
268	31	8	DP	Kinboko	Bison	hit	FSLoose	thorax	0.0884	25.3	28.29	2.24	-1201	106	11	272	272
270	33	1	DP	Kinboko	Bison	hit		thorax	0.0904	24.5	27.13	2.21	-548	50	4.8	415	363
271	108	1	DP	Kinboko	Bison	hit		thorax	0.0896	24.8	27.55	2.22	-1555	139	14.7	217	217
273	34	1	DP	Kinboko	Bison	hit		back	0.0849	25.6	27.82	2.17	-702	60	6	200	200
276	172	5	JW	SDC	Bison	hit		thorax	0.1278	22.8	33.22	2.91	-1259	161	15.4	310	310
282	127	5	JW	SDC	Bison	hit		thorax	0.124	22.9	32.51	2.84	-1342	166	15	405	405
288	51	5	DP	GBI1	Bison	hit		thorax	0.1183	24.4	35.22	2.89	-1432	169	16.7	300	300
290	136	7	CG	CGperson al	Bison	hit		belly	0.2043	22.9	53.57	4.68	-1348	275	24.3	495	495
291	136	7	CG	CGperson al	Bison	hit		back	0.2043	25.1	64.36	5.13	-1200	245	16.1	146	146
293	170	7	CG	CGperson al	Bison	hit		belly	0.2278	23.3	61.84	5.31	-454	103	10.3	720	540
298	24	3	DD	TSSA	Bison	hit	FSLoose	shoulder	0.2021	28	79.22	5.66	-714	144	15.4	303	303
319	64	4	DP	GBI1	Bison	hit		thorax	0.1059	26.5	37.18	2.81	-941	100	12	460	460
321	5	4	DP	GBI1	Bison	hit		back	0.1	26.8	35.91	2.68	-1424	142	17.4	202	202
322	174	7	CG	DPcustom	Bison	hit		belly	0.1814	27.3	67.6	4.95	-1223	222	25.4	510	510
334	157	A5	DP	Cherokee	Bison	hit		shoulder	0.0263	39.4	20.41	1.04	-2302	61	7.4	383	383
335	110	A6	DP	Cherokee	Bison	hit		thorax	0.0269	37.6	19.02	1.01	-3339	90	9.7	300	300
338	94	A6	DP	Cherokee	Bison	hit		thorax	0.0256	39.5	19.97	1.01	-2498	64	8.3	337	337
339	96	A5	DP	Cherokee	Bison	hit		shoulder	0.0235	40.4	19.18	0.95	-2953	69	10.9	310	310
340	96	A5	DP	Cherokee	Bison	hit		belly	0.0235	39.4	18.24	0.93	-2195	52	7.2	453	453

Column heading key: 1. shot number, 2. armature identifier, 3. mainshaft identifier, 4. shooter initials, 5. platform (atlatl or bow) 6. carcass experiment, 7. nature of impact, 8. impact qualifier, 9. impact locus, 10. total projectile mass (kg), 11. velocity (m/s), 12. kinetic energy (J), 13. momentum (kg-m/s), 14. acceleration (m/s^2), 15. force (N), 16. work (J), 17. MaxPen (total penetration into and through the target), 18. wound length (MaxPen - penetration through)

Table A-6. Shot record continued.

19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
66.2	51.1	135	79.2			0.0007				1543	705.18	0.8	1.55			1.3	T	T
64.8	49.2	110.4	69.2			0.0008			39	1525	870.84	1	1.72			1.5	T	T
66.7	47.4	124.2	75.2			0.0007				1552	654.12	0.9	1.57			1.4	T	T
66.7	47.4	124.2	75.2			0.0007				1552	767.88	0.9	1.57			1.4	T	T
74.2	57	131.6	78.1			0.0007			37	1522	627	1	1.89			1.4	F	T
74.2	57	131.6	78.1			0.0007			37	1522	655.5	1	1.89			1.4	T	T
89.7	48.6	112.7	70			0.0008			32	1470	899.1	1.3	1.63			1.4	F	T
85.1	48.3	140.3	83.2			0.0008			20	1833	859.74	0.7	1.21			1	T	T
85.1	48.3	140.3	83.2			0.0008			20	1833	1564.92	0.7	1.21			1	F	T
85.1	48.3	140.3	83.2			0.0008			20	1833	1043.28	0.7	1.21			1	F	T
85.1	48.3	140.3	83.2			0.0008			20	1833	941.85	0.7	1.21			1	T	T
100	52.5	165	93.6			0.0008			24	2020	1097.25	0.8	1.32			1.1	F	T
100	52.5	165	93.6			0.0008			24	2020	1050	0.8	1.32			1.1	F	T
100	52.5	165	93.6			0.0008			24	2020	1244.25	0.8	1.32			1.1	T	T
98.8	54.2	167.7	93.6			0.0008			25	2015	910.56	0.8	1.36			1.1	T	T
66.2	43.8	117.6	73.4			0.0009			20	1813	494.94	0.5	1.1			1	F	T
66.2	43.8	117.6	73.4			0.0009			20	1813	670.14	0.5	1.1			1	T	T
66.2	43.8	117.6	73.4			0.0009			20	1813	858.48	0.5	1.1			1	F	T
66.2	43.8	117.6	73.4			0.0009			20	1813	876	0.5	1.1			1	F	T
66.2	43.8	117.6	73.4			0.0009			20	1813	797.16	0.5	1.1			1	F	T
162	79.7	241.8	116.4			0.0006			24	2005	1936.71	1.3	2			1.1	F	T
197	95.5	296.1	133.7			0.0005			22	2013	2597.6	1.5	2.38			1.1	F	T
114	76.9	191.9	101.5			0.0006				1944	922.8	0.7	1.69			1	F	T
78	49.7	76.8	58.2			0.0012				1743	1028.79	1	1.6			1.3	F	T
52	34.5	69.6	50.9			0.0005				953	669.3	0.8	1.21			1	F	T
72.2	40.9	92.2	61.5			0.0003				894	719.84	1.2	1.51			1.1	F	T
35.2	38.7	71.2	52.1			0.0004				861	619.2	0.9	1.74			1.1	F	T
66.2	43.8	117.6	73.4			0.0009			20	1813	1235.16	0.5	1.1			1	T	T
66.2	43.8	117.6	73.4			0.0009			20	1813	1073.1	0.5	1.1			1	F	T
66.2	43.8	117.6	73.4			0.0009			20	1813	854.1	0.5	1.1			1	F	T
109	54.6	165.1	92.3			0.0008				2012	829.92	0.9	1.41			1.1	F	T
36.1	38.8	58	47.3			0.0005			31	912	970	1.1	1.87			1.2	T	T
82.8	49.9	129.6	77.2	189.6	56.3	0.0016	0.0011	2.9	38	2065	673.65	0.6	1.22	1.43	1.38	1.1	F	T
27.2	28.4	57.1	44.8	67.9	32.8	0.0004	0.0004	2.7		856	616.28						F	T
71.5	45.9	124.3	75.9			0.0007			37	1561	991.44	0.9	1.46			1.4	F	F
27.2	28.4	57.1	44.8	67.9	32.8	0.0004	0.0004	2.7		856	613.44						F	T
82.5	46.5	126.5	77.1	194.1	57.9	0.0008	0.0005			1833		0.6	1.16	1.51	1.44	1	F	F
63	43.7	105	67			0.0003			30	883	830.3						T	T
67.2	49.3	127.2	76.1	133.1	53.9	0.0002	0.0002	2.7	25	870	1183.2	1.1	1.78	2.19	1.95	1	F	F
75	51.4	125	75			0.0007			38	1530	611.66	1.2	1.82			1.5	F	F
109	58.1	162.4	89.6			0.0006			32	1715		1	1.54			1.1	F	F
141	83.2	336.2	149.2	351.1	91.8	0.0004	0.0003	2.2	31	1965	2288	0.8	1.8	2.07	1.99	0.9	F	T

68.6	56.9	170.8	93.2	223.9	62.9	0.0007	0.0005	3	32	1875	1877.7	0.6	1.49	1.92	1.64	1.1	F	T
95.7	59.5	145	83	146.4	53.4	0.0007	0.0006	2.8	26	1518	1249.5	1.3	1.97	2.02	1.77	1.4	F	T
83.7	55.4	156.6	87.6			0.0006			35	1540	2105.2	0.8	1.5			1.2	F	T
70.2	53.1	146.9	83.9	170.8	60.8	0.0006	0.0005	3.1	36	1545	2177.1	0.8	1.63	2.01	1.86	1.3	F	T
107	59.9	178.4	95.8			0.0011			38	2023	1377.7	0.9	1.54			1.2	F	F
65.6	47.4	130	77.9			0.0015			41	2022	1090.2	0.7	1.35			1.3	F	F
162	91.1	357.8	153.2			0.0005			38	2146	2505.25	1.1	2.1			1.2	T	F
154	79.4	280.1	129.6			0.0006			37	2187	3017.2	1.1	1.87			1.2	F	T
75	51.4	141.2	81.9	148.6	58.4	0.0006	0.0006	3.2	38	1535	1490.6	0.9	1.59	1.78	1.81	1.3	F	T
75	51.4	141.2	81.9	148.6	58.4	0.0006	0.0006	3.2	38	1535	1850.4	0.9	1.59	1.78	1.81	1.3	F	T
93.2	48.8	131.1	78.5	150.1	53.7	0.0002	0.0002	2.4	30	710	1708	1.2	1.59	1.99	1.75	1	F	T
86.8	57.4	180.6	97.6			0.0005			35	1779	1354.64	0.9	1.65			1.1	T	T
113	60.6	203.6	106.9	242.3	68.1	0.0005	0.0004	2.5	30	1766	1999.8	1.1	1.69	2.38	1.9	1.1	T	F
124	67.7	237.6	117.8	252.5	75.8	0.0004	0.0004	2.9	29	1726	913.95	1.2	1.86	2.39	2.08	1.1	F	T
124	67.7	237.6	117.8	252.5	75.8	0.0004	0.0004	2.9	29	1726		1.2	1.86	2.39	2.08	1.1	F	F
92.6	60.1	183.8	97.9	204.8	66.5	0.0006	0.0005	3	34	1775	1472.45	0.8	1.6	1.81	1.76	1.2	F	T
92.6	60.1	183.8	97.9	204.8	66.5	0.0006	0.0005	3	34	1775	2608.34	0.8	1.6	1.81	1.76	1.2	F	T
67.2	56.8	159.6	88.5	157.2	63.1	0.0006	0.0006	3.4	36	1662	1988	0.8	1.77	1.92	1.97	1.3	F	T
45.2	42.9	112.4	70.6	122.2	48.8	0.0008	0.0007	3.4	39	1655	1166.88	0.6	1.41	1.65	1.6	1.4	F	T
72	49.5	140.4	82.2	147.6	58.3	0.0006	0.0006	3.2	36	1580	1796.85	0.8	1.45	1.58	1.7	1.3	T	T
87.8	54.8	151.6	85.7	161.3	59.7	0.0006	0.0006	3.4	33	1417	1189.16	1.3	1.88	2.38	2.04	1.5	F	T
65	53	130	77			0.0007			39	1512	1060	0.8	1.64			1.3	T	F
97.9	52.6	182	102.8	239	59.4	0.0007	0.0005	3.6	26	2020	1630.6	0.9	1.4	2.11	1.58	1.2	T	T
92.3	52.7	177.1	99.6	221.2	62.1	0.0007	0.0006	3.1	29	1998	2134.35	0.8	1.4	1.96	1.65	1.2	F	T
105	61.6	201	104.9	223.6	70	0.0006	0.0005	3	34	1903	1848	1	1.66	2.05	1.89	1.2	F	T
116	55.2	204.9	113.8	290.6	64.5	0.001	0.0007	3.1	28	2246	2732.4	0.8	1.26	1.89	1.47	1.1	F	T
116	55.2	204.9	113.8	290.6	64.5	0.001	0.0007	3.1	28	2246	805.92	0.8	1.26	1.89	1.47	1.1	T	F
162	67.8	299.7	150.4	363.8	74.5	0.0008	0.0006	3.3	27	2210	3661.2	0.8	1.35	1.81	1.48	1	F	T
67.5	51.2	115	71.2	133	56.4	0.0018	0.0015	3	40	2157	1551.36	0.9	1.63	1.69	1.8	1.4	F	F
79.3	53.4	158.6	89.2	184.2	58	0.0007	0.0006	2.9	23	1817	2456.4	0.7	1.39	1.58	1.51	1	F	T
83	44.9	119.7	74.5	184.1	64.4	0.0008	0.0005	3.1	29	1776	906.98	1	1.37	2.17	1.97	1.2	T	F
85.7	55.8	204	110.6	280.4	64.3	0.0009	0.0007	4.4	37	2245	2845.8	0.7	1.37	2.11	1.58	1.2	F	T
40.1	34.8	78.5	55.5	92.1	39.1	0.0003	0.0003	2.6	29	874	1332.84	0.8	1.39	1.83	1.56	1.1	F	T
42.5	38.9	96.4	63.8	106.7	44.7	0.0003	0.0003	2.8	32	858	1167	0.7	1.39	1.72	1.6	1	F	T
36.8	42.6	87.2	59.2	88.3	47	0.0003	0.0003	2.6	34	835	1435.62	0.8	1.72	1.8	1.89	1.1	F	T
28.1	32	53.8	43.1	70.1	37.5	0.0004	0.0003	2.5		840	992	0.7	1.38	1.63	1.61	1.1	F	T
28.1	32	53.8	43.1	70.1	37.5	0.0004	0.0003	2.5		840	1449.6	0.7	1.38	1.63	1.61	1.1	F	T

Column heading key: 19. TCSA, 20. TCSP, 21. $TCSA_h$, 22. $TCSP_h$, 23. $TCSA_{hPV}$, 24. $TCSP_{hPV}$, 25. sectional density (SD), 26. SD_{hPV}, 27. drag coefficient (C_d), 28. center of mass (CM), 29. total projectile length, 30. wound surface area (WSA), 31. area ratio (AR), 32. perimeter ratio (PR), 33. AR_{hPV}, 34. PR_{hPV}, 35. shaft ratio (SR), 36. projectile impacted bone, 37. the shot is suitable for terminal ballistic analysis (PenAnalysis)

The following filters were used to isolate select shots in the Shot Record table for statistical analysis in JMP:

- 33 darts and arrows (Figure 4):
    - Exclude MS 3
    - Exclude Exp = Hog
    - Include PenAnalysis = T
- 41 darts and arrows (Table 3):
    - Exclude MS 3
    - Exclude shots without **a** values
- 51 darts (Figure 8):
    - Exclude MS 3,A1,A2,A3,A4,A5,A6
    - Include PenAnalysis = T
- 28 darts and arrows (Figures 10, 11 and Table 4):
    - Exclude MS 3
    - Exclude shots without $\mathbf{C_d}$ values
    - Include PenAnalysis = T

ParaView analysis

The following steps are used to obtain values for TCSA and TCSP from photogrammetry models in the open-source ParaView program (https://www.paraview.org/). These steps apply to models oriented tip up along the Y-axis:

<u>TCSA</u>:

1. Set view direction to -Y

2. Enable “Camera Parallel Projection”
3. Use “Select Points On (d)” to select the cells
4. Extract Selection
5. Use the “Transform” filter to rotate the cells 90º on the X axis, and scale 1e-5 on the Y axis
6. Reorient view direction to +Z and rotate 180º
7. Apply the “Delaunay 2d” filter with Alpha set to a value just large enough to create a solid model (usually 0.5 on my models)
8. Apply the “Integrate Variables” filter and view resulting Cell Data

<u>TCSP</u>:

1. Follow steps 1-7 for TCSA
8. Apply the “Feature Edges” filter and enable “Boundary Edges”
9. Apply the “Integrate Variables” filter and view Cell Data

Computational Fluid Dynamics

To create 3d models of the armatures, the end of the foreshaft was pressed into clay and the foreshaft set upright on a turn wheel in front of a black backdrop or dark room. The armatures were photographed 30 to 50 times from at least two angles (slightly above and slightly below the armature), and the photos were aligned and meshed in Agisoft Metashape.

Figure A-7. Example of a modeled armature in Agisoft Metashape, in this case armature 136.

After meshing models in Agisoft Metashape, they were processed in the open-source Meshmixer program (https://www.meshmixer.com/). First the models are oriented along on the Y axis using the “Align” and “Transform” functions. Next the “Plane cut” function is used to apply a 90º cut across the foreshaft directly behind the lashings of the haft. The Unit/Dimensions are then set to the width of the armature. The “Make Solid” function is then applied to the model, with the Solid Type set to accurate, Solid Accuracy set to 200, Solid Density set to 150, and the Minimum Thickness set to 0.3mm. Next the “Select” tool is used to fix small errors in the geometry using the erase and fill function. These errors sometimes occur during the meshing process and manifest as small spikes or dents in the model that do not occur on the real armature. Under “Primitives” a tube is then snapped to the end of the haft and made as large in diameter as possible without creating visible overlapping cells between the tube and armature model. The goal is to mimic the diameter of the foreshaft as closely as possible, but foreshafts of natural wood shoots are not always perfectly round, and overlaps can occur where cells of the tube are visible outside the haft area where it intersects with the model. These will create areas with high Aspect Ratios when the model is meshed in SimScale, and the problem areas will need to be fixed using the "Select" function in MeshMixer before the model can be uploaded and meshed again. If this is not done errors will occur in the simulation or the simulation will fail to converge. The tube is then lengthened to five times the length of the hafted armature and solidified using the "Make Solid" function. Keeping the tube and armature as separate solid bodies will allow functions to be applied only to the hafted armature in SimScale.

Once the model is uploaded to SimScale, an enclosure is built around it that is 2x the length of the hafted armature above it, 1 to 1.5x on the sides, and 5x below (cut off just before reaching the end of the attached tube). The solids are then deleted from the geometry. A simulation is then created using a Newtonian laminar flow with density and viscosity values from porcine muscle (ρ=105kg/m^3, μ=1.26Pa·s) [*Note*: ρ=105kg/m^3 is falsely given by Hughes (1998), where a more accurate value is ρ=1060kg/m^3 (Kneubuehl 2011:137). All tabulated C_d resulted from models using ρ=105kg/m^3 but changing this value to 1060 and rerunning the models for a selection of armatures did not change the resulting C_d]. Boundary conditions are set with an inlet velocity at the top of the enclosure and velocity corresponding to the shot with the armature from the experiment, a pressure outlet at the bottom of the enclosure, and slip walls on all sides. Because these simulations are otherwise slow to converge, relax factors are set to Pressure=0.3 and Velocity=0.7. The simulation is set to run 2000+ iterations and Potential Flow Initialization is enabled. The Forces and Moments Coefficients are applied with a Reference Area Value applied from the TCSA obtained in ParaView.

Before creating the mesh, Automatic Boundary Layers is disabled and the following refinements are applied: a region refinement directly around the armature and extending behind it with Maximum Edge Length=0.02 m, Local Element Size applied to the hafted armature with Maximum Edge Length=0.006 m and Inflate Boundary Layers applied to the hafted armature with 20 layers, 0.3 relative thickness, and 20% growth rate. The mesh is then created and checked for problems in the meshing log that could create a problematic or inaccurate simulation. SimScale recommends the following values not be exceeded, although Non-orthogonality for the meshes is consistently 89 due to the boundary layer settings:

- tetAspectRatio: $\ll$ 100
- Non-orthogonality: $\ll$ 75
- tetEdgeRatio: $\ll$ 100
- VolumeRatio: $\ll$ 100

At this stage the simulation can be run until it has fully converged or C_d has stabilized. In the process of designing the CFD analysis in SimScale, simulations were tested on armatures 33 and 136 with varying qualities of the meshed models (different solid accuracy and density settings in MeshMixer), differing boundary layer settings, relax factors, and with and without the attached tube at the back of the model. Each simulation resulted in slightly different values of C_d. Once effective settings were discovered the same settings were applied to all modeled armatures. The most important thing is to ensure a non-problematic mesh, which can create unrealistic C_d values, and to ensure that boundary layers are dense next to the model and expand outward into the computational domain (Hirsch 2007:604).

On two occasions models that did not present noticeable problems in the meshing log provided unrealistic C_d values. When this occurred, pronounced geometries, such as pieces of sinew in the haft area that projected outward and were modeled as atypical projections relative to the other models were removed in Meshmixer, and the simulation ran again, resulting in typical C_d values. Simulations were also performed on armature 33 that extended up to 8,000 iterations until full convergence had been achieved. No marked change occurred in C_d after 2,000 iterations.

The test simulations on armatures 33 and 136 and the simulation runs on the other armatures are accessible to the public on the SimScale website (https://www.simscale.com/users/depe1522/#viewMode=listView&sortBy=null).

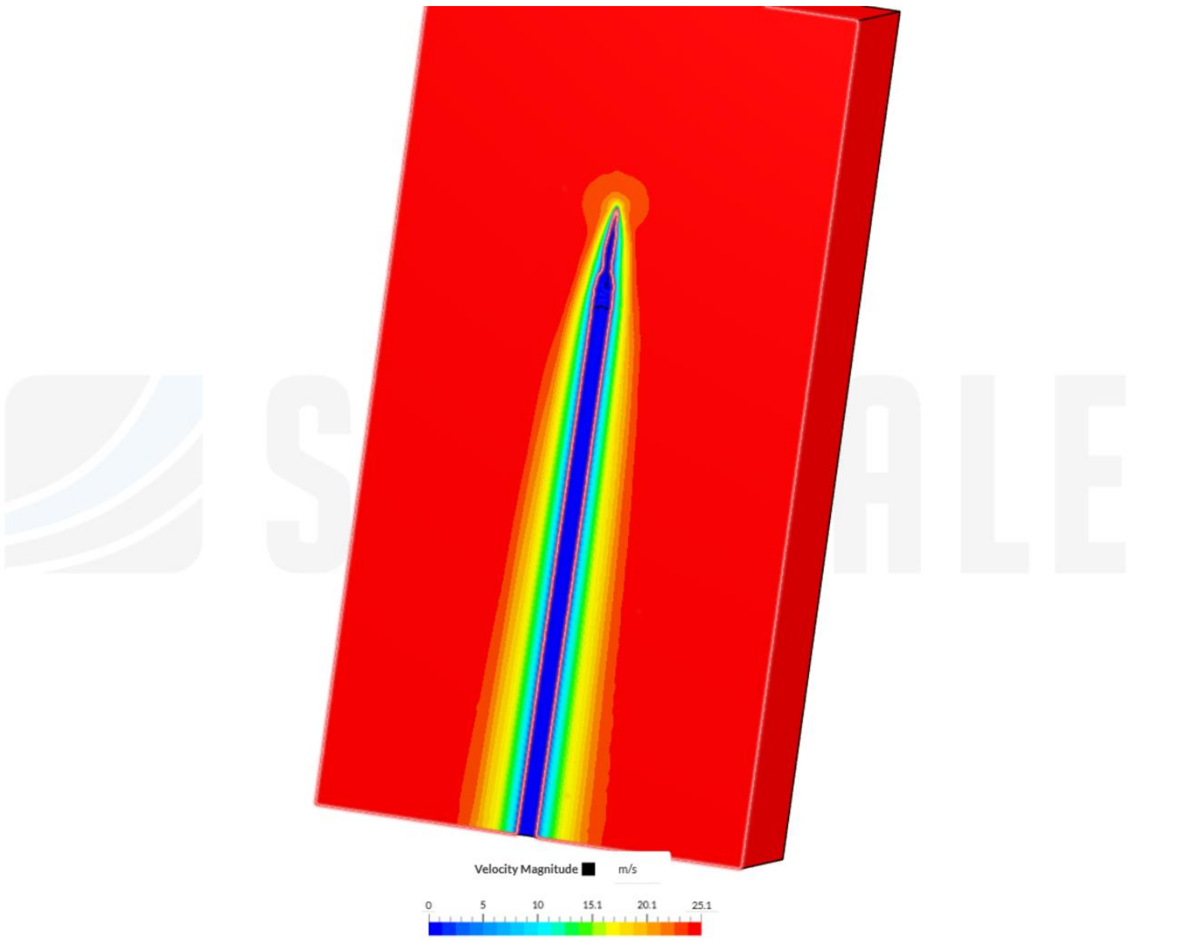

Figure A-8. SimScale output showing velocity of flow around armature 33.

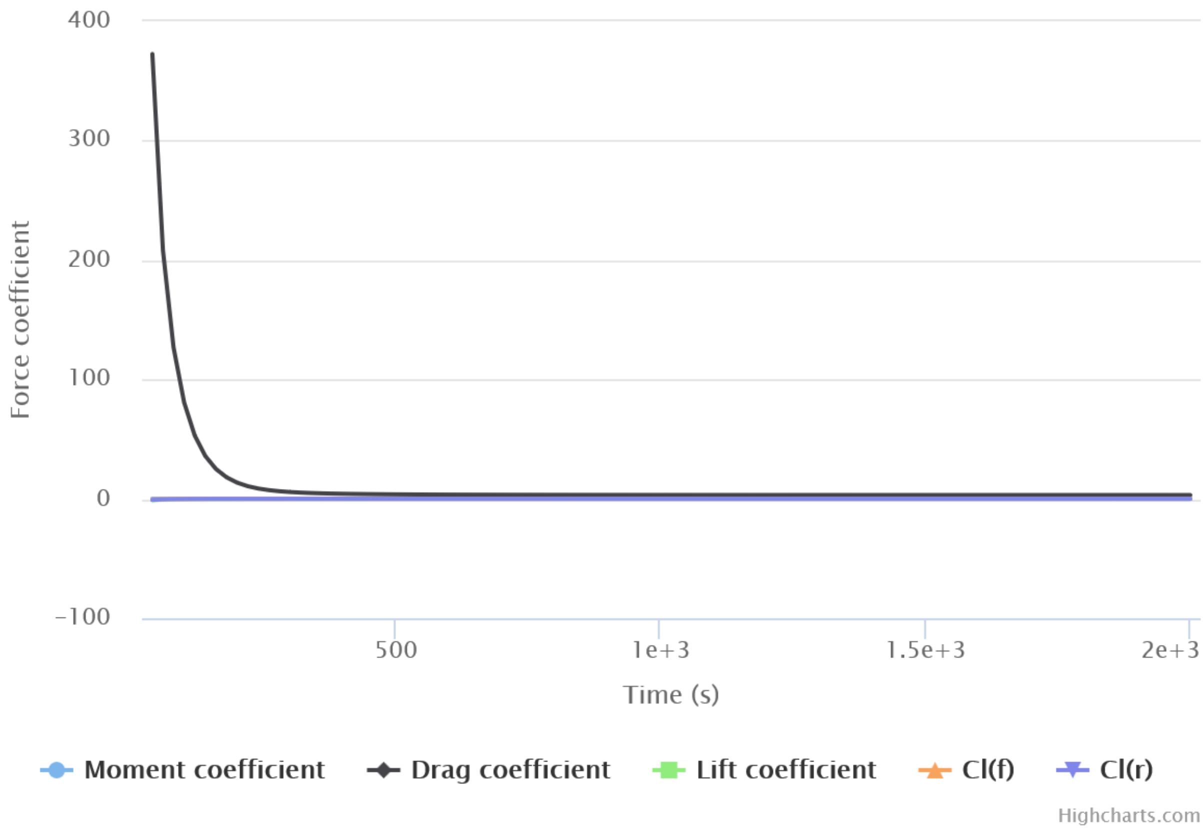

Figure A-9. A typical force coefficients plot, in this case from a simulation of armature 33.

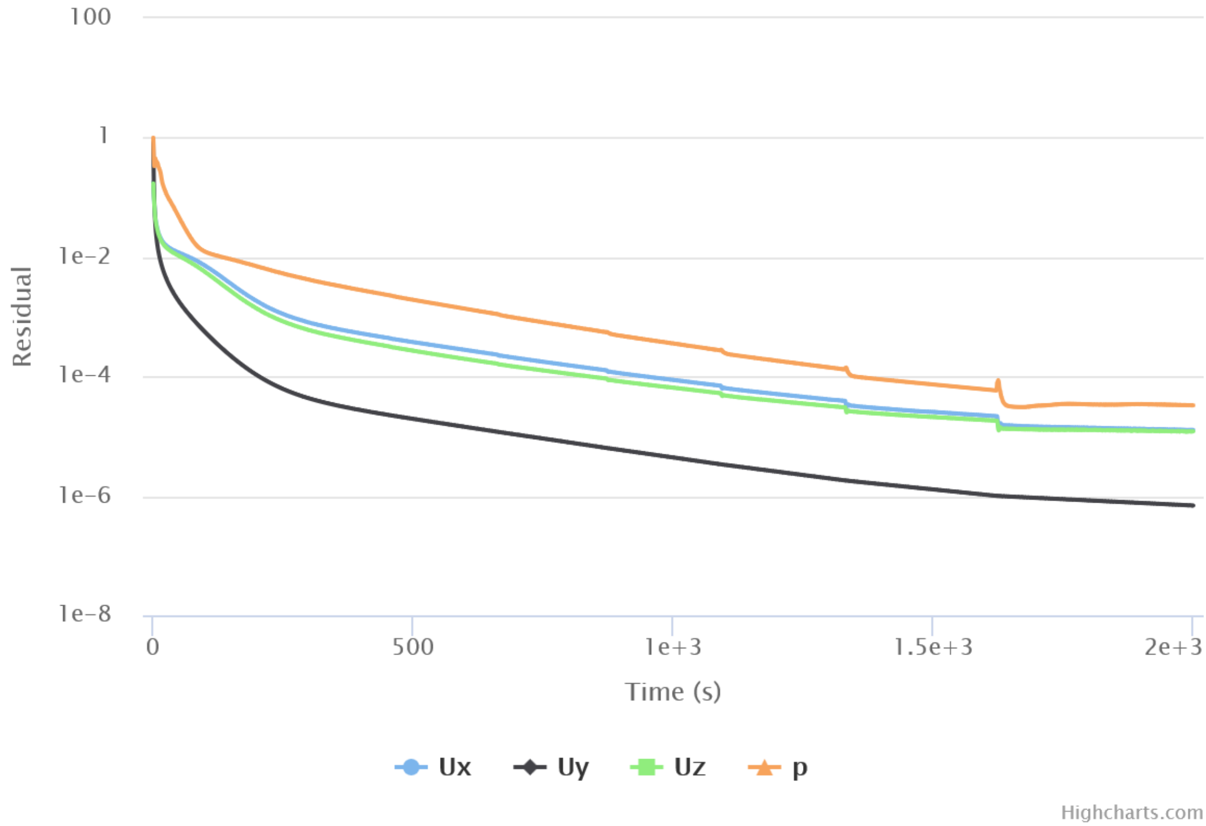

Figure A-10. A typical convergence plot showing the residuals of a simulation run on armature 33. Uy stabilizes past 7k iterations, but Cd does not drop appreciably past 2k iterations.

Appendix B. Chapter 3 Supplementary Materials

Details of the experimental arsenal

The crossbow constructed for this experiment is comprised of a 155 cm long steel prod made by Alchem Incorporated (http://www.alcheminc.com/crossbow.html) lashed to a heavy 4x6 inch oak stock with hemp cord following a method typically used by medieval crossbowmen (Payne-Gallwey 1995:Figure 28). The stock is supported by oak legs in the rear and a car scissor jack in the front for adjustable height. A groove for the bolt was carefully drawn and excavated with chisels and sandpaper. A 1000 lb hand-crank winch was attached at the back of the stock. To the end of the cable an archery trigger was fastened to draw the bow via a “D-loop” attached to the string. Each click of the locking gear on the winch drew the string ~5 mm. The string was made of 30 strands of synthetic Dacron fiber. Although this setup allowed the bow to be drawn to variable lengths along the stock, the D-loop was the weakest component and had to be replaced several times. Polishing the interior of the trigger helped reduce abrasion to the D-loop. At 70 cm the bow pulls 68 kg, although this draw length both over-shoots the necessary ballistics and is hard on components. But the bow can mimic even the heavy atlatl darts used by Frison (1989) against elephant carcasses. Initial tests found a draw length of 55 cm to produce adequate penetration into the gel and a relatively consistent velocity around 28.5 m/s that matched the upper range of typical atlatl dart speeds (Whittaker et al. 2017). This draw length was used throughout the experiment.

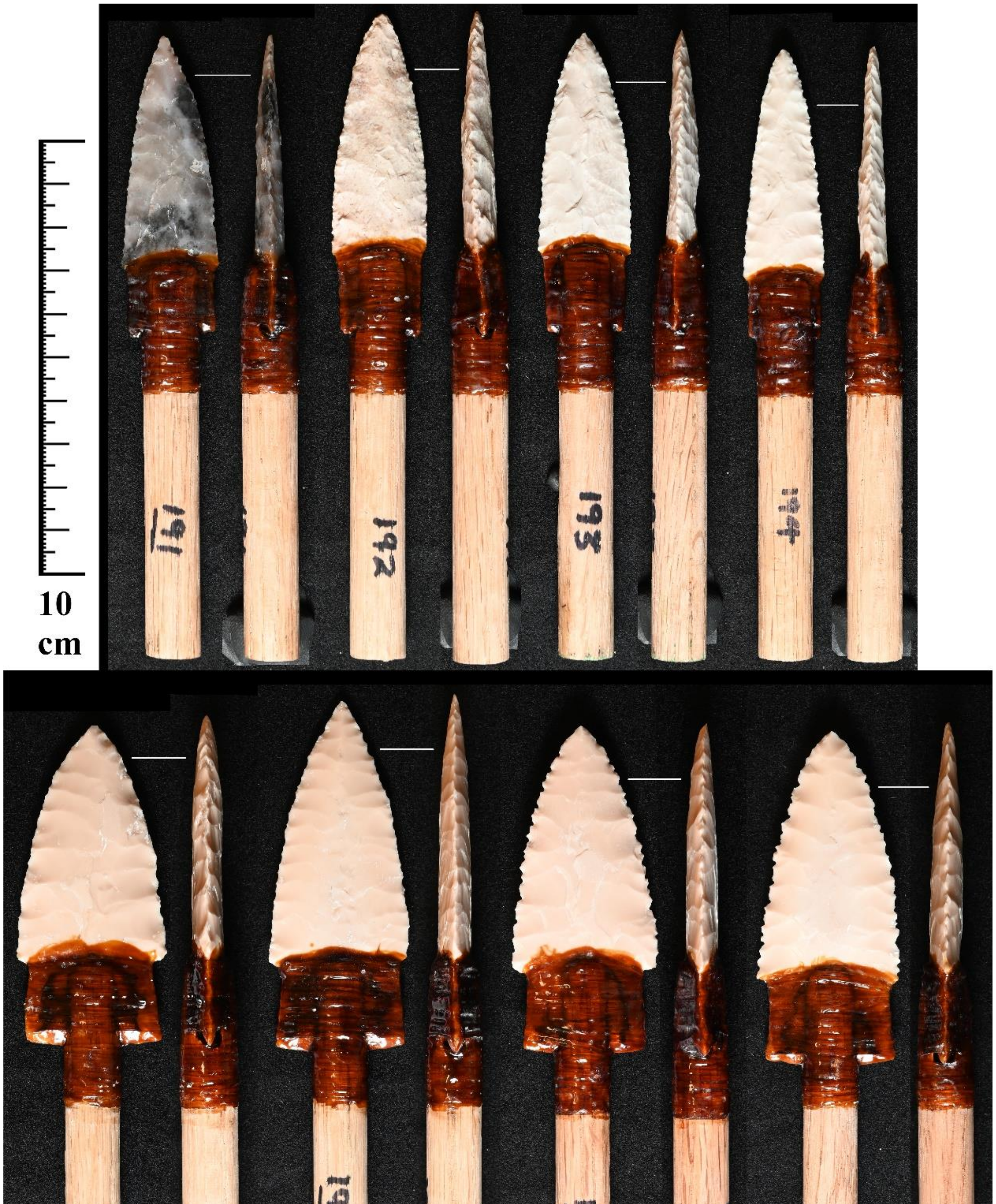

Figure B-1. Brazilian agate (191), Burlington chert (192-194), and glass (197-200) armatures used in the controlled experiments.

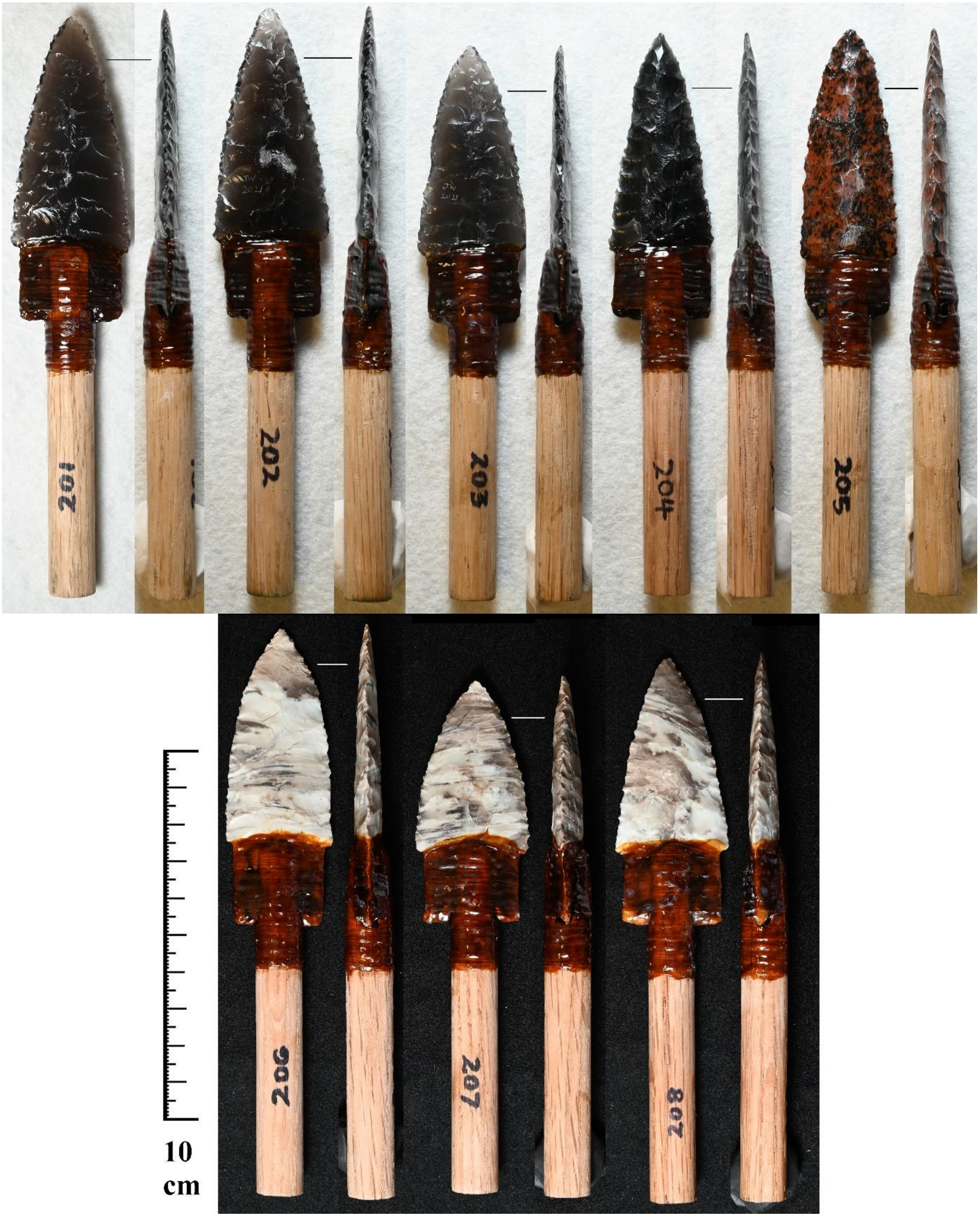

Figure B-2. Obsidian (201-205) and Mozarkite (206-207) armatures used in the controlled experiments.

The bolt was constructed of a 13 mm diameter oak dowel with a slight indention to fit against the string and a 306 mm long brass sleeve of 13 mm inner diameter and 13.4 mm outer diameter, peened to the back of the shaft with a brass pin and projecting 60 mm in front to accept the insertion of foreshafts. The mainshaft weighs 94 g and is 670 mm long. The test armatures included 16 Scotts Bluff points representing five raw material types that were knapped and donated by John Whittaker. An archery field point and two types of steel broadheads with plain and serrated edges (100 grain 2 blade Stinger® Killer Bee and Buzz Cut) were also tested on a tapered foreshaft that held an adapter for screw-in points. The 16 stone and glass projectile points (Figure 3.2; Table 3.1) were hafted into sawn and carved notches in short sections of 13 mm oak dowels with Titebond® Genuine Hide Glue and elk and deer backstrap sinew. Sinew lashings extended for 10 mm below the points and were covered in several layers of shellac to reduce friction and solidify the haft. Shellac is derived from secretions of the lac bug in SE Asia. It is both organic and soluble in alcohol, allowing it to be removed if desired. However, applying shellac in several layers can require several days or even weeks to properly cure. Once the hafts were dry, lead fishing sinkers were glued into holes pre-drilled into the bases of the dowels with hide glue until all foreshafts weighed 30 ± 0.2 g. The foreshafts fit into the sleeve of the mainshaft to the base of the haft.

This arrangement allowed variation in the projectiles to be isolated to the points and hafts. A problem arose in how to apply markings to the brass sleeve that would be visible to the high-speed camera. An expedient method was chosen in which correction fluid (Wite-Out®) was painted over small sections on the brass abraded by scraping with a knife and painted over with reflective paint. The scale was then drawn on with black sharpie and a red dot was added to facilitate tracking a small point in the video analysis. These markings stayed in place until bolts were shot into and extracted from heavy tooling leather, at which point the forward most markings rubbed off, but the rear markings remained viable.

Performing video analysis in Tracker

Clear markings on the mainshaft with small red dots facilitated use of the autotracker function in the Tracker program, which automatically tracks features of the same shape, size and color by way of an evolving template. When the tracked feature is clear, autotracker is highly consistent in placing the markers (Figure 3.3). This makes processing velocity from videos not only much faster but also reduces sampling error. Given the high frame rate (8810.57 frames/sec) many data points are achieved prior to penetration, which can be averaged to get velocity data. These averaged velocity data are highly consistent (mean=28.6 m/s, std dev=0.27 across the formal experiment), demonstrating the accuracy of the video analysis and crossbow setup.

The bigger issue comes with processing acceleration data (or deceleration in this case [-a]). When tracked points are close together, as from high frame rate video, the acceleration readings are highly sensitive to subtle changes in marker placement. This means that a degree of error comes with the acceleration data provided by Tracker that when averaged produces inconsistent and artificially high acceleration. Higher frame rate video can improve acceleration data of dynamic impact events, since more precision can be obtained in tracking the precise timing of an event (bracketing the event), but this requires certainty in the ending velocity, which cannot be averaged from several points if penetration continues. Small and clear markers and good video improve the certainty of the readings and the operation of autotracker. This could be better achieved with even smaller markers and brighter lights than were used in this experiment. High illumination is necessary when filming at high frame rates.

Implementing the experiment: problems and boundary conditions

Prior to the formal experiment, an attempt was made to calibrate the procedures and design, but alterations were required throughout the experiment. The biggest hurdle was finding a way to position the gelatin target. The effects of the inertia of gelatin as a function of the location where the projectile impacts and any surrounding mechanisms to hold it in place are not clearly laid out in reports of previous tests I have come across. A notable example is again provided by Waguespack and colleagues (2009), who's experiment deployed a human torso gelatin mold. No mention is made of the type, manufacture, or condition of the gelatin. In addition, it cannot be ascertained from the article where impacts to the gelatin torso occurred. This seems important for their penetration data given that the torso was not a continuous thickness throughout, being thickest in the chest area, while their arrows shot from a powerful compound bow penetrated entirely through the target. It also seems likely that shots near the bottom of the target would penetrate better than shots near the top where the elastic gelatin has lower inertia. The overall structural dynamics of a target retard the motion of slow moving projectiles like darts and arrows by way of elastic strain acting against the surface (Carlucci and Jacobson 2018). This would seem to be especially true of large and slow-moving darts. In the realistic carcass experiments I discovered that hanging small carcasses like goats reduced penetration of atlatl darts relative to those tied to planks or lying down, which had higher inertia (Pettigrew in press).

Firearms testing frequently proceeds by lying or standing a block of gelatin on a table with no further support. Multiple shots may be fired into a single block depending on its size and the type of projectile (Mabbott et al. 2016). The experiment began by lying the blocks on the stand and shooting the armatures oriented horizontally to the ground. Two or three shots could be stacked vertically to increase the amount of data obtained in one day. But penetration was higher near the bottom where the block was in contact with the stand. The gel was also observed vibrating violently in the high-speed video. A lid of the same wood as the bottom (a 20 mm thick plywood with a bamboo vernier) was attached by hinges to the vertical back board and aligned to rest perfectly on top of the blocks, the idea being to reduce extreme vibrations in the blocks by tying the lid down. But this produced inconsistencies in the amount of pressure applied to the blocks. In addition, one glass armature (197) snapped at the base from the weight of the shaft and vibration of the gel when oriented horizontally and with the lid tied down.

The formal experiment proceeded with the lid simply resting on the block, the armatures oriented vertically in the mainshaft and shot into the center of the block. The raw gel adheres to the boards, so the lid and support boards seem to reduce displacement of the gel from compression parallel with the trajectory of the bolt as the armature penetrates. This arrangement gives consistent results even when shots are taken within 1 cm of each other. Shots >3 cm from the outside of the blocks still suffer from reduced penetration. Because shots only penetrated to the middle of the blocks. The blocks could be turned and shot from both sides with no noticeable difference in penetration. Several times I checked whether shots had intersected prior wound channels on the other side of the block, but I never noticed this occurring.

Both organic collagen-based gelatin and synthetic gelatin change with temperature. Perma-Gel is supposed to be less subject to changes in temperature but the best conditions range between 65º-75º F (Forensics Source 2020). The temperature of the room of the experiment was consistently 76º, however, it took some time before I realized that inconsistencies in penetration resulted from a high internal temperature of the gel blocks. Having been remelted the day prior and allowed to cool overnight, the blocks could still be 100º F on the interior at noon the next day and fall gradually over several hours. I then established the convention of inserting a thermometer into the center and proceeding when the internal temperature dropped to 82º F. After recalibrating shots with each test armature into the uncovered gel, penetration was generally 4-5 mm shallower for the cooler blocks.

Jussila and colleagues (2005) describe the use of thin plastic film (kitchen wrap) to hold skin simulants against the gel. Presumably the film has very little impact on penetration. I attempted this but the setup is rather difficult to maintain with large points that tear holes in the film. Perma-Gel is reusable but it is also sticky and difficult to keep clean. Small pieces of leather adhere to it and the nitrile rubber leaves a black residue that mixes into the gel when remelting. Placing plastic film between the leather and rubber leaves small shreds of plastic in the wound channels. The best method was to place the slick side of the leather and rubber directly against the gel and scrap away as much detritus as possible before remelting. Often these materials stick to the face of the gel with no need for support, but I also used rolled plastic film "cords" at the tops and bottoms when needed. The orientation of the skin simulant and how it interacts with the gel thus changed as the experiment matured. But when comparing shots into 2 mm tooling leather, no noticeable changes in penetration occurred as a result.

I aimed the crossbow by simply sighting down it. At first, I attempted to align the crossbow to measured marks on the floor using a plumb bob, but this did not give the necessary flexibility in moving and aiming the crossbow. Slight deviations of the shaft from being perpendicular to the camera will produce error in calibrating the video, but this was apparently insubstantial. Like Anderson and colleagues (2016) I used a grid (graphing paper glued to a box and aligned with the tile marks in front of the target) to check for distortion in the camera lens, but I never noticed distortion or moved the camera as a result. Some degree of error is expected in velocity measurement with any device (e.g. Eren, Romans, et al. 2020; Whittaker et al. 2017), but velocity measurements in this experiment were highly consistent (often ±0.1 m/s between sequential shots). Some of this error can be explained by changes in precise draw length, since the act of winding the steel cable onto the winch produced slight differences each time the bow was drawn to the 55 cm mark.

Finally, error occurred from the method of measurement. Depth in firearm testing in gelatin can be measured by inserting thin rods or vernier calibers into the channel (Cronin and Falzon 2011; Mabbott 2015), or from slow motion video when the shot channel is visible and an accurate scale can be applied. Placing electric tape against the face of the target becomes challenging when thick leather or rubber turns outward away from the gel face due to displacement from the shaft. The placement of the tape was estimated as closely as possible in these cases and penetration depths were often consistent to within one or two mm.

Errors resulting from the peculiarities of an experiment are not unexpected. Some degree of error will occur during any experiment. The most substantial error I noticed appeared to be a result of the viscoelasticity of the gelatin and its interaction with the stand. While processing the data, error also occurred due to inconsistencies in precise marker placement for acceleration readings in Tracker. This is the likely cause of much of the variability in acceleration readings for the same armatures presented below.

Additional notes about errors and boundary conditions

- Tight tolerances: Penetration from uncovered to covered gelatin means that error from preconditions has stronger potential to affect the results
- The camera was simply set on a box and pile of books! Part way through the experiment I noticed it was not perfectly level.

- Slight discrepancies in the position of the bolt with the scale to the camera lens (not being perfectly orthogonal) can affect the calibration of the video, and this can vary slightly from shot to shot. I tested the impact of this by moving the scale in Tracker to the outer edges of the white markings, a real-world distance of 3mm in both directions. Doing so changed the reading from 29-26 m/s. The shaft would need to be significantly skewed to be 6 mm smaller or larger, so small inaccuracies in the orientation of the shaft probably don't have a big impact.
- Crossbow winch variability: As the crossbow was fired and vibrated it occasionally began shooting lower. Every few shots the level needed to be checked. The impact of some shots being lower than center was not dramatic.
- Occasionally the skin simulant came away from the gelatin slightly and deceleration starts when the armature has to first press the simulant into the gel. This did seem to have an impact on deceleration.
- The crossbow shoots slightly to the right, I had to learn how to properly aim it, and this problematizes aligning the crossbow by tile lines on the floor with a plumb bob anyway! I think this was caused by the knots of the D-loop.
- Residue was occasionally left on the brass shaft by the electrical tape, which I merely rubbed off with my fingers
- Loose foreshafts: This became a substantial issue. If foreshafts were too tight in the sleeve I scraped them with my pocketknife or sanded them to fit. IF they were too loose they would remain in the gel and had to be extracted with pliers. IF they were very loose the mainshaft could bounce out of the wound channel slightly during vibration of the gel. I established the convention of pressing the mainshaft in to ensure it had not bounced out

any. I also tried to tighten loose foreshafts in the sleeve by applying layers of hide glue to the wood. The foreshafts with larger armatures had to be very snug in the sleeve to ensure they would come out with the mainshaft when it was extracted.

- Measurement errors and aiming errors necessitated reshooting of armatures. Occasionally I was too hasty taking shots and hit too close to another shot, or even forgot to measure. This increased the duration of the experiment and necessitated more shots of some armatures into a simulant.
- More powerful lights are definitely needed to produce clearer frames for measurement and point tracking.

Figure B-3. Showing the layout of the experiment.

Figure B-4. Setting the electrical tape marker to record penetration depth from a shot through 3 mm tooling leather.

Appendix C. Chapter 4 Supplementary Materials

Table C-1. Past archaeological research in ancient weapon terminal ballistics.

Author	Year	Type	Mode	ModeQualif	Target	TargQualif	Armature	ArmQualif	Arm *N*	Distance	Goals	Goals qualif.
Ahler	1971	R	javelin		ground, vegetation		lithic		5		use-wear	
Albarello	1986	R	bow	wood holmegard	organic composite	bone, meat, hide	lithic	transverse arrows	33	3-6 m	use-wear	DIFs, microwear
Anderson	2010	C	gravity		gel		synthetic	plastic casts	11		performance	penetration
Arndt & Newcomer	1986	R	bow	49 lb glass	carcass, organic composite	fresh ewe, and lamb shoulder-scapulae-pelvis composite	osseous	bone and antler	20	5-7 m	use-wear	DIFs
Barton & Bergman	1982	R	bow		carcass	suspended deer	lithic	microliths		4-8 m	performance, use-wear	DIFs
Bebber & Eren	2018	C	crossbow	mounted 29lb compound	clay		lithic, metal	copper and chert arrows	20	2.75 m	performance	penetration
Bebber et al.	2020	C	crossbow	mounted 29lb compound	clay, wood	birch boards	ceramic, lithic	knapped vs fired clay arrows	105	2.75 m	performance	penetration, durability
Bergman & Newcomer	1983	R	bow	48lb osage	organic composite	bone, meat	lithic	Ksar Akil, retouched blades	26	3-15 ft	use-wear	DIFs
Bergman	1987	R	bow	40lb Mesolithic	organic composite	bone, meat	osseous	Ksar Akil bone and antler points	?	5-8, 15 m	performance	durability, hafting
Binneman	1994	R	bow	bushman	carcass	calf	lithic	transverse arrows			performance	penetration
Brindley & Clarkson	2015	C	crossbow	mounted 45lb compound	carcass	skinned, suspended lamb	lithic	Wardaman points	40	5 m	use-wear	DIFs
Browne	1940	R	atlatl, bow	wood bow	carcass, wood	elk (hunted with bow) & boards	lithic, metal			30 yds	performance	penetration, accuracy
Buc	2011	R	bow	glass recurve	fish, meat		osseous			8-12 m	use-wear	microwear
Butler	1980	R	atlatl		carcass	elephant (not fresh)	wood	pine	2	3-4 m	performance	penetration
Callahan	1994	R	atlatl		carcass	elephant (not fresh)	lithic	Clovis	52	10-15 yds	performance	hafting
Carrère & Lepetz	1988	C	crossbow		foam, gel, rawhide		osseous		?	?	performance	penetration
Caspar & De Bie	1996	R	bow		carcass	?	lithic	blades	?	?	use-wear	DIFs

Castel	2008	R&C	bow, crossbow		carcass	suspended cow & horses (not fresh)	lithic, osseous	various	?	?		
Cattelain & Peppere	1994	R	atlatl, bow	wood holmegard	carcass	suspended goats	lithic, osseous	Gravettian backed points	100	10 m	performance, use-wear	penetration, macrowear
Chaptal & Plison	1989	R	atlatl, bow	50lb yew	carcass	goat	lithic	notched	?	?	skeletal lesions, use-wear	
Cheshier & Kelly	2006	R	bow	32lb hickory	bone, hide, meat	suspended gutted deer	lithic	obsidian side-notched arrow pts	50		use-wear	durability, DIFs
Churchill et al.	2009	C	crossbow		bone, hide, meat	2 dressed juvenile pigs	lithic	Mousterian & Levallois		<1 m	skeletal lesions	
Clarkson	2016	R&C	atlatl, bow, crossbow, javelin, lance		gel, meat, bone	beef ribs	lithic	various	154	5 m	performance, use-wear	TCSA/TCSP & DIFs
Coppe	2020	R	atlatl, bow, javelin, lance		gel organic composite, pendulum	complete skeleton set in ballistics gel	lithic				performance, skeletal lesions, use-wear	kinetic energy
Cox and Smith	1989	R	bow	45 & 15lb compounds	carcass, hide	fresh deer and stack of 10 deer hides	lithic	Perdiz arrow points	21	3 m	performance	penetration, durability
Crombé et al.	2001	R	bow	60lb walnut	carcass	sheep	lithic	Mesolithic microliths	184	20 m	use-wear	DIFs & microwear
Duches et al.	2016	R	bow	60lb yew & 40lb ash	carcass	4 sheep and 1 goat, suspended	lithic	microliths	160	10-13 m	skeletal lesions	
Eren et al.	2020	C	crossbow	mounted 29lb compound	clay		lithic	ground Clovis	7	1.8	performance	penetration
Eren et al.	2021	C	crossbow	mounted 29lb compound	wood	oak boards	lithic	ground Cloivis	7	2	performance	durability
Fischer et al.	1984	R	bow, javelin	50lb glass	carcass, ground, meat, vegetation	suspended boar, sheep, pike	lithic	N. EU transvers arrows and Brommian points	153	?	use-wear	DIFs & microwear
Flenniken	1985	R	javelin		carcass	sheep (live)	lithic				reworked morphology	
Flenniken & Raymond	1986	R	atlatl		ground, vegetation	trees and thick brush	lithic	Elko points	30	12 m	reworked morphology	
Forsom & Smith	2017	R	bow	wood	bone		metal				skeletal lesions	
Frison	1989	R	atlatl		carcass	elephants (culled)	lithic	Clovis		17 m	performance	penetration
Frison & Ziemens	1980	R	lance		carcass	elk	osseous	Clovis	1	0	performance	
Gaillard et al.	2016	C	crossbow	mounted wood bow	gel, carcass	boar shoulder	lithic	microliths	?	?	performance	hafting, penetration
Geneste & Hughes, Geneste & Plisson	1990, 1993	R&C	atlatl, bow, crossbow	45-55lb yew	carcass	suspended goats	lithic	Solutrean		~18 m	use-wear	DIFs & microwear

Goldstein & Schaffer	2017	R	bow	40 and 60lb	org/synth composite	pig ribs, cow hide and gel	lithic	obsidian microliths	128	13 m	use-wear	DIFs
Guthrie	1983	C	bow	compound	carcass	moose (350kg)	osseous, wood	various antler, bone, hardwood		5 m	performance	
Huckell	1982	R	lance		carcass	elephant (not fresh)	lithic	Clovis	9	0	performance	penetration
Hunzicker	2008	C	crossbow		bone, hide, meat	bovine rib cage	lithic	Folsom	25	15 m	performance	hafting
Hutchings	1998	C	crossbow		organic composite, stone	layers of bovine ribs	lithic		115	~3.5 m	use-wear	fracture velocity
Ikäheimo et al.	2004	R	bow	40lb elm	carcass	suspended reindeer	lithic, osseous, metal		10		performance	penetration
Iovita et al.	2014	C	other	air gun	org/synth composite	leather over plastic bone-like plates in gel	lithic	soda glass Levallois	234	<1 m	use-wear	DIFs
Iovita et al.	2016	C	other	air gun, swinging device	org/synth composite	leather over plastic bone-like plates in gel	lithic	soda glass Levallois	277	<1 m	use-wear	DIFs
Jardon Giner et al.	2015	R	bow	34lb glass, 40 & 50lb wood	carcass	suspended boar, roe deer, goat (not fresh)	lithic	Mesolithic microliths		3, 6, 10 m	use-wear	DIFs, hafting, microwear
Kelterborn	1999	R	bow	48 lb yew	gravel	controlled target boxes	lithic	Horgen triangular arrows	44	4 m	performance	hafting, durability, reworking
Key et al.	2018	C	crossbow	mounted 29lb compound	meat, clay		lithic	ground Clovis	1	3.5 m	performance	target comparison
Knecht	1991, 1993	C	crossbow		carcass	suspended goats	osseous			?	use-wear	
Lafayette & Smith	2012	R	javelin	pine dowel	carcass	suspended deer	lithic	Great Basin stemmed	18	2 m	use-wear	DIFs
Lenzi	2015	R	atlatl		water, wood	skipping experiment	lithic	Great Basin crescents and stemmed				
Letourneux and Pétillon	2008	R	atlatl, bow	61.5lb yew	carcass	suspended fallow deer and ox calves	osseous	various Magdalenian	90	10-13 m	skeletal lesions	
Loendorf et al.	2017	C	crossbow		foam, gel, raw hide		lithic	SW arrow points, side, corner notched, and serrated	72	2.3 m	performance	hafting, serrations
Loendorf et al.	2018	C	crossbow		foam, gel, raw hide, bone	bovine scapulae in gel	lithic	SW arrow points, 4 different materials	58	2.3 m	performance	material testing
Loendorf et al.	2019	C	crossbow		foam, gel, raw hide, bone	bovine scapulae in gel	lithic	SW arrow points, reworked from previous exp.	52	2.3 m	performance, reworked morphology	
Loi & Brizzi	2011	R	bow	45-79lb	carcass	fresh wild boar	lithic	small obsidian arrows	?	20 m, close	use-wear	DIFs

Lombard and Pargeter (& Pargeter 2007)	2008	C	other	large mounted sling shot	carcass	suspended impala, cold, organs removed	lithic	Howieson Poort MSA	33	4 m	performance	hafting position
Lombard et al.	2004	R	javelin, lance		hide, wood, bone, meat	wildebeest quarter against log	lithic	S. Africa MSA	47	0-4 m	use-wear	DIFs, residue distribution
Lowe et al.	2019	C	crossbow	mounted 29lb compound	wood	plywood	lithic	ground, percussion & pressure flaked	120	2.75	performance	durability
Lowrey	1999	C	crossbow	mounted 50lb bamboo	armor	hide, rod, slate	lithic, osseous, metal	mostly ground arrow points	28	~1 m	performance	penetration
Lundstrom	2019	R	lance		hide, meat	pork belly	lithic	spearheads	6	N/A	residue analysis	
Maguire et al.	2021	C	crossbow	mounted 29lb compound	wood	birch boards	lithic	triangular obsidian points varying in size	30	2.75	performance	durability
McBryde	1985	R	javelin		ground, vegetation		lithic	backed bladelets	?	?	use-wear	DIFs
Mika et al.	2020	C	crossbow	mounted 29lb compound	clay		lithic	triangular arrow tips		2.75 m	performance	penetration
Moss & Newcomer	1982	R	bow	45lb osage	meat, bone, ground, tree	meat and scapula inside box	lithic	backed bladelets		<5 m	use-wear	microwear
Morel	1991, 1993, 2000	R&C	atlatl, bow, crossbow		carcass	4 goats	lithic, osseous	Solutrean			skeletal lesions	
Mullen et al.	2021	C	crossbow	mounted 29lb compound	clay		metal	bi & trilobed bronze arrows	4	2.75 m	performance	penetration
Nuzhnyy	1990	R	bow	40lb	carcass, bone, wood	3-4 month calf	lithic	microliths		8-10 m	use-wear	DIFs
Nuzhnyy	1998	R	bow		carcass	2 fresh wild boars	osseous	Aurignacian split base points	3	?	performance	hafting, durability
Odell and Cowan	1986	R	bow, javelin	45lb	carcass	dogs dispatched by vet	lithic	various bifaces and unmod. flakes	80	4-12 m	performance, use-wear	DIFs, durability
O'Driscoll and Thompson	2014, 2018	C	crossbow	mounted 48lb compound	bone, meat	skinned and gutted lamb	lithic	Levallois and Howieson Poort	40	9 & 1.4 m	skeletal lesions	
O'Farrell	2004	C	crossbow		carcass	bovine	lithic	Gravettian backed points	51	9 m	?	
Osipowicz and Norwood	2017	R	bow	19kg	organic composite	bone, meat, hide, straw	lithic	various arrows	122	10-15 m	use-wear	
Pargeter et al.	2016	R	bow, lance		bone, meat	pork ribs, foam	lithic	quartz backed microliths	150	?	use-wear	DIFs
Petillon & Letourneux	2003	R	atlatl, bow	yew	carcass	suspended fallow deer and ox calves	osseous	various Magdalenian	42	10-13 m	use-wear, skeletal lesions	

Pétillon	2005	R	atlatl, bow	yew	carcass	2 euthanized calves	osseous			12-13 m	use-wear	DIFs
Pétillon et al.	2011	R	atlatl		carcass	suspended young reindeer, rocky ground	lithic, osseous	composite osseous core and microliths				
Pettigrew (& Pettigrew et al.)	2015	R	atlatl, bow	40lb locust	carcass	220 lb hog	lithic	various types	29	12 m	performance, use-wear, skeletal lesions	penetration, rotation, DIFs, microwear
Plisson et al.	1998	R	lance		carcass	young chamois	lithic	Levallois	12	0	?	
Pokines	1998	R	javelin		hide, meat, bone	half goat against soil mound	osseous	Canabrian spear points	20	3-5 m	performance	
Pokines & Krupa	1997	R	lance, javelin		carcass, hide, meat, bone	5lb buffalofish, and half goat	osseous	elk antler harpoon tips	5	0-5 m	performance	
Pope	1923	R	bow	various	parafin		various	blunt, steel lance, stone, cartridge		10-50 yds	performance	penetration
Rots	2016	R	bow, javelin, lance	35-60lb wood	carcass	fresh suspended deer & sheep	lithic	Levallois, composite tip and barb arrows	215	0-20 m	performance, use-wear	Hafting, microwear
Rots Plisson	2014	C	crossbow		carcass	bovine	lithic					
Rozoy	1992	R	atlatl		ground, rocks		osseous	sagaies of several type	8000	variable	performance	
Salem & Churchill	2016	C	crossbow	60lb	gel		lithic, wood	flakes and souverneirs	7	5 m	performance	wound size
Sano & Oba	2012, 2015	R&C	crossbow, lance		bone, gel, hide, wood		lithic	Japan UP backed points	40	0-1.5 m	use-wear	DIFs
Schoville et al. (& Schoville & Brown 2010)	2017	C	crossbow		carcass, gel	3 culled springboks	lithic	Howieson Poort MSA	117		Performance, use-wear	Penetration, DIFs
Shea et al.	2001	C	crossbow		carcass	2 suspended goats	lithic	Levallois	54		use-wear	
Sisk & Shea	2009	C	bow	40lb, drawn consistently	org/synth composite	leather+foam / goat hide+rack of ribs	lithic	Levallois	51	4 m	performance	penetration
Smallwood et al. 2020	2020	R	atlatl		carcass	75 lb pig	lithic	Dalton	10	?	use-wear	microwear
Smith	2003	R	javelin, lance	Schöningen & Lehringen	carcass	2 15kg lambs against straw bales	wood	self pointed yew spears		6 m	skeletal lesions	
Smith et al.	2007	R&C	bow, other	impact machine, yew bow	bone	ribs and scapula, some flesh remaining	lithic	various arrows		0-5 m	skeletal lesions	
Smith et al.	2020	R	javelin, lance		carcass	2 fresh wild pigs, gutted, stuffed, suspended	lithic	obsidian & soda glass Levallois	?	8-10 m	skeletal lesions	

Snyder	2017	C	crossbow		org/synth composite	weathered elk ribs in gel with 1.5mm leather	lithic	Clovis, Folsom, Midland	33	5 m	performance, use-wear	durability, hafting, penetration
Soriano	1998	R	bow	28-45lb longbow	meat, hide and bone	suspended gutted sheep and boar	lithic	Gravettian backed points		13 m	use-wear	DIFs
Stodiek	1990, 1993, 2000	C	crossbow		meat, hide and bone	suspended gutted deer	lithic, osseous	various types	~45	15 m	performance, use-wear, skeletal lesions	Hafting, DIFs, penetration
Titmus & Wood	1986	R	atlatl		dirt, sand, gravel, wood		lithic	Elko points	39		performance, use-wear	DIFs, durability
Towner & Warburton	1990	R	atlatl		wood	dead pine tree	lithic	Elko points	29		reworked morphology	
Tyzzer	1936	R	bow	45lb ironwood	loam, gravel, rocks, wood		osseous		9?	8-40 yds	performance	durability
Waguespack et al.	2009	C	crossbow	mounted 60lb compound	gel, hide		lithic, wood	self pointed and small corner notch arrows		1.1 m	performance	penetration
Weitzel et al	2014	R	atlatl, javelin		carcass	suspended sheep	lithic	Fishtail projectile points	22	?	use-wear	
Werner et al.	2019	C	crossbow	mounted 29lb compound	clay blocks, moose antler		lithic	ground lanceolate, half retouched at base	60	3.4 m	performance	hafting
Wilkins et al.	2012	C	crossbow		carcass	2 suspended springboks	lithic	Levallois	32		use-wear	DIFs
Wilkins et al.	2014	R&C	crossbow		gel		lithic, wood	Levallois and self-tipped javelins	5	<1 m	performance	penetration
Wilson et al.	2021	R	bow	45lb glass recurve	foam	construction foam with vinyl cover	lithic	Arrows hafted with 3 adhesives	30		performance	hafting
Wood & Fitzhugh	2018	R	bow	18kg maple recurve	carcass, gel	suspended reindeer	lithic, osseous	osseous, knapped, and composite	30	5 m	performance	penetration
Yaroshevich et al.	2010, 2012	R	bow	17.5kg glass	carcass, meat, bone, cardboard	goat, skinned sheep thorax	lithic	composite microlith arrows	265	13-8 m	performance, use-wear, skeletal lesions	DIFs, microwear