Origins and Comparative Performance of the Composite Bow

by

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I declare that *Origins and Comparative Performance of the Composite Bow* is my own work and that all the sources used or quoted have been indicated and acknowledged by means of complete references.

SIGNATURE
(Mr)

January 10, 2016
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SUMMARY

This thesis shall identify the date origin of the composite bow within Mesopotamia and Elam. and both identify and quantify the design factors which lead to increased performance possible with composite construction. To accomplish this, the thesis begins by summarizing the problems and flaws that currently exist in the field of history as it applies specifically to archery and bow use. With problems identified, the thesis will then introduce the reader to the basics of bow mechanics, thereby laying the basis for physical testing. This in turn will empirically demonstrate flaws in the current iconographical method of bow identification. The thesis will then devise a new method for iconographic identification of composite construction that has greater proven accuracy, based upon proportional length, which will link extant artifacts with both physical test results and iconographic evidence.

The reader shall then be led through a complete reevaluation of iconographical evidence for Mesopotamia and Elam starting at the beginning of the second millennium BCE and working backwards using this new method of iconographic evaluation to determine the point at which composite bow technology first appears in the ancient Near East. The thesis will finish with an overview of the above accomplishments and their potential impact on the study of ancient and military history.

KEY TERMS

Ancient History, Military History, Archery, Bow, Composite, Experimental Archaeology, Egypt, Mesopotamia, Elam, Arrow

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[*] Unpublished photo taken by the author or one of the author's assistants during the course of research.

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* Unpublished photo taken by the author or one of the author's assistants during the course of research.

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ABBREVIATIONS

ANE	Chavalas, Mark W. *The Ancient Near East: Historical Sources in Translation* (Oxford: Blackwell Publishing, 2006)
ARM	*Archives Royale de Mari* (Paris: Imprimerie Nationale, 1950 ff.), cited by volume number and text number (e.g. 1.10 = volume 1, text 10)
CAG	Smith, George. *The Chaldean Account of Genesis* (New York: Scribner, Armstrong & Co., 1876)
PI	Cooper, Jerold S. *Presargonic Inscriptions* (New Haven: The American Oriental Society, 1986)
QT	Decker, W. Quellentexte zu Sport und Körperkultur im alten Ägypten (St. Augustin: Verlag Hanz Richarz, 1975)
RA2	Grayson, A. Kirk. *Royal Inscriptions of Mesopotamia, Assyrian Periods, Vol. 2: Assyrian Rulers of the Early First Millennium BC I (1114-859 BC)* (Toronto: University of Toronto Press, 1991)
R4	Frayne, Douglas. *Royal Inscriptions of Mesopotamia, Early Periods, Vol 4: Old Babylonian Period (2003-1595 B.C.)* (Toronto: Toronto University Press, 1990).

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Special thanks go to Jason Moore, whose welding skills were invaluable for completing the chariot build. Jason was also kind enough to help with physical testing, along with Alenza Xinnia and Kirana Wiryawan. The three of you spent many hours in both sun and cold on behalf of this project, and you have my thanks. The examiners also deserve thanks for their comments, which were invaluable in shaping the thesis into its current form. The entire project would have taken a significantly greater amount of time were it not for my former department supervisor Chul-Gyu Kim who was kind enough to grant a certain degree of flexibility with regard to scheduling my teaching load. Finally, thanks of course go to the Kyungsung University Library for the acquisition of a number of works necessary for me to complete the thesis.

PREFACE

Inspiration for this project first began in a class on warfare in the ancient world with Professor Dorothy Slane as a part of the author’s Master's studies at American Military University. During a discussion on the benefits of composite bow technology, range estimates, the relative merits of a shorter weapon and reasons for range increase flew thick and fast. While all of these claims came from reputable sources, many contradicted each other and almost none tied back to any kind of hard physical proof. Even agreeing on the most basic ideas was very difficult as a number of my fellow students used differing terminology, making consensus on any given point incredibly difficult.

As a student not only of ancient history, but an (albeit rather poor) amateur archer and bowyer I came to realize that a great deal of misinformation existed within this rather narrow field. While I certainly did not have all the answers, I decided that I could certainly resolve some of the confusion and wrote a paper on relative range comparison for the final research paper. Although the project was immensely satisfying the final comment by Professor Slane during the initial class discussion that "the composite bow cannot be reliably dated to earlier than the start of the second millennium BCE" continued to nag at me even after I finished graduate school. After all, I reasoned, the process of mixing materials to create a bow hardly required a highly stratified society or knowledge of metals technology. If it did, the composite bow would perhaps not have developed in North America prior to European contact.

After extensive reading I found that the current method of evaluating the construction method of a bow depicted in ancient artwork, which thus far has almost exclusively been based upon an examination of bow profile, was deeply, inherently flawed. Further investigation identified several artifacts from different periods and locations in history that clearly showed that the stereotypical "cupid" shaped bow could (and historically had) been produced using a variety of different construction techniques. Yet more artifacts proved that the reverse was also true, and that composite construction indeed could (and did) take on a variety of different profile shapes, and that the existing method of evaluation was based upon ethnocentric preconceptions of what a composite bow "should" look like based upon the standard found in Greek vase paintings. While this added a great deal of clarity by permitting unbridled skepticism with regard to more or less all existing iconographic arguments, it also meant that to be able to accurately evaluate ancient artwork (necessary due to the relative scarcity of artifact evidence), I would first need to design an entirely new method of iconographic evaluation.

To design a new, more accurate paradigm for iconographic evaluation of bows however, I first needed to have a much better understanding of how bows worked over and above the insights gained as both an archer and a bowyer. In short, in order to be able to evaluate the “when,” I first needed to have a firm grasp of the “how much” in terms of the comparative performance differential between bows of composite and non-composite construction as well as why this differential existed. The majority of the existing literature however only tended to confuse the issue, as it either was contradictory or failed to cite any source material. Figures quoted in history texts often matched world records for distance archery, but were (presumably) derived independently without citations to the latter. Modern texts on bow-making using traditional materials and methods contradicted both of the above, but matched historical performance comparisons from the Middle Ages. A complete survey revealed that performance potential estimates varied so widely that they were essentially useless.

At first it was difficult to believe the level of discrepancy. The lack of consensus was surprising given that archery maintains a level of popularity even in the modern day. While the number of bowyers working in traditional materials is relatively small, I had believed that more than enough data would have been available for a more reliable estimate of comparable range.

Attempts to pin down reasons for increased performance were even worse. Some sources claimed that composite bows were "difficult to use," that composite bows had inherently higher draw weights, or that composite bows had a higher rate of fire. All of the above were posited by respected historians, and yet I knew from personal experience that all of them were categorically incorrect.

Other sources said that materials strength was key to increased performance, but only when material mass was not taken into consideration. Bow reflex was claimed by different sources, but according to mathematical modeling was only beneficial to a limited extent. Bow mass and string mass were also variously hailed as the answer, and if not mass then certainly bow length, which even if it didn't help bow performance was surely key to the adoption of the chariot as a mobile-archery platform. Through it all ran the singular recurring theme that composite construction did indeed yield (some highly variable degree) of increased performance.

It was clear that part of the reason why range estimates varied to the degree they did was that there was no consensus of and in general a limited understanding among historians as to how bows actually worked. The formation of well-designed testing, at least with regard to the question of comparative performance between composite and non-composite construction, is however in large part predicated on a working knowledge of how bows function. Without this foundation, the question of both performance and dating would remain in the realm of speculation.

It was at this point that it became clear that if I was to ever pin down the "how much" and "why" of comparative performance (both of which were necessary precursors to a determination of “when”), I would need to conduct my own theoretical modeling and physical testing. In short, to get my answers, I would need to shoot a lot of arrows from a lot of bows, and probably make several bows as well. By this time it was also more than evident that the amount of research involved and results thereof were more than enough to justify several journal articles and that the combined effort could act as a foundational work within the field and was perhaps worthy of a doctoral thesis. Thankfully, Doctor Martine De Marre at the department of Classical Studies and the evaluation committee at the University of South Africa agreed.

Given the amount of preliminary work that was needed with regards to both bow performance and evaluation before a more accurate date of usage of the composite bow in the ancient Near East was even possible, the thesis very much progresses in a sequential fashion, with each section building progressively upon the findings of earlier chapters. As this process includes large sections of both theoretical modeling and physical testing (and interpretation of how those results apply to artifact and iconographic evidence), the work is to a large extent data-driven and encompasses experimental archaeology, engineering, and physics as much as it does history. In large part because of this data-driven approach, the vast majority of the conclusions presented herein, particularly with regard to bow performance (and comparative performance between differing construction methods) can be applied to bow artifacts from any time period irrespective of culture. As the results and conclusions for these sections of the thesis are more generalized, they occasionally draw upon source material not pertaining to the ancient Near East including classical Greece and Rome, medieval Europe and Turkey, and both pre and post-contact North America.

The final goal of the thesis, focusing as it does on composite bow use in Mesopotamia and Elam in the third and fourth millennia BCE, then in essence represents the practical application of results gained from earlier chapters, an effort that can potentially be applied to other periods and cultures by others in the future. The revised iconographic analysis and conclusions show not only that the composite bow was fully integrated into Mesopotamian and Elamite artwork by 3000 BCE, but that this integration was preceded by a transitional period that lasted somewhere between three and ten centuries. Furthermore, the results do not stand alone, but are supported not only by both theoretical modeling and physical testing but also by ancient and medieval artifacts in a system of mutually supportive evidence.

CHAPTER ONE

INTRODUCTION

Few innovations were more important to early man than the bow. Constituting a major advance in technology, the use of the bow allowed humans to bring down both man and beast at a much greater distance and with practice, a greater degree of accuracy than the thrown spear. The use of the bow in its most basic form extends back to at least the Maglemosian period (9000-6000 BCE), but likely was developed much earlier. Indeed, the bow may very well represent man's first means of directly storing energy. These early weapons were of all wood construction and had a string made of natural plant or animal products, evolving locally into a variety of different designs. So ubiquitous was the bow that it was used in almost every culture across around the world throughout history. Used for war, hunting, and sport, bows, arrows, and (more commonly) arrowheads of different materials form a frequent part of the material culture available to archaeologists worldwide. Historically, archery played a major and at times dominant role in warfare throughout the ancient world onward until the early modern period when the bow was eventually replaced by handheld firearms. This popularity continues in the modern day, where it can be found in sport (shooting for both accuracy and distance) and in hunting. As such, the bow and an understanding of both its history and its capabilities form a small but important part of understanding the vast majority of human history and prehistory.

This understanding becomes perhaps ever more critical the farther back one goes in history as early records and monumental artwork become skewed toward the interests of the social elite of the time. As such a high percentage of early records and art focuses on military exploits and conquests, military history is a field that can directly benefit from an understanding of weapon (and armor) capabilities. Furthermore, while the vast majority of historians focus their attention in other areas, early military history and the performance capabilities of weapons (and by extension, bows) used in the pre-modern world remains a popular touchstone to engage public interest, and as such is worthy of a base level of understanding unto itself.

While bows of all wood construction continue to be used in the modern day, at several points in history it was discovered that a combination of different materials could be used in bow construction, and that these combinations could result in increased performance. Such bows are known as composite bows, and are typically made by combining horn, antler or bone with sinew and/or wood (Gray, 2002, p. 46; Hickman, 1959, p. 21). While deceptively simple in principle, in practice the development of composite construction relates to the growing awareness of people of the varying attributes of different materials. The combinations of materials that characterize a composite bow thus reflect a major transformation in humankind's understanding of material characteristics. The composite bow therefore marks a fundamental shift in human technology, being perhaps the first tool/weapon system to draw upon the contrasting and complementary aspects of different materials.

It is these differences in material characteristics and their resulting performance that is the driving force behind this thesis. As such, the goals herein are fourfold. The first is to conclusively identify the reasons for the potential of increased performance that typically accompanies composite construction. Second is to isolate each of these factors in turn through field testing so that they can be quantified. Third, using the results for field testing the thesis will determine an improved methodology which can accurately identify composite construction in artwork. And fourth, this improved methodology will be applied as a means of identifying a date of arrival for or transition to composite construction technology in Mesopotamia and Elam. The first two goals are the primary focus of the thesis, laying a foundation which can be applied to a number of questions on the topic of archery within the fields of history, archeology and anthropology. The third and fourth thesis objectives are the practical application of field test results as applied to a particular problem - evaluation of bow iconography within ancient Mesopotamia and Elam during the third and fourth millennia BCE. It should be noted that while the fourth goal of the thesis concentrates on the composite bow in ancient Mesopotamia and Elam, the foundation provided in the identification of composite construction can be applied to other periods and cultures, so long as it correctly used. Finally, the quantification of performance variables are applicable to *all* bows across *all* regions and time periods, making the thesis very much a meta-work which can act as a base of knowledge for historians, archaeologists and anthropologists to draw upon for any time period or culture where the bow was used.

Given that these four thesis goals very much cross disciplines, and that the first three goals are more general in nature, a range of textual, iconographic and artifact source material will be used throughout the thesis. Works not only in the field of history, but also archaeology, ballistics, mechanical engineering and physics are drawn together with studies in proportional anatomy, craft design, art history, and textual sources from Ancient Egypt, Mesopotamia and Classical Greece and Rome. Efforts have also been made to address the vast majority of claims that have previously been made with regard to composite construction as it appears in ancient art, and as such includes iconographic material again from Ancient Egypt, Mesopotamia and Elam but also includes representations found in Western Europe. Artifact evidence is of course the least common and most valuable evidence from the ancient world with regard to the thesis goals, and as such particular importance is given to the evaluation of artifacts from ancient Egypt. The combination of artifact, textual and iconographic evidence is then matched with theoretical modeling and physical testing. As such, conclusions drawn herein do not depend only on a single source of evidence, but instead on the corroboration of all of these sources of evidence such that they form a coherent system that fits *all* of the available evidence regardless whether it is ancient or modern in origin.

As the third goal of the thesis focuses on an improved methodology for iconographic evaluation, bow artifacts from other time periods and cultures are also occasionally referred to. These artifacts include specimens from medieval England, Neolithic Western Europe, the Ottoman Empire, Siberia and both pre and post contact North America. Their inclusion in the thesis is relatively minor and is used primarily as examples showing that a range of different bow styles and methods of construction are not only physically possible, but that they actually existed at different points in history (Hayes, 1990b, p. 4; Strickland and Hardy, 2005, p. 17; Allely and Hamm, 1999, p. 36; Karpowicz, 2008, p. 177). In particular, the exemplar artifacts from North America directly contradict the current method of construction evaluation based upon profile, highlighting the need for an improved evaluation methodology.

CURRENT STATE OF KNOWLEDGE

Archery was and is a common, indeed almost a ubiquitous activity across almost every culture from pre-history into the modern day. And yet despite its commonality, the topic of bow design and performance lacks a foundational work from which historians and archaeologist can draw conclusions and inferences of bow use as it impacts their specific area of research. Indeed, the state of research within the field of archery is in many ways strangely dichotomous: more general works only mention archery in passing, and provide insufficient information from which an historian, archaeologist, or anthropologist can derive detailed conclusions or likely inferences for bow artifacts and references that exist within their chosen specialty. In contrast, research dealing specifically with archery is often so specialized that it can often only be applied to the given culture or phenomenon discussed within that particular study. Because of this dichotomy, researchers in areas for which bow artifacts exist or in which archery was commonly practiced have been unable to make the most of the source material available to them unless they choose to become specialists in this niche topic themselves.

In other areas, it would be normal for a researcher to utilize pre-existing, specialized research already done by experts within the field of interest. Within the topic of archery however this has proven to be difficult, as many of the specialized articles and works provide differing and at first glance what often appear to be contradictory results. In the face of such adversity however lies opportunity; in this case it became readily apparent to the author that a properly targeted framework of research that was broad enough to account for all of the existing data, specialized enough to ensure that a number of conclusions that could be made with regard to bow performance, and yet basic enough to be understood by the interested layperson would be of great benefit to the field as a whole. This thesis in short seeks to create such a framework that successfully reconciles these contradictions through a combination of basic engineering and experimentation. Testing later herein reveals that the vast majority of these performance claims are in fact highly accurate, but coexist within a matrix of performance results that varies with draw weight.

The first of these apparent contradictions is also perhaps of the widest interest (and as a result is perhaps the most widely reported) - the range increase when comparing bows of composite construction over and above those using an all wood or "self" construction. While it is generally agreed that the composite bow has a greater range than an otherwise equal bow of self construction, and that this increased range is likely one of the primary reasons for its development, the exact amount this range increase varies. Estimates vary substantially, and range from 13%-600% (Baker, 1992, p. 115; Gizurarson, 1998, p. 67; Hamblin 2006, p. 95; Anglim et al., 2002, p. 10).

The fact that a number of scholars are in agreement with regard to the potential benefits of adopting the use of composite construction is reassuring, but reasons claimed for this increase in range are myriad. The clear identification of the exact sources of potential performance improvement is the first goal of the thesis, and the goal upon which all subsequent objectives within the current work hinge. Several sources clearly identify the increase in bow performance as due to increased draw weight (Gabriel, 2004, p. 27; Yadin, 1963, p. 7). Others insist that it isn't draw weight at all and instead derives from material choice (Kosiorek, 2002, p. 51; Landels, 2000, p. 106). Another claim is firmly laid at the degree of reflex when unstrung (the degree to which a bow bends *away* from the archer when the bow is held in hand without the string) (Baker, 1992, p. 115; Kooi, 1994, p. 18). Finally, claims have been made that the differences in range can be attributed to a shorter overall bow length, leading to less massive bow limbs and bowstring (Denny, 2007, p. 44). The exact reasons for any increased range, and their amounts will be assessed in relation to existing arguments and experiments later within the thesis, with Chapter Four providing a basic theoretical framework. The impact of bow length, and more specifically the potential for bow length to influence the adoption of composite construction with regard to chariot archery is discussed and tested in Chapter Five. Chapter Six evaluates the factors of bow mass, materials choice and bow profile.

Problems also face the evaluation of bow construction in iconography. The most commonly accepted methodology for iconographic identification of composite construction has thus far been the close examination of bow profile. If a given image shows a typical "cupid's shape" or "angular" profile bow when strung, it has generally been accepted to be of composite construction (Yadin, 1963, p. 81; Gabriel, 2004, p. 27; Miller, 1986, p. 182; Collon, 1983, p. 53; Rausing, 1967, pp. 38-39). Bow profile however varies from weapon to weapon and is represented across a spectrum rather than by a selection of a few, disparate shapes (Baker, 1992, pp. 54, 57-58). Additionally, many of the paintings, stele, carvings and seals concerned are no longer in pristine condition, an occurrence which is unsurprising given their age. This combination of profile variation and damage has resulted in scholars at times making opposing claims to the same image, most notably the Victory Stele of Naram-Sin (Hamblin, 2006, pp. 86-87; Gabriel, 2004, p. 27).

Disagreement regarding the evaluation of a single image would not normally be a problem if evaluation of existing evidence was always done in a consistent manner, but sadly this has not been the case (Hamblin, 2006, pp. 91-94). An even more serious problem however has yet to be acknowledged by the majority of scholars; the method of relying entirely on bow profile to determine composite construction is in itself inherently flawed, and some new or supplementary means of iconographical evaluation needs to be determined before visual sources can be recognized as potential sources of evidence with regard to the evaluation of composite construction (Rausing, 1967, p. 20). Artifacts, combined with theoretical modeling described in detail later herein validate Rausing's concerns, while physical testing proved to be invaluable with regard to the formation of a new methodology for the evaluation of bow manufacture from imagery that is both repeatable and based on a basic understanding of material stress (Engineer's Edge, 2015; Credland, 1994, p. 21; Galilie, 2000, p. 159).

With the new methodology developed in this thesis, it is possible to conduct a re-evaluation of ancient iconographic evidence, allowing the issue of the date of appearance for composite technology within Mesopotamia and Elam to be examined with a greater degree of accuracy. This question of dating, the final goal of the thesis, is also in contention with dates ranging from the last quarter of the second millennium BCE at the latest to the start of the fifth millennium BCE at the earliest (Kelekna, 2009, p. 63; Collon, 1983, p. 54).

TOPICAL IMPORT

The direct application of the improved iconographic methodology is fairly straightforward – the identification of composite construction of bows depicted in artwork. *Indirect* applications of this methodology however are more varied. Differences between artwork and artifact evidence seen in New Kingdom Egypt outline the contrast between aspirations versus the reality of material wealth (Spalinger, 2009, p. 117; Healy, 1992, p. 13). Similarly, through the process of seriation depictions of the equipment used by the Pharaoh versus those used by the masses shown in battle scenes chronicle not only the incremental adoption of this new technology but also its potential limitation to the social elite within that particular time (Gamble, 2001, p. 5; Spalinger, 2009, p. 251; Casson, 1969, p. 65; Bard, 1999, p. 225). New Kingdom artwork also potentially delimits the sphere of adoption of composite construction for adjacent areas where contemporary artwork and textual records do not exist, as can be seen by the continued depiction of Nubian troops with longer bows with a double-convex profile of self construction while Egyptian infantry is shown with shorter bows of an angular profile (Westendorf, 1968, p. 72; Yadin, 1963, p. 216; Hamblin, 2006, p. 424). Within Mesopotamia and Elam, analysis using the new methodology shows not only that composite construction was known in the fourth millennium BCE, but also delineates the transition between bows of a static recurve to a working recurve design, and then eventually to an angular profile.

A basic understanding of bow design can also provide the historian or archaeologist with insights as to bow use within a given culture as well as materials availability and suitability. To wit – a bow with a substantially asymmetric design is strongly indicative of mounted use, while bows with a deep, narrow limbs of all wood construction maximizes material efficiency, potentially indicating that local materials were perhaps somewhat limited (Fagan and Trundle, 2010, p. 372; Rausing, 1967, p. 18; Sinclaire, 2004, pp. 120-1). Indeed, the strong preference for yew wood for the English longbow encouraged this design, and import quotas were required to keep up with demand (Hageneder, 2007, p. 105; Hardy, 2006, p. 129). Similarly, basic information such as draw weight provides usage data. With average draw weight remaining largely static between 18-23kg across the vast majority of cultures throughout history, significantly lower draw weights would tend to indicate that a given bow could be designed for use by a youth, or if a low draw weight is common within a given culture, that poison was regularly used (Baker, 2000, pp. 57-58; Gray, 2002, p. 73; Grayson et al., 2007, p. 139; Spotted-Eagle, 1988, pp. 15-16). In contrast, draw weights significantly higher than this average could potentially represent a bow designed for strength training or an unusually strong person if found in a single artifact. If such an increase were common within a given culture however it could signify that it was used to hunt extremely large game such as elephants, or that it was designed for war and that substantial armor was commonly used by enemy troops (Tukura, 2000, p. 148).

Of course, a culture's choice of weapons is also reflective of the amount of training and specialization of its military as well as its cultural mores with the spear utilized in block formations representing the minimal amount of time devoted to military training, while archers required substantially longer periods of training to be effective (Archilochus, fr. 3; Euripides, *Heracles*, 160; Connor, 1988, pp. 28-9). This differentiation in weapon use can easily be seen in the contrasting cultures of classical Greece and Persia, the former with the *hoplite* representing middle and upper class citizens who spent (albeit with Sparta being a notable exception) a minimal amount of time devoted to military matters (Greenhalgh, 1973, p. 74; Hanson, 2005, p. 4; Hanson, 2009, p. 31; Hill, 1961, p. 21).

The issue of bow performance (and more particular to the thesis, comparative performance) is similarly enlightening, but particularly so when two cultures with differing bow construction methods clash. Analysis from Chapters Four and Six indicate that the invading Hyksos would likely have had a 45% advantage in range over the local Egyptian troops, not including the force multiplier effects offered by the mobility of chariot use. A similar advantage would have been available to New Kingdom Egyptian troops when expanding their later control of Nubia and Kush. Finally the thesis shows in Chapter Six that comparative performance changes with draw weight, thereby allowing draw weights to be determined in cases where comparative ranges are known but bow artifacts are unavailable for evaluation. New insights can also be applied to the field of sports history, which often directly applies to either the question of range, or of penetrative power, as can be seen in archery demonstrations in both Egypt and Assyria QT, 17; QT, 19; Poliakoff, 1987, p. 108). Nor is bow performance solely limited to sport and war, as the Germanic and Indian customs have at times claimed land by shooting an arrow over it have wide-ranging implications with regard to not only land measurement but also by extension land fertility and population density in rural areas in both of those regions (Nibley, 1949, pp. 332-3; MacCulloch, 1930, p. 201; Hopkins, 1902, pp. 144, 147).

Taken as a whole then, the subject of bow design and performance impacts a number of areas throughout the ancient world with applications not only in military history but also material culture (bow design and material availability), regional trade patterns (for material acquisition), social economics (differentiation of bow style or construction by wealth or social class) and even the cultural values important within a given culture with regard to the preference of ranged or melee weapons as well as hunting and sport (Spalinger, 2009, p. 15; Diamond, 1999, p. 258; Hamblin, 2006, p. 3; Nash, 2005, p. 80). The vast majority of these applications can be applied across a range of periods and cultures, and as such the thesis is in many ways a foundational work with regard to design, performance and iconographic evaluation methodology, with the final goal of tracing of composite bow technology within Mesopotamia and Elam representing a proof of concept that ties together an easy to understand theoretical framework and field testing results with both artifact and iconographic evidence.

Additionally, the potential impact of the composite bow on chariot warfare will be assessed beyond the primary benefit of increased range. While the concern of this topic within the thesis focuses on identifying length limitations on bow usage within a chariot cab, insights were also gained with regard to positioning between driver and archer that are impossible to glean from iconography due to artistic conventions (Wilkinson, 1991, p. 87; Spalinger, 2009, p. 18). Experimental discovery also confirms the belief that the curved front of the Florence chariot likely indicates that it was meant for use by a single person (Littauer and Crouwel, 1979, p. 76).

Finally, the thesis presents the first set of comprehensive terminology that can be used for both bow construction and bow profile. This new nomenclature system has the potential to tackle several outstanding problems within the field and provide a clear framework for analysis within the thesis and provide a concise, accurate and complete system by which further research by other scholars into the topic of archery can be described.

METHODOLOGY AND CHAPTER PROGRESSION

Chapter Two begins with a brief examination of the history of bow nomenclature, examining the strengths and shortcomings of the different systems of terminology which have been used in the past with regard to method of construction (Pitt-Rivers, 1877, p. 48; Mason, 2007, pp. 5-7;

Longman and Walrond, 1894, p. 21). A similar process is then done with regard to describing bow profile, the most common means of evaluating construction from iconographic sources (Rausing, 1967, p. 20; Manhire et al., 1985, pp. 164, 167; Baker, 1992, p. 57; Yadin, 1963, p. 7). The thesis then proposes two revised, separate systems of bow nomenclature, which taken together create a clear and complete system that can be applied to all bows regardless of their period, place, or method of manufacture. The resulting terms will thereafter be used throughout the remainder of the thesis and represent the best portions of existing systems, while ensuring a degree of specificity that can be used across the full spectrum of designs and construction methods used for bows of both modern and traditional manufacture (Randall, 2015, pp. 44-46).

The discussion next turns to the question of the capabilities of the bow and arrow as a weapon system, with a focus on the range and more particularly the comparative range between bows of composite and self (all wood) manufacture. Sources for this discussion include a critical evaluation of ranges cited in the ancient world, several works on ancient warfare, and references by modern bowyers who work with traditional materials (McLeod, 1969, p. 13; Drews, 1993, p. 110, Hamblin, 2006, p. 95; Baker, 1992, p. 115). While all of the sources surveyed cite increased range for bows of composite construction, the amount of range improvement varies widely, from a low of 13% to a high of 600% (Anglim et al., 2002, p. 10; Baker, 1992, p. 115). Claims to the advantage of composite construction are then examined. Like the range estimates, reasons cited for the range improvement are varied, with increased draw weight, bow length, bow mass, materials choice, profile and even string mass all deemed to be the key factor by different scholars (Kosiorek, 2002, p. 51; Denny, 2007, p. 20; Cotterell, 2005, p. 57).

Data specifically gathered from within the field of experimental archaeology is evaluated next, which reveals that while a great of information is extant, the gaps which remain cannot be filled using ancient sources, and that further testing is needed. Efforts thus far dealing with practical testing have focused primarily on armor capabilities, and generally deal with bow performance as an ancillary topic (Blyth, 1977, pp. 58-9; Godehardt et al., 2007, p. 139; Matthew, 2012, p. 58). Several of these efforts do however begin to fill in questions with regard to both design and performance, and as importantly provide both examples of test design and methodology which are used later in Chapters Four, Five, and Six (Kooi, 1994, p. 2; Hulit and Richardson, 2007, pp. 58-60; Baker, 1992, p. 93). Although the methodology of these works varies, given the goals of the current thesis, much of the work herein is largely (but not entirely) processual, focusing on providing a foundation upon which future works with a more cultural bent can be based.

The question of dating the appearance of composite construction within Mesopotamia and Elam is then addressed. The majority of the debate on this point has thus far centered on the iconographic evaluation of the victory stele of Naram-Sin. Opinion on this point remains divided, with a number of authors following the opinion of Yadin, who believes that the work in question does in fact depict a composite bow, while Hamblin presents the main source of opposition and believes that composite construction did not appear until the start of the second millennium BCE (Yadin, 1963, p. 150; Hamblin, 2006, p. 94). The question of dating is however dealt with by most authors in a rather cursory fashion, with the exception of the previously mentioned Hamblin, and Rausing, who take opposing sides on the issue (Rausing, 1967, p. 20; Hamblin, 2006, pp. 92-94). As these two scholars are essentially unique in the level of detail provided in their analysis and reasoning, the issue of dating the appearance of composite bow use in Mesopotamia and Elam will address both of their concerns with regard to iconographic evaluation.

This of course turns the discussion to a brief description of iconographic methodology, which to date with the exception of Rausing, has focused almost entirely on the evaluation of bow profile (Hamblin, 2006, pp. 86-87; Yadin, 1963, p. 81; Gabriel, 2007, p. xvi; Collon, 1983, p. 53). Rausing however claims that any given bow profile can be made using any construction method (Rausing, 1967, pp. 38-9). From an engineering standpoint he is correct – if a bow is long enough to sufficiently reduce material stress. His assertion that profile evaluation is flawed as a means of identifying method of construction is then backed by the presentation of several bow artifacts from North America that contradict the profile methodology and is further re-affirmed during physical testing performed later in Chapter Six. Chapter Two then concludes with a summary of these results and a call for a theoretical model upon which performance factors can be identified for later physical testing.

Chapter Three continues the discussion with an evaluation of ancient source material, which is organized into sections by source type so that artifact, textual and iconographic evidence may be discussed separately. Within each section, sources are further separated by place of origin, and then by reverse chronological order. While the vast majority of sources utilized herein date to the second, third, and fourth millennia BCE, textual sources from Mycenaean Greece and Classical Greece and Rome are also included as they provide the only known references from the ancient world which refer to bow range. Given the fact that average bow draw weight has remained constant at between 18-23kg throughout much of history and across most cultures, and that bows did not have different draw weights for war (as opposed to hunting or sport) in the ancient world, the range estimates remain useful even when applied to earlier periods (Spotted-Eagle, 1988, pp. 15-16; Baker, 1992, p. 79; Rausing, 1967, p. 29). These range estimates from the ancient world also match modern estimates, and as such can indirectly act as a means of confirming draw weight assumptions.

Artifact evidence is of course the most clear-cut and useful as applied to the goals of the thesis, and as such is given careful examination. Bow artifacts from the ancient world however are exceptionally rare as the base materials are not only biodegradable but also due to the fact that, save for ceremonial purposes, a non-functional bow was generally considered to be useful only as kindling. This is markedly different than many other weapon artifacts such as spears or swords with valuable metal components which could potentially be re-purposed. Some artifacts have however survived, and consist of several single examples and caches from New Kingdom Egyptian tombs (McLeod, 1962, p. 15; McLeod, 1970, p. 32; Griffith Institute, 2004). Additionally, some partial remains for which claims of composite construction have been made come from both Western Europe and Mesopotamia, but after evaluation have been deemed inconclusive (Woolley, 1934, p. 461; Rausing, 1967, p. 55). Finally, a cache of remains which most certainly are composite bows dating to the end of the third millennium BCE comes from the Lake Baikal region in Siberia (Michael, 1958, p. 12; Rausing, 1967, p. 113).

In contrast to artifact evidence, cuneiform tablets and tomb inscriptions from the second half of the third millennium BCE Mesopotamia and New Kingdom Egypt form the backbone of contemporary literature sources, describing both bow use and profile (descriptions of which match both artifact and iconographic sources). These sources also outline the bow’s importance in chariot warfare, a topic that is examined in greater detail in Chapter Five with regard to the potential need for a reduced bow length that could potentially mandate the use of composite construction.

Last but not least, iconographic examples form the largest group of evidence with regard to the possible use of composite construction methods in the ancient world. The section begins with a brief discussion regarding the difficulties in iconographic evaluation, stressing the importance of interlocking iconographic analysis with both textual and artifact source material whenever possible to ensure that a high degree of accuracy is maintained. Again, tomb art from ancient Egypt, dating to both the New and Middle Kingdom periods is examined. Particular attention is given to details such as degree of proportional accuracy, bow profile and both relative bow length and draw length compared to figure height. It is also noted that while iconographic representations of bow length as measured from tip-to-tip match extant artifacts, length as measured along the arc of the bow is excessive when bows are shown at full draw.

Mesopotamian and Elamite art are even more heavily featured, as it is in these areas during the third and fourth millennia BCE that are the focus of the fourth thesis goal. Source material from these areas includes both the very large, consisting of monumental cliff-side rock reliefs, and the very small, which include a number of cylinder seals, *bulla*, and potsherds. As Hamblin raises questions with regard to several aspects of these representations, the thesis addresses these issues partially in Chapter Three and in greater detail in Chapter Seven (Hamblin, 2006, p. 92).

The chapter also features a short section on iconographic representations from Western Europe to which claims of composite construction have been made. As a group, these works consist of pecked rock art, and cave paintings. While both Klochko and Rausing make claims to these works, evaluation shows that they lack sufficient context, detail or realism to make any firm conclusions with regard to their potential method of construction (Klochko, 1987, p. 19; Rausing, 1967, pp. 38-39). Enough information can however be gained to show that, like in ancient Egypt, Mesopotamia and Elam, a number of different bow profiles appear to have concurrently existed.

Chapter Three concludes that composite construction methodology was indeed in use by the end of the third millennium BCE in Siberia, but that while the artifact evidence is conclusive it could potentially represent a technological anomaly. Also, repeated examples in textual, artifact and iconographic form show that the co-existence of differing bow profiles was common throughout the ancient world, and that while the composite bow was rapidly integrated into Egyptian iconography during the New Kingdom period, it did *not* result in the outright replacement of bows using both laminate and self (all wood) construction (Griffith Institute, 2004; McLeod, 1970, p. 32; McLeod, 1981, p. 38). Finally, it is noted that while bow profile is insufficient to determine a bow's method of construction, shifts in representations of bow profile can be seen over time, a point that will be examined in greater detail in Chapter Seven.

Chapter Four consists of an in-depth examination of bow mechanics theory. This topic is vital to the thesis as it provides a basis for understanding how bows function, giving the reader a framework to understand and properly evaluate both the physical test design and results outlined later within the work. The chapter is organized into two primary sections: factors which directly impact energy storage, and factors which are impediments to the efficient transfer (or release) of this stored energy to an arrow. A total of four energy storage factors are identified: draw weight, draw length, brace height, and unstrung bow profile (Baker, 1992, pp. 45-8). Each factor is described in turn.

The concept of the draw-force curve as a graphical representation of energy storage is then introduced. As an easy to comprehend graphic representation of draw length, draw weight (force) and stored energy (total area under the curve), the draw-force curve provides a visual representation of the impact of changing any of the four previously mentioned variables on the total amount of stored energy (Baker, 1992, p. 45; Godehardt et al., 2007, p. 125; Kooi, 1991, p. 26).

The next section focuses on inefficiency factors which includes (but is not limited to) such issues as bow limb mass, elastic hysteresis (creep), string mass, string stretch, and nock friction. While the discussion of potential inefficiencies includes a great number of variables, it also points out that the vast majority of these variables either remain constant (i.e. gravity), can be easily rendered constant with careful test design (i.e. string mass, draw weight) or are too small to be accurately measured (i.e. nock friction). The discussion also explains the impact of several environmental and use-based constraints, including cost, and climate suitability for a given construction method and how different traits can be desired in a bow (and arrow) depending on its intended use, such as hunting, flight (distance) shooting, war, or target competition.

Chapter Four concludes with the assertion that by removing the various factors which can be rendered constant either with regard to energy storage or release, any factors which remain can then be identified as potentially contributing to differing bow performance resulting from differences in bow design and/or construction. This short list of three remaining variables is comprised of bow limb mass, unstrung bow profile, and materials choice. The process firmly indentifies factors of potential performance improvement, thereby simplifying the process of physical testing done in Chapter Six to a manageable level.

Finally the variable of bow length *independent of changes in mass* was identified as being of potential impact, as it in part acts as a physical limitation with regard to use either within the confines of a chariot cab or while mounted (Laubin and Laubin, 1980, p. 25; Baker, 1992, p. 78). As the question of impact of bow length was of potential import to the practice of archery in the ancient Near East, it was also identified as being in need of separate physical testing, which is performed in Chapter Five.

Chapter Five specifically examines what length of bow can be reasonably used within the confines of a chariot cab. While this question has not previously been examined by other scholars, it potentially impacts the spread of composite bow use, as it could have encouraged the adoption of a shorter bow design that could not be supported using self construction.

The discussion begins with a review of previous chariot-archery research, followed by an examination of representations of bow and chariot use in New Kingdom Egypt artwork. The analysis shows that bow length, measured from tip-to-tip as represented by a comparison of bow length to figure height closely matches artifact evidence from the same time and place. It also revealed that while bow length as measured along the arc was similarly accurate when depicted at brace (strung, but not drawn), artwork overstates bow length when shown at full draw. This examination of proportionality between bow length and figure height, and its dimensional accuracy forms a basis of evaluation for iconographic analysis performed later in Chapter Seven, and also reveals that maximal usable bow length could not be definitively determined from ancient source material.

Physical test design is handled next, with separate sections outlining the needs and variables involved with both bow and chariot design. These design parameters are then used for the creation of full-sized functional replicas which then underwent physical testing.

Testing shows that interference occurred at a length that did *not* mandate the use of composite manufacture, although it potentially did *encourage* composite use. This proof that bows of self manufacture were feasible for chariot use in turn separates the early development of the composite bow from the development of the chariot, disproving implications that the two innovations were somehow co-dependent (Hamblin, 2006, p. 94). A number of ancillary points that have otherwise remained unaddressed in previous research were also discovered, including details regarding optimal placement of both driver and archer within the cab, and the resulting implications with regard to iconography for ancient Egypt as well as Hittite and Assyrian art. The chapter concludes that the results of physical testing, artifacts and iconographic evidence mutually reinforce each other, and that all of these points fit within the theoretical framework discussed in Chapter Four.

Chapter Six focuses on physical testing, specifically the verification and quantification of the bow performance factors previously identified in Chapter Four, thereby achieving the first and second thesis goals. The detailed experimental data provide an empirical platform to define and describe differences in bow performance. From this perspective, the historical conditions of different bow designs can be assessed; thereby allowing the formation of an improved methodology for iconographic evaluation of bow construction. Taken together, the results provide a basis to build upon existing knowledge to develop a clearer understanding of not only how and why a composite bow performs as it does, but also re-evaluate bow use, methods of manufacture, and impact on the ancient world.

Materials choice is investigated first, and begins with the creation of an all wood bow and taking detailed measurements with regard to its mass, physical dimensions, unstrung profile, and energy storage data represented in the form of a draw-force curve. The bow limbs are then modified with the application of a sinew backing, and the measuring process repeated. Actual results are then compared to predicted figures based upon changes in limb thickness. Wood slats are then added to the belly of the limbs as a control measure to ensure that the model generating predicted results is indeed accurate. Changes in energy storage are then subtracted from the actual results, confirming that the predictive model is indeed correct. The wood slats are then removed, followed by another round of measurements to ensure that energy storage returns to the exact point prior to the addition of the control material. A horn belly is then added, and a final round of testing performed.

Results indicate that contrary to expectation, the use of horn and/or sinew resulted in *reduced* performance compared to a design comprised solely of wood. While counterintuitive, these results make sense when viewed in a larger context. While both horn and sinew have higher ultimate break strengths than wood, they both also have decreased *stiffness* (Klopsteg, 1943, p. 182; Gabriel, 2007, p. 72; Baugh, 1994, p. 119). Both also have a higher density than wood. The combination of these factors means that while a bow constructed of horn, wood and sinew can accept a much more highly stressed design it also, *ceteris paribus*, will be lower in draw weight compared to a bow with an all wood design. The implication then is that the use of composite (as opposed to self) construction is beneficial if and only if it is used with a design such that it would exceed the material strength of wood alone (Kooi, 1994, p. 18). Such a design would include one or more features of large amounts of bow reflex and short overall length, and that the point of threshold where composite construction would result in increased performance can be reached more easily at higher draw weights. As a performance variable unto itself however, materials choice only facilitates the potential of the remaining two variables of unstrung bow profile and bow limb mass.

Shifts in bow profile are examined next. Draw-force curves of bows with identical draw weight but differing profile are compared. The differences in the area under these curves represent differences in energy storage, and show that increased limb reflex does indeed result in increased energy storage. A key finding shows that on a percentage basis, differences in energy storage *remain constant over changes in draw weight*, meaning that while bow profile does account for some of the performance differential between bows of self and composite construction it does *not* reconcile variances in performance differential reported in source material.

The investigation then shifts to mass testing, and utilizes both energy transfer efficiency and arrow velocity rather than draw-force curve comparisons. Test progression includes the addition of increasing amounts of mass to bow limbs to measure the impact on arrow velocity. As expected, increases in bow limb mass result in decreased arrow velocity, as a greater amount of energy is required to return bow limbs from full draw to rest. Additionally, examination of energy transfer efficiency reveals that composite bows are able to maintain a high level of efficiency as draw weight increases. Self bows however suffer from decreasing efficiency levels at higher draw weights. This identifies differences in bow mass not only as a factor which contributes to differences in bow performance, but also as the source of (and solution to) the high degree of variation in comparative performance reported to date.

Chapter Six concludes then that advantage of composite construction is real, and that this advantage is comprised of two factors: bow profile and bow limb mass (and mass placement). Furthermore, it conclusively determines that while the benefits of a reflexed profile remain constant (on a percentage basis), the benefits of differences in bow limb mass varies with changes in draw weight. This proves that the comparative ranges discussed in Chapter Two which appear to be in conflict instead merely represent the comparative range benefit at different draw weights, making them equally valid within a larger context of bow performance. The results show that while the range advantage of composite construction can indeed potentially reach 200-300%, this increase only exists at draw weights in excess of 45kg. At the draw weights known from the ancient world however, this range increase is estimated at a more modest 45%.

Chapter Seven returns to the question of iconographic analysis, and while fundamentally qualitative, it is built upon the new methodology determined by quantitative testing. The improved methodology consists of a comparison of bow length to figure height (quantitative measurement) combined with an examination of the level of proportional accuracy of a given artwork (qualitative evaluation), and allows a more accurate measure of evaluation with regard to visually determining the method of bow construction for a given image, thereby fulfilling the third thesis goal.

The discussion then describes this new methodology in detail, laying out its strengths and limitations, and notes that while it could be applied to the iconography of any time period or culture, it will only be functional in cases where the body of work under analysis is proportionately accurate. This is followed by a brief analysis of the artistic canon and evaluation of the level of proportional accuracy of art in Mesopotamia and Elam of the third and fourth millennia BCE (Tomabechi, 1983, p. 124; Mosteller, 1990, p. 389). As a part of this process, perceived inconsistencies in Mesopotamian and Elamite art identified by Hamblin are examined. When viewed from a larger context however, it can be seen that these “inconsistencies” are instead evidence for bow profile variation, a phenomenon which also exists in prehistoric Europe, ancient Egypt, and North America (Dams, 1984, pp. 54, 63; Rausing, 1967, p. 50; Griffith Institute, 2004).

Attention then turns to the analysis itself, which is divided into three sections, each corresponding to a particular bow profile and design. The first section examines bows with an angular profile and ties examples of Mesoptamian and Elamite art to examples from New Kingdom Egypt, and covers the period between 2300-1850 BCE. The second section looks at bows with a double-concave profile and a working recurve design, which can be found from between 2400-1900 BCE. The final section analyzes bows with a double-concave profile and a static recurve design, which appear in imagery dating between 3800-2400 BCE. Each section draws upon an analysis of large, monumental art of the period as well as examples of cylinder seals and *bulla*. Taken as a whole, the art in Chapter Seven is the most comprehensive collection of archery and bow related images for Mesopotamia and Elam for the period under investigation. While the primary purpose of the is iconographic evaluation using the new methodology, it also draws out as much information as possible regarding the depicted bows, including profile, brace height and depending on the perspective of a given representation, limb cross-section. Within each section physical data is also summarized in chart form, allowing the reader to quickly compare the brace heights and bow lengths for bows of a given profile. Additionally, as a part of this process a number of issues specifically raised by Hamblin are addressed (Hamblin, 2006, pp. 92-4).

Analysis concludes that while not all of the artwork examined had sufficient proportional accuracy to apply the improved methodology, works from the period dating to between 3000-1850 BCE are uniformly short enough to be deemed of composite construction. In the period prior to 3000 BCE however, several works feature bows of greater proportional length that are indicative of self or non-composite construction. Taken as a group, the works of this earlier period suggest that this was perhaps a transitional period in iconographic bow representation, and that by the start of the third millennium BCE the composite bow had become fully integrated into mainstream iconography of Mesopotamia and Elam. This does *not* however prove that bows of self construction had been completely replaced. In fact it is the author’s belief that Mesopotamia and Elam likely followed a similar pattern as that seen in New Kingdom Egypt wherein bows of self construction continued to be used by at least some portion of the populace even after the composite bow had become fully integrated in artwork. The analysis then acts as a proof of concept for the implementation of the improved methodology, fulfilling the fourth and final goal of the thesis. Finally, the results of the thesis and potential benefit to academia are summarized in Chapter Eight.

CONCLUSION

The thesis as a whole is a product of the existing research by previous scholars combined with the practical experience of the author as bowyer and archer as well as experimental data. The syntheses of these streams of knowledge combine in such a manner that they reconcile apparently conflicting data into a deeper understanding of the field of archery.

Applications of the results herein are applied both directly in the identification and quantification of variables that provide improved performance to bows of composite construction, but also indirectly in the form of development in an improved methodology by which iconographic evidence can be evaluated. The resulting analysis in both cases is surprising; showing that composite construction *unto itself* is no guarantee of improved performance but instead is reliant upon utilizing the greater material strength of composite construction in a more highly stressed *design*. The resulting iconographic analysis pushes back the development of composite technology by approximately a millennium and explains why the improved performance that typically accompanies composite construction did not result in a major shift in military strategy until it was later combined with the chariot as a mobile archery platform.

CHAPTER TWO

NOMENCLATURE AND LITERATURE REVIEW

While the previous chapter briefly outlined the current state of knowledge within the field of archery in the ancient world, it should also be noted that potential to extend our knowledge further is high, and that by building upon the body of literature developed over the past century through the contribution of new observations and analytical results the current field of knowledge can be considerably expanded. It is the goal of this chapter to outline the present state of the art by developing discussions of key points within the field established by other scholars. I will begin by laying out a clear discussion of bow construction and profile terminology consisting of a brief outline of the history of both of these sections of bow nomenclature followed by an explanation of the strong points and drawbacks of the existing systems. Taking the best and most widely accepted points of these existing systems, the chapter will then suggest new systems of nomenclature for both the elements of construction and profile. This is done not only to ensure that the reader and author have the same understanding of a given term for the remainder of the work, but also to improve the precision of bow nomenclature as a whole. Most particularly, advocates the term "composite" to all bows constructed using differing materials, but only within a context where these materials leads to an overall improvement in bow materials strength, thereby removing cases where such construction serves a purely decorative purpose (Randall, 2015, p. 43).

The discussion next turns to the question of bow capabilities and presents current findings on bow range and arrow velocity, with special interest in comparing the relative performance of otherwise identical weapons of both composite and non-composite construction. This will be followed by current theories regarding how and why composite construction has the potential for increased performance. Taken together these discussions form a basis for both the theoretical framework and physical testing covered later in Chapters Four, Five, and Six respectively.

All of the above points draw upon research and results from a broad range of regions and time periods from the Ancient Near East, to Medieval Europe, to pre and post-contact North America as a means of roughly outlining the wide variety of bow shapes and construction methods. The author makes no claims that these diverse cultures and time periods are directly connected in an unbroken lineage. Rather, they are used to show that the various bow profiles and construction methods are not only possible, but historically existed, thereby bringing them from the realm of theory to that of a well-grounded historical reality. Finally, the chapter turns to an examination of the development of composite bow technology from its origins to its widespread dissemination in the first quarter of the second millennium BCE.

NOMENCLATURE

HISTORICAL CONSTRUCTION TERMINOLOGY

As the thesis focuses on the comparative performance of the composite bow, an understanding of what "composite" means is of singular importance. The term "composite" as it applies to archery was first used by Pitt-Rivers, the first person to attempt to classify and differentiate between different bow types, in 1877 (Pitt-Rivers, 1877, p. 48). While Pitt-Rivers' attempt to standardize bow terminology was laudable, it has also been described as being "extremely vague and superficial" (Balfour, 1890, p. 220). The essential problem was that it could not suitably differentiate between bows made of layers of similar material (laminate construction), and bows which consist of different components (potentially of the same material) joined together such that they increase bow length.

Table 2.1 Pitt-Rivers Bow Construction Nomenclature (1877)

Structural Type	Type Description
Plain Bow	Bows made of a single material (typically wood).
Composite Bow	Bows made using different materials.

In 1886, Mason put forward a slightly more detailed system outlining different methods of bow manufacture, followed by Longman and Walrond in 1894 (Mason, 1886, p. 674; Mason, 2007, pp. 5-7, Longman and Walrond, 1894, p. 21). Most notably, Mason is the first to describe composite manufacture using the term "compound," a convention that was used by Howard Carter when recording his excavation notes of Tutankhamen's tomb (Griffith Institute, 2004). Mason's system provided a great deal more information regarding material combinations, but again like Pitt-Rivers’ attempt was ambiguous with regard to whether the term "compound" referred to an extension of bow *length* (joining several pieces together to make the unified structure longer) or of bow *thickness* (to take advantage of differing materials strengths).

In contrast, Longman and Walrond attempted to create a nomenclature that unified both construction and profile terms into a single system. The resulting system was detailed but incomplete, as it failed to consider several different known bow profiles, and assumed that a given method of construction inherently limited the resulting profile. Additionally, Longman and Walrond utilized unstrung bow profiles for their classification system. While this makes it an excellent choice for working with bow artifacts, it is inherently *less* useful when describing iconography, which usually (but not always) depicts bows in either a strung or drawn position.

Table 2.2 Mason Bow Construction Nomenclature (1886)

Structural Type	Type Description
Plain or "Self" Bow	Bows made of a single piece of hard, elastic wood, in each locality the best that could be found.
Compound Bow	Bows made of two or more pieces of wood, baleen, antler, horn or bone fastened together.
Sinew-Lined Bow	Bows made of a single piece of yew or other wood, on the back of which shredded sinew is plastered by means of glue.
Sinew-Corded Bow	Bows made of drift or other wood and backed with finely twisted or braided sinew cord and reinforced with wedges, splints and bridges.

In 1899, Von Luschan created a further set of competing nomenclature (Von Luschan, 1899, p. 27). While primarily focused on construction, Von Luschan's system was the first to include a separate category for the Andaman bow with its unique S-shaped profile when unstrung as well as to include the pellet bow which, as its name implies, is designed to shoot small stones, pebbles or clay balls instead of arrows (Jett, 1991, p. 95; Annandale and Robinson, 1902, p. 120).

In 1940, Rogers attempted to combine the best features of each of these pre-existing systems (Rogers, 1940, p. 257). Rogers' nomenclature was a definite improvement over previous naming systems, but has not been universally adopted, in part due to his decision that the term "composite" only apply to bows that incorporate the full triumvirate of horn, wood and sinew, but not other combinations (Baker, 1992, p. 66; Insulander, 1999, p. 80; Grayson, 2007, p. 181; Grayson, 1993, p. 129). At least some portion of early nomenclature debate was fueled by early scholarly doubt that Native American weapons were comparable in construction, profile and performance to weapons of the ancient Mediterranean and Near East despite evidence to the contrary (Ingersoll, 1895, p. 121; Hamilton, 1982, p. 69; Gray, 2002, p. 19). Similarly, Rogers' use of the term "shaft" has always been commonly applied to arrows and was never widely used for lengths of bow wood, which generally used the term "stave" in the case of a full length piece of wood, or "billets" when referring to a pair of half-length pieces (Bertalan, 2007, p. 531; Baker, 1992, p. 35, 209; Hein, 2007, p. 75). Finally, developments in modern archery have led to confusion with the term "compound" as this now refers to a bow that utilizes pulleys and cams such that it is easier to hold at full draw in exchange for a higher initial draw weight (Bertalan, 2007, p. 533; Paterson, 1984, p. 18; Raymond, 1986, p. 171).

Table 2.3 Longman and Walrond Integrated Bow Nomenclature (1894)

Weapon Type	Structural Type	Subtype	Profile Description
Bow	**Wooden**	Single Stave	Simple arc bending in one continuous curve.
			Upper limb bends more than lower limb.
			S-shaped.
			Ends more or less reflexed.
		Made of two or more pieces	Two 'self' staves joined in the hand.
			Made of two or more pieces joined longitudinally.
	Horn	n/a	n/a
	Composite	With free backing of cords and sinews	Simple longitudinal backing.
			Longitudinal backing complicating with cross lacing.
		With close backing of sinews molded to the bow	Sinews roughly molded close on to the back of the bow.
			With close backing of sinews carefully worked into the composition of the bow. The whole encased in bark or lacquer.
Crossbow	**Wooden**	n/a	n/a
	Metal	n/a	n/a
	Composite	n/a	n/a

Table 2.4 Von Luschan Bow Construction Nomenclature (1899)

Structural Type	Type Description
Simple Bow	Bows made of a single piece of wood, bamboo, or very rarely - horn.
Andaman Bow	Bows made of a single piece of wood with limbs of equal length, such that the bow forms unequal arcs when strung.
Composite Bow	Bows made of a core of wood, to which are affixed, either alone or in combination, tendon fibers, horny plates, or wood panels of a different kind or bamboo.
Pellet Bow	Bows made such that they are designed to shoot pellets, rather than arrows.

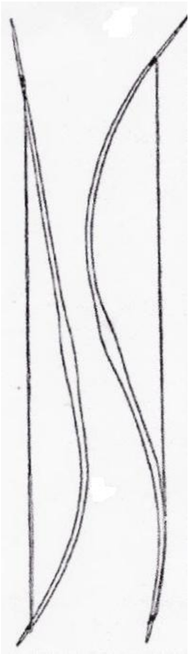

Figure 2.1 Andaman Bow braced (at left) and reverse strung (at rest, at right). Note the asymmetric curvature of the limbs and unstrung S-shape.

Figure 2.2 Chinese pellet bow. Note the pocket formed in the center of the string designed to fit a stone or pellet.

Table 2.5 Rodgers Bow Construction Nomenclature

Structural Type	Type Description
Self Bow	Plain wooden bow consisting of a single piece of wood.
Composite Bow	Bow, the shaft of which embodies a laminated construction involving more than one type of material such as wood, sinew, and horn, or two woods of different properties.
Backed Bow	Bows wrapped with sinew or other tough substance in order to prevent splitting and provide greater elasticity.
Compound Bow	Bows in which the shaft is assembled from several short segments bound or riveted together.

Table 2.6 Bow Construction Nomenclature: Proposed

Structural Type	Type Description	Notes
Self Bow	Plain wooden bow consisting of a single piece of wood.	
Laminate Bow	A bow of identical or nearly identical materials (typically wood) which have been laminated together, creating additional thickness (and at times width) rather than length.	Performance gains from this construction method primarily derive from pulling the laminations into reflex prior to gluing rather than from the different mechanical properties of the materials involved.
Composite Bow	A laminate bow, the working portion of whose limbs consist of more than one type of material such as wood, sinew, and horn, or two or more woods with different material properties such that overall materials strength of the bow is increased.	Performance gains come from increased limb reflex and/or decreased limb length such that the resulting design exceeds the materials strength of wood alone. Includes cable-backed bows.
Joined Bow	A bow whose *length* is composed of different segments of material joined or spliced together, typically by means of rivets or wrapping.	May be combined with other bow types to indicate a spliced construction, such as "a joined wood bow" or "joined antler-sinew composite bow." May or may not indicate the number of segments needed to create the full bow length.
Takedown Bow	A bow of joined construction specifically designed to be separable into shorter lengths such that it can be quickly and easily re-assembled.	Such bows may separate into two halves, or into a pair of limbs and a handle or riser.
Double Bow	A very rare bow type that has a set of secondary limbs, usually attached to the main limbs at or near the handle as a means to increase draw weight.	Such bows appear to quite literally have a smaller "second" bow attached to the outside of the main bow as seen in figures 2.3 and 2.4.
Compound Bow	A bow which uses cams and/or pulleys to gain a mechanical advantage.	First invented in 1969, its inclusion herein is mainly provided as a means to clearly differentiate the modern invention from traditional bows of composite construction.
Pellet Bow	A bow designed to shoot small stones, pellets or clay balls instead of arrows.	This design may incorporate the use of a pocketed or doubled string, and/or a side-by-side double bow.
Asymmetric	A bow made with upper and lower limbs significantly different in length.	The most notable example of this construction style is the Japanese *yumi*.

PROPOSED CONSTRUCTION TERMINOLOGY

In light of these problems, the author will provide a standardized set of definitions using the most widely accepted terms of existing systems. The author's proposed revisions, outlined in table 2.6, have several advantages over existing nomenclatures. First and foremost, it clearly differentiates between the terms "compound" and "composite," a source of confusion for many, and a subject which has been previously identified as a source of potential confusion (Patterson, 1968, pp. 14-15; Jackson, 1988, pp. 61-62). Additionally, it distinguishes between bows made of different materials (composite), and those pieced together to achieve their full length (joined). Joined bows are further subdivided such that bows capable of being quickly and easily dismantled and reassembled are given their own category (takedown) (St. Charles, 2000, p. 163; Elmy, 1989, p. 24). Finally, it specifies that the mere inclusion of a separate material does not qualify as a composite bow unless that material is an element of the working part of a limb and positively contributes to the materials strength of the bow, a concern noted in 1983 by G. D. Gaunt (Gaunt, 1983, p. 42).

As such under the proposed system a bow with a decorative wrapping of leather would not be considered composite, nor would a bow consisting of two horns joined together with a wood plug; a bow with ears of bone or a different type of wood from the limbs would similarly be excluded. In contrast, a bow which consists of two or more different kinds of wood layered together such that the wood variety with the greatest strength under tension makes up the back while the wood variety with the greatest strength under compression makes up the belly would qualify as a composite bow, while a bow made of layers of wood arranged purely on an aesthetic basis (typically based upon coloration) or which does not take advantage of the different wood properties but is pulled into reflex prior to gluing would be considered of laminate construction, rather than composite. While all the above examples certainly consist of two or more materials, only the leather wrapping potentially includes the working (bending) portion of the limbs, and even then it fails to positively contribute to the materials strength of the bow. Finally, the proposed system is the first to include asymmetric construction - a bow with upper and lower limbs of significantly different lengths (Halls, 1962, p. 14).[1] When drawn, the longer limb bends proportionately more than the shorter limb, which is also significantly thicker (stiffer) (Hoff, 2002, p. 33; Onuma, et al., 1993, p. 41). This method of construction is one way in which a longer bow can be easily used on horseback (Clements, 2010, p. 23; Kure, 2002, p. 43).

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[1] Historically most bows were slightly asymmetric to account for grip length, hence the note that limbs must be *significantly* different in length, as typified by the Hunnish bow and Japanese *yumi*, the latter of which is likely more familiar to the average reader.

Figure 2.3 Double bow from the tomb of Tutankhamen (unstrung).

Figure 2.4 Double bow (strung), Penobscot tribe, North America.

HISTORICAL PROFILE TERMINOLOGY

The above system however only describes differing means of bow *construction*, which is both different and separate from how a bow is *shaped* i.e., its profile. A given bow will have different profiles depending on whether it is unstrung, braced (strung but not drawn) or drawn. While the thesis does specifically evaluate bow reflex and/or deflex (the degree to which a bow, when not strung, curves either away from or toward the archery respectively), the iconographic analysis contained later in Chapter Seven deals almost exclusively with depictions of bows either at brace or some degree of draw. Further, as the profiles of most bows become increasingly alike as draw progresses (compound bows excluded), fully drawn bow profiles are generally not useful as a descriptor.[2] As such, profile nomenclature herein will focus on braced profile. A number of descriptive systems have been used by different authors, shown in table 2.7.

Assigning a single profile to a given bow can at times be problematic as profiles exists more or less across a continuous spectrum of shapes, raising the question of at what point a bow shifts from one profile category to another. For example, bows described as "double-convex" by both Rausing and Yadin often, but not always, contain a "set back grip." Scholars studying African rock art at times refer to this same bow profile as either "double curved" (Donato, 1994, 42), or "triple curved" (Maggs, 1979, p. 68). Degree of curvature (or recurvature as the case may be)

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[2] As compound bows are a modern invention they fall outside the purview of this study.

similarly varies to the point that Rausing, admits that the only difference between Qum-Darya and Scythian types in his system is in fact not profile at all, but length (Rausing, 1967, p. 20).

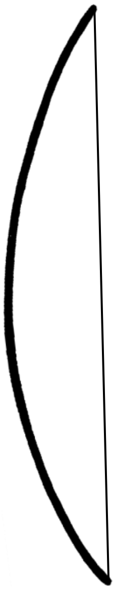
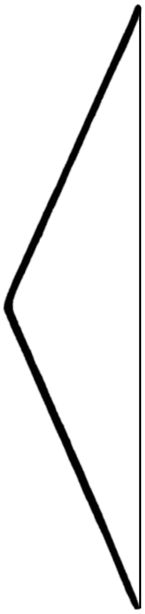
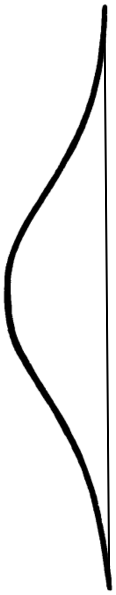
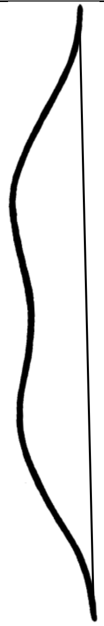
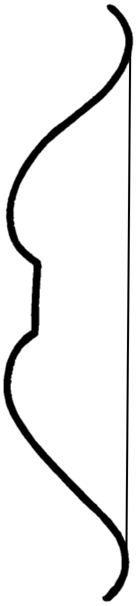
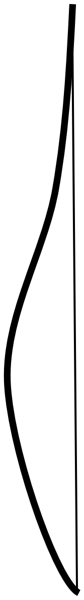
That being said, several authors have come to represent several sets of "most common" terms, as outlined in table 2.7. The naming system used by Manhire et al. is somewhat unique as it is an attempt to apply a completely new descriptive taxonomy based on the concept of curve counting (Manhire et al., 1985, pp. 162, 163, 170). While the descriptions are visually evocative, the system lacks precision, as bows with exactly opposite strung profiles (what others more commonly refer to as double-convex and double-concave) would have the same name (double-curved). Numerous other terms have been used by a host of other scholars, however those outlined herein are the most influential or in the case of Manhire et al., unique.

PROPOSED PROFILE TERMINOLOGY

To ensure clarity for the remainder of the thesis, a single consistent nomenclature is needed. While the simple expedient of using Rausing's profile system would certainly work, not all of his terms have been popular among other scholars. As bow length will be examined later as a separate variable, the "Qum-Darya" and "Scythian" types are combined (dropping the Scythian bow as a separate category). Additionally, a combination of terms will be used to describe Rausing's "Qum-Darya" designation, which in essence is a variation of the double-concave bow profile, and shall henceforth be referred to as a double-concave bow with a set-back grip or riser. Finally, a category for the unique profile of bows from the Andaman Isles is included (Belcher, 1867, p. 49; Man, 1878, p. 465). While the thesis at hand will not deal with either iconographic or artifact evidence of bows with this profile, it is included for the sake of completion, allowing bows from any region or time period to be accurately described. The resulting naming system is listed at the bottom of table 2.7 (Randall, 2015, p. 46).

The author has no illusions that the above revised naming systems will quickly become an accepted standard. Rather, it is presented as a means of differentiating bow types within this thesis, such that those previously unfamiliar with bow design or terminology may have a straightforward set of standardized terms to work with. Key to this undertaking is an understanding that all of the above bow profiles can be made using *either* self or composite (or other) construction as shown later herein, a point proven later within the current chapter and again as part of the physical testing performed in Chapter Six. Thus far, this factor has not been adequately taken into consideration.

Table 2.7 Bow Profile Nomenclature: Current (top) and Proposed (bottom)

Existing (Braced) Bow Profile Nomenclature							
							
Rausing	Segment	Angular	Double Convex	Double Concave	Qum-Darya	Scythian	N/A
Yadin	Curved	Triangular	Double Convex	Double Concave	Double Concave	Double Concave	N/A
Manhire et al.	Single Curved	N/A	Double Curved	Double Curved	Triple Curved	Triple Curved	N/A
Baker	Simple	Angular	Whip-Ended	Simple Recurve / Deflex - Reflex	Recurve with Set Back Grip	Recurve with Set Back Grip	N/A
Randall (Proposed)	Segment	Angular	Double Convex	Double Concave	Double Concave (with set-back grip)	N/A	Andaman

WEAPON CAPABILITIES

With terminology for both bow construction and bow profile defined, it is possible to discuss the primary focus of the thesis: the relative capabilities of composite versus non-composite construction. The evaluation of the performance of composite bows is a major concern, as an understanding of bow performance directly affects the expectations of historians and archaeologists as it relates to their interpretation of pictorial and artifact evidence.

The most comprehensive examination of the effective range of the composite bow from historic sources was done by McLeod in a pair of articles in the Journal *Phoenix* in 1965 and 1972, respectively (McLeod, 1969, p. 8; McLeod, 1972, pp. 81-82). Through careful evaluation of classical Greek and Roman sources, McLeod concludes that bowmen were "quite accurate up to 50-60m," that for the composite bow "the effective range extended to at least 160-170m, but not as far as 350-450m," and that "500m was an exceptional flight (distance) shot" (McLeod, 1969, p. 8). McLeod's analysis is both careful and methodical, but leaves a number of gaps that cannot be filled using ancient sources, including the draw weight and length of the bows in question. Bow mass, the average arrow length (and mass), as well as bow profile (both braced and un-braced) remain similarly unavailable. The author's personal experience with traditional Korean archery can confirm that a composite bow with a draw weight of 23kg and a draw length of 75cm can indeed reach well beyond 200m (target distance in traditional Korean archery is set at 145m, while the Turkish target range is 160-190m), although exactly how effective a shot would be would depend upon the type of arrowhead used and the nature of the target (Tomka, 2013, p. 554). Hunting generally relies on significantly shorter ranges to maximize accuracy, and while some large game can have a hide that is difficult to penetrate, in general anything short of the largest game (elephants and rhinoceros for example) can be reliably taken with a well-place shot from a bow with a draw weight of 23kg (Pope, 1947, pp. 112-113; Baker, 1992, p. 79; Marcy, 1886, p. 528). As the references evaluated by McLeod would apply to war, the type and amount of armor worn by an opponent, as well as if they were using a shield and its constituent construction as well as how it was carried (in a single grip, hand grip and forearm brace, or neck strap) become important (McLeod, 1969, p. 13). Additionally, it should be noted that an *effective* shot in war (one that has a reasonable chance to inflict serious injury) need not be *accurate* (Howard, 2011, p. 55; Karasulas, 2004, p. 23; Baker, 1992, p. 79). To wit, a volley of arrows loosed en masse can wreak havoc amongst enemy troops or keep them pinned in position even when archers are not aiming for a particular soldier. Conversely, fire from a bow with a low draw weight at close range against a heavily armored target will be much more accurate, but may not be effective at all.

Indeed, this list of variables is the core difficulty in assessing the effective range of a bow of any type, and likely a fundamental reason why a more comprehensive framework for the evaluation of bow performance is not already in place. In short, sources from ancient Greece and Rome can provide a reasonable estimate of effective range (as outlined by McLeod), but give no information as to the exact properties of the equipment used, although comparison to composite bows of modern construction using traditional materials corresponds to a bow with a draw weight of perhaps 23-25kg (Baker, 1992, p. 115; Spotted-Eagle, 1988, pp. 15-16; McLeod, 1969, p. 13). Finally, McLeod offers a comparison, stating that the English longbow often had a target range of 220m (with no mention as to effectiveness), but that flight (distance) shots seldom exceeded 265m (McLeod, 1969, pp. 13-14). The resulting figures are difficult to resolve with certainty, a problem made more complex by the fact that the arrows generally (and more accurately arrow mass) used by both styles of archery are quite different, and made more complex again by the use of different types of arrowhead depending on the nature of the target (Parker, 1993, pp. 267-8; Starley, 2005, p. 210; Tomka, 2013, p. 554).

Many authors tend to list a comparative range between composite and non-composite bows, but whether this comparison is meant to indicate effective range or maximum range is seldom indicated. Generally, the composite bow is claimed to have between 200-300% the range of a bow (presumably with an equal draw weight) of non-composite construction (Anglim et al., 2002, p. 10; Drews, 1993, p. 110; Hamblin, 2006, p. 95; Archer, 2010, p. 61).[3]Anglim et al. extends their claim yet further, stating that early composite bows had a range equal to twice that of a self bow, and that "later models" had a range of three times that, yielding a 600% increase in range (Anglim et al., 2002, p. 10). General reference works such as the *Greenhaven Encyclopedia of Ancient Mesopotamia*, make no range comparison but claim that a composite bow had a range of 400m, but only 150m with accuracy (Nardo, 2007, p. 322). Yadin also does not make a direct range comparison, but holds that a composite bow could shoot 400m with accuracy but had a range of twice that, or 800m (Yadin, 1963, pp. 7-8). Payne-Gallwey also contributes to the body of evidence, citing historical distances for Turkish flight (distance) archery, with ranges varying between 571-766m (Payne-Gallwey, 2007, p. 29).

These claims of increased range by the above scholars however tend to conflict with those of not only McLeod, but others who either actually practice archery or again have carried out extensive analysis of ancient or medieval source material. A Scientific American article makes no direct reference to range, but does directly compare arrow velocities, claiming that a "replica composite bow" (of unspecified profile and construction materials) "with a draw weight of 27kg will shoot an arrow as fast as a replica yew longbow with a draw weight of 36kg" (McEwen et al., 1991, p. 80). Again, insufficient details are provided to ensure that the comparison is fully valid, but when all of the above sources are taken as a collective body of evidence is it indicative that the composite bow out-performs a bow of self construction, a point investigated at length in Chapter Six. While the composite bow cited by McEwen et al. clearly shows improved performance, the 33% increase in velocity falls more than a bit short from the claim of "twice the range and penetrating power." The shift between range and velocity deserves special note: historically, bow power was measured by range, a method that is subject to variance in both wind and angle of release. In the modern day however, arrow velocity is the preferred measurement (with the exception of distance shooting records) as it avoids these problems and can be performed in a comparatively smaller area, including indoors if so desired. It should also be noted that arrow velocity (and when speaking historically, range) and effectiveness is at least as much a product of arrow design as it is of bow design, with changes is shaft diameter, height and length of flights and choice of arrowhead all having their own impact (Tomka, 2013, p. 554). To prevent the sheer number of variables becoming out of hand arrows are assumed to remain constant during

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[3] Use of theterm “presumably” is intentional, as all of the cited references, and indeed all of the references relevant to the question at hand fail to specify the exact details of bows used (or implied) for range comparison.

the theoretical modeling of Chapter Four, while physical testing conducted in Chapter Six used the same arrows throughout.

The more modest results posted by modern testing done in Scientific American also have the benefit of more closely matching tests done by modern bowyers, which report a velocity increase of 13% and a range increase of 20% when comparing bows of equal draw weight (22.7kg) and draw length (71cm) with a straight profile compared to a severely recurved profile (Baker, 1992, p. 115; McEwen et al., 1991, p. 80). Along similar lines, Gizurarson reports that an English longbow has a range of 300 meters (consistent with the findings of modern reconstructions done by Hardy but farther than those reported by Longman) and that a composite bow having the same draw weight (undocumented) had a range of 400 meters, an increase of 25% (Gizurarson, 1998, p. 67; Hardy, 2005, p. 409; McLeod, 1969, pp. 13-14). Finally, modern results from the World Archery Federation show that the current men's distance record for a composite bow (using the latest in modern, synthetic materials) is 1222m, while the distance record for the American longbow (more properly identified as a flatbow) is 439m and English longbow 379m (World Archery Federation, 2014).

Much like the initial estimates done by McLeod, the results appear to be mixed at best. The consistent refrain of a 200-300% increase by the majority of scholars in print differs from results claimed by those posted by actual archers and bowyers save for the world record results. Despite appearances, this does not necessarily mean that there is a discrepancy in the estimates or data from either side. It should be remembered that the current world records deal with bows of extremely high draw weight. The results claimed by Gizurarson, McEwen et al. and Baker however specifically deal with bows designed for hunting and everyday shooting by the average physically fit individual with a draw weight of approximately 20-25kg (Gizurarson, 1998, p. 67; McEwen et al., 1991, p. 80; Baker, 1992, p. 115).

This would tend to indicate that performance differences between composite and non-composite construction likely vary with draw weight, a conclusion investigated in more detail and proven to be correct later in Chapter Six. The repeated claims of range increases of between 200-300% however are troubling if they only apply to bows of extremely high draw weight for with these claims come a certain level of expectation (Hamblin, 2006, p. 95; Drews, 1993, p. 110; Anglim et al., 2002, p. 10; Archer, 2010, p. 61). If a weapon in the modern day had twice the range of its predecessor, one would potentially expect it to be rapidly adopted, a point which Hamblin makes when reviewing potential dates of development (Hamblin, 2006, p. 94). Conversely, if such a weapon was *not* rapidly adopted, it could be a sign that one or more barriers to its adoption exist, such as excessive cost, suitability to a given environment, or restriction to a given social class within a given culture (Cotterell and Kamminga, 1992, p. 3). The import for hunting, in comparison to military concerns, is that a bow with a draw weight of between 18-23kg is sufficient to kill the vast majority of large game regardless of construction so long as the bow is well made and capable of 73cm or more in draw length (Baker, 1992, p. 79; Pope, 1947, p. 13). Certainly increased arrow velocity would allow the taking of the very largest game (elephants) or the killing of game from a longer distance, but any progress in range typically suffers from increased losses in accuracy (Baker, 1992, p. 79).

With regard to sport archery, the advantage of increased arrow velocity would very much depend on what the objective happens to be and to what extent accuracy is degraded in exchange for arrow velocity (Baker, 1992, p. 75; Miller et al., 1986, p. 181; Rausing, 1967, p. 29). In light of this tradeoff, flight archery (distance shooting) would benefit the most from increased velocity, but shorter range target archery such as that described in the funeral games of Patroclus would potentially suffer depending on the bow design (Homer, *Iliad*, 23.850-858; Willis, 1941, p. 410). The famous shot by Odysseus however would likely have benefitted from increased velocity, as the feat of shooting through a series of axe head eyes (*τοὺς πελέκεας*) would directly benefit from a flatter trajectory, presuming that the added power did not cause extensive fishtailing of the arrow shaft prior to reaching the first axe (Homer, *Odyssey*, 19.572-81, 21.73-76, 21.420-430; Richardson, 1993, p. 266; Brain and Skinner, 1978, pp. 55-58; Pocock, 1965, pp. 12-21).[4]

As important as the apparent discrepancies between the majority of scholars and the majority of archers and bowyers however is their universal commonality: that the composite bow has the potential to out-perform (in terms of either maximal range or arrow velocity) bows of non-composite construction, even if the exact amount of improvement remains subject to debate and further investigation. The question then becomes how and why this performance increase occurs, a question that will be subjected to theoretical and physical testing in Chapters Four and Six.

THE ADVANTAGE OF COMPOSITE CONSTRUCTION

A number of historians have attempted to address the question of why composite construction appears to have the potential to improve bow performance. Gabriel purports that this increase in range was due to its increased draw weight, which made it difficult to use (Gabriel, 2004, p. 27). This same fact is repeated again in the book *From Sumer to Rome*, claiming that the resulting composite bows had twice the draw weight of self bows (Gabriel and Metz, 1991, p. 9). Yadin agrees indirectly, stating that stringing a composite bow took "great strength" (Yadin, 1963, p.7). The results of estimations and recreations of Egyptian angular bows however average 18.2kg in draw weight (Blyth, 1980, p. 34; Spotted-Eagle, 1988, pp. 15-16; Hulit and Richardson, 2007, p. 57). While not directly contradictory, it implies that Egyptian double-convex self bows would then have a draw weight of less than ten kilograms.[5] This would be unusual because such low draw-weights would not make an efficacious weapon.

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[4] Axe heads are mentioned also in the example of the *Iliad* as prizes, ten double axes and ten single ones. With regard to chronology it is notable that these were of iron rather than bronze (*ἰόεντα σίδηρον*) (Homer, *Iliad* 23.850; Richardson, 1993, pp, 266-7).

[5] In fact, it appears almost as if these scholars were speculating what would happen if one took a self bow, applied horn and sinew and *then* compared the results. Such a comparison however would be problematic as to be valid such a comparison would require that the two bows in question to have identical (or nearly identical) draw weights.

Bows however, can be made in a range of draw weights, regardless of their manner of construction. While not directly pertinent to the ancient world, the longbow artifacts recovered from the wreck of the Mary Rose are illustrative of this point, and range from 45kg to 81.5kg in draw weight (Hardy, 2005, p. 17). Turkish bows from the Topkapi Palace Museum, reveal an even wider range in draw weight from 20kg up to 110kg (Karpowicz, 2007, p. 678).[6] The question of draw weights of ancient weaponry is of course exceptionally difficult to determine with accuracy given the dearth of artifacts available, but the Medieval/Renaissance artifacts mentioned above show that a range of draw weights is more than possible regardless of the means of construction used. As for claims relating to difficulty of use, it is true that the stringing of a composite bow should be done with some care, a detail that dissuades using one’s foot to apply pressure or step on the lower limb, a practice at times referred to as “treading on the bow” seen in figure 3.10. In actual draw and release however the composite bow is no more difficult to use than a bow of equal draw weight made of self construction (Emerton, 2003, pp. 472-3; Tukura, 2000, p. 155).

In comparison to the above authors, Kosiorek attributes the improved performance of composite bows over bows of self construction to material choice (Kosiorek, 2002, p. 51). These assertions are potentially supported by engineering data: sinew is stronger under tension than wood, while horn (as well as antler and baleen) are comparatively stronger under compression (Landels, 2000, p. 106; Baugh, 1994, p. 119; Kooi and Bergman, 1997, p. 129). Kelekna provides additional detail, stating that sinew is four times as strong under tension, while horn is twice as strong under compression (Kelekna, 2009, pp. 76-77). Rausing's position accords with this, stating that a bow of composite construction can be made with shorter limbs than a bow of self construction (Rausing, 1967, p. 20). It has also been noted that profile may also have an effect upon bow performance, a belief that has been at least partially supported by both mathematical modeling and physical testing, a point reinforced by physical testing herein in Chapter Six (Hamblin, 2006, p. 90; Kooi, 1994, p. 18; Baker, 1992, p. 115).

One scholar specializing in ballistics has suggested that increases in composite construction come indirectly from material choice as this allows for a shorter overall construction, a feature that allows for shorter, less massive bow limbs and string to which the actual performance increase it then attributed (Denny, 2007, p. 44). While the comparative effect of string mass is likely quite small, the fact that composite bows can in fact be made shorter than a bow of self construction has also been noted by a number of authors. Rausing notes that a composite bow can be constructed shorter than that of a comparable bow of self construction (Rausing, 1967, p. 20). Simiarly, a number of authors specifically note a shift in bow technology with the introduction of the *short* composite bow (Credland, 1994, p. 21; Kelekna, 2009, pp. 76-7; Raulwing, 2000, p. 91; Cotterell, 2005, p. 57).

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[6] Draw weights for these artifacts are estimated based upon an analysis of their limb dimensions and cross sectional shape, and then verified by Karpowicz by means of testing of exact physical recreations.

The physical descriptor of "short" is of potential importance for two reasons. First, bow limbs can be made with less mass, thereby consuming less energy as they return from draw to rest upon release (Klopsteg, 1943, p. 184; Rausing, 1967, p. 20). Second, shorter overall bow length may be considered beneficial unto itself as both Laubin and Laubin and Baker specifically mention that a shorter bow is easier to use, a point of potential import when within the confines of a chariot and most certainly while on horseback, a question that could potentially have influenced the speed at which the composite bow was adopted within chariot-using cultures (Laubin and Laubin, 1980, p. 25; Baker, 1992, p. 78). This second point will be will be examined in detail in Chapter Five.

While a number of claims as to how and why a composite bow outperforms a comparable self bow exist, two key aspects include choice of materials and unstrung profile while bow mass (and length) also likely has some effect. Exactly how much each of these factors contributes to performance, and if other factors related to composite construction also influence arrow velocity remain unmeasured and form the first two major goals of the thesis.

EXPERIMENTAL ARCHAEOLOGY

The vast majority of the gaps which remain within the field of archery in the ancient world simply cannot be filled with existing source material. Physical dating remains at an impasse with an almost total lack of artifact evidence that pre-dates the Hyksos invasion of Egypt. The issue is further complicated by the fact the current evaluation method of bow profile analysis has proven to be insufficient and has been inconsistently applied, undermining attempts at iconographical analysis. Claims of differences in performance similarly cannot be resolved with existing data. Furthermore, comparative (composite versus self construction) bow performance potentially varies with draw weight, meaning that differing claims could be equally valid depending of the draw weight used as a point of comparison. Reasons why the composite bow has the potential to outperform a bow of non-composite construction appear to be reduced to material choice, differences in bow profile or differentness in bow mass (the latter of which is affected by bow length), either singularly or in combination with each other. How much each of these potential factors contributes to bow performance if at all remains unknown, and again have the potential to vary with draw weight. The question of co-dependence between the composite bow and chariot similarly cannot be answered with available information.

We can however develop a range of resources to help equip us to tackle many of these gaps through a carefully designed program of experimental archaeology using bows designed either to replicate a given artifact or bow type used within a given culture, or with specific parameters such that it allows performance testing of a given feature of a given bow design. Such functional replicas, when properly designed, allow individual variables including materials choice, degree of reflex or deflex in a bow stave and bow limb mass to be isolated and tested. To a certain extent these variables can be understood purely within the confines of mathematical modeling, particularly within the bounds of energy storage, a topic outlined in Chapter Four (Galilie, 2000,

p. 159; Physics Classroom, 2013; Wolfram Alpha, 2013a; Kooi, 1994, p. 2). It is only through the production and testing of functional artifacts however that actual bow performance, as measured in arrow velocity and energy transfer efficiency, can be accurately assessed, as this further accounts for the various differences that produce real-world (as opposed to theoretical) results (Denny, 2007, p. 28; Baker, 1992, p. 71; Klopsteg, 1943, p. 179).

In this regard, experimental testing can fill in gaps that otherwise remain when examining only artifact evidence and mathematical models based upon a knowledge of physics and engineering. How far (or at what velocity) can a bow of a given design shoot? How does this distance compare to other bows of differing designs, or of the same design but different material construction? In this regard experimental testing can provide a great deal of value and provide verifiable, reproducible results that would otherwise be unattainable.

The use of testing with regard to ancient armor and weapons has benefited from previous work that is similar in nature to that undertaken herein. Gabriel and Metz measured both the performance characteristics of ancient weaponry and armor, as did Matthew (Gabriel and Metz, 1991, p. 59, 63; Matthew, 2012, p. 58). Blyth undertook a more specialized effort for his doctoral thesis which focused specifically on penetration of armor by arrows (Blyth, 1977, pp. 58-59). These works have greatly expanded our knowledge regarding the protective capabilities of different forms of armor, and an understanding as to the force generated by different weapons. While providing an excellent baseline of information of weapon and armor capabilities, their main focus remained on armor, and archery only formed a small part of their results.

Another study by Blyth focused on the stiffness of arrows from ancient Egypt, but not bows (Blyth, 1980, p. 34). The effectiveness of Bronze Age shields has been done several times, each focusing on different aspects or weapons but again the main focus was on shield performance, and bow testing comprised only a small portion of their work (Molloy, 2010, p. 413; Coles, 1962, p. 185). Hulit and Richardson have also contributed to studies in armor effectiveness with regard to chariot archery while Littauer and Crouwel have contributed to the evolution of the chariot and its use (Hulit and Richardson, 2007, pp. 58-60; Littauer and Crouwel, 1979, p. 11).

With regard to bow performance, the research which comes closest to that of the thesis is likely Godehardt et al., who constructed sets of bows of both composite and laminate design (Godehardt et al., 2007, p. 112). While this work includes a higher level of detail, including exact draw lengths, draw-force curves (described in detail later in Chapter Four), and arrow velocities the testing does nothing to identify or isolate any of the variables that could potentially contribute to composite construction. Similarly, while a greater level of archery related detail is reported than other sources, the provided data falls short of that needed to answer the goals of the thesis at hand. In the end, the effort is an excellent piece of scholarship, but relates primarily to the penetration of differing types of arrowheads when use against a recreation of a Mesopotamian shield, making it more of a study of armor, rather than of archery (Godehardt et al., 2007, p. 139).

Of the above works, almost all focus on armor performance rather than weapon performance, and only the works by Blyth, Hulit and Richardson and Godehardt et al. include archery as a major portion of their work. Even in these works however, save for Godehardt et al., little attention is paid to bow design, potentially because detailed questions of bow design generally require that one learn the craft of bow making, an esoteric undertaking in the modern world. Additionally, the testing undertaken herein cannot be done with a single exemplar, but must utilize a number of weapons produced with specific variations to allow an accurate comparison.[7]

Despite the lack of general interest in building bows using traditional materials in the modern day, several authors provide a foundation of research with regards to bow performance and design. First and foremost, the authors of the Bowyer's Bible have done much to further the understanding of bow mechanics and design, and have collected a large set of data from which generalized measurements can be taken with regard to bow performance in general and shifts in bow profile in particular (Baker, 1992, pp. 43, 115; Hamm, 1992a, p. 257). Bergman, Klopsteg, and Kooi have all done extensive work with regard to bow performance, mostly with regard to mathematical modeling (Bergman and Kooi, 1997, p. 129; Klopsteg, 1943, p. 177; Klopsteg, 1992, p. 90; Kooi, 1994, p. 2). Karpowicz has done extensive testing and measurement of Turkish bows, including details of manufacture, draw weight estimates of ancient artifacts and an examination of design efficiencies (Karpowicz, 2005; Karpowicz, 2007, p. 677; Karpowicz, 2008, p. 177). Finally, Strickland and Hardy have tested accurate recreations of medieval longbow relics from the wreck of the Mary Rose, providing valuable evidence with regard to the performance of self bows at high draw weights (45-87kg) (Strickland and Hardy, 2005, p. 17). All of the above authors are both archers and bowyers themselves, and it is this select group that has helped further the understanding of the capabilities and use of the bow as well as bow design. None to date however has focused specifically on the comparative capabilities and reasons thereof with regard to the composite bow, a gap in our current knowledge that the current thesis both seeks to fill and is well-suited to experimental testing.

Given the breadth of research discussed above, it should not be surprising that the research to date has been performed with different methodologies and foci. The focus of the majority of the investigations outlined above primarily relate to the acquisition of physical data such as arrow velocity, range, or the force and/or energy needed to penetrate armor of a given construction, whether it be bronze, iron, quilted cloth or (in the case of shields), wood. In this (superficial) point of view, it could be said that as a collective body, these works and their conclusions easily fit within the context of processual archaeology (Renfrew and Bahn, 2005, p. x; Gamble, 2001, p. 25). The actual methodology used within individual works however varies. While the mathematical works of Kooi, Bergman and Klopsteg indeed can be said to be processual, as can

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[7] The set of three composite bows constructed by Godehardt et al. were all of identical design, and varied in draw weight only by a margin of ±6% (Godehardt et al., 2007, p. 125). The differential is enough to show that the construction of identical weapons from traditional materials is difficult, but insufficient to show how performance varies across a range of draw weights as will be done later herein in Chapter Six.

the shield testing done by Coles and arrow spine (stiffness) testing performed by Blyth, a number of other works focus, or at least include factors either caused or influenced by the user.

The Bowyer's Bible notes that that there is no singular perfect bow as "perfect" depends not only on to what purpose a bow is to be put (hunting, war, target accuracy or distance shooting), but also the environmental conditions it is to be used in (wet or dry conditions, forest, scrub or rain forest), and even touches upon the immediate needs, abilities and resources of both the bowyer and archer (including skill level, materials availability, time and costs) (Baker, 1992, p. 44). Along similar lines, Hulit and Richardson note that shooting from within the confines of a chariot (and their chariot's lack of suspension) directly influenced their firing arc (Hulit and Richardson, 2007, p. 62). Molloy takes the point further, making his shield testing user-centered and decidedly post-processualist in its approach (Molloy, 2007, p. 95).

Within the framework of the thesis, the author takes a strongly (but not exclusively) processual approach. The thesis goals of identifying and quantifying factors influencing the comparative performance of differing methods of bow construction are themselves strongly data-driven, and lend themselves naturally to this style of investigation as can be most clearly seen in Chapters Four and Six. The former of these chapters presents a theoretical model as a basis of understanding how bows work, and concludes by identifying potential variables which could potentially lead to comparative increases arrow velocity. The latter takes these variables, isolates them and quantifies them across a range of draw weight (11-45kg) wide enough to ensure that performance trends can be noted, with results showing that the vast majority of "conflicting" performance measures mentioned previously herein are instead the result of measuring comparative performance at different draw weights.

The formulation of a new methodology of iconographic evaluation of bow construction follows in the similar vein, basing it directly on insights gained from both theoretical modeling and physical testing and cross-referenced against ancient artifact evidence. Even the evaluation of ancient iconography performed in Chapter Seven strives to quantify the evaluation of artwork as much as possible, albeit with a number of caveats to ensure that the new methodology based on proportional length is applied appropriately.

This is not to say that the influence of the user is ignored. The testing of bow length performed in Chapter Five also assesses bow use with regard to use with the confines of a chariot cab, and as such directly involves the user; testing results provided a number of insights into bow use. In all cases however the thesis seeks to ensure that sufficient information is provided so that any interpreted results include sufficient information such that the circumstances in which the results were achieved can be independently repeated and verified.

DATING THE INCEPTION OF COMPOSITE BOW TECHNOLOGY

As the final goal of the thesis, the results of testing in Chapter Six will be applied to iconographic evidence in Mesopotamia and Elam using a new methodology outlined in Chapter Seven to identify the date at which composite technology first appeared in these areas. As such, the conclusions of physical quantitative testing, in conjunction with the theoretical model developed in Chapter Four and matching the physical attributes of both length and profile shape of extant artifacts from the ancient world, provide a new method of evaluation of ancient iconography. The results indicate that the inception of the composite bow appears to have occurred sometime in the fourth millennium BCE, a conclusion which is approximately a thousand years earlier that commonly claimed by scholars. This is not to imply that composite construction only occurred at a single time or in a single place: bow artifact evidence from North America indicates that composite technology was developed independently at least twice (Mason, 2007, pl. 61; Sonneborn, 2007, p. 17; Mathaissen, 1930, p. 607). That being said, the thesis will follow the available evidence as far back chronologically as possible; a trail of evidence that to date ends in the greater Mesopotamian region, but moving forward quickly encompasses not only Egypt but Siberia and potentially (but not conclusively) Western Europe.

The question of dating the advent of composite construction dates to the late nineteenth century. By 1890, Balfour expressed the belief that the bows of Pandarus the Lycian and Odysseus were composite, and that composite weapons were known to the Parthians, Dacians and Scythians (amongst others) in the ancient world (Balfour, 1890, pp. 226-227; Harrod, 1981, p. 429; Rostovtzeff, 1943, p. 177). Along similar lines, Howard Carter's excavation of the tomb of Tutankhamen in 1922 held an entire cache of composite bows which date to 1323 BCE (Griffith Institute, 2004).

Certainly by the year 1900 the composite bow was known to have existed, at least amongst those with an interest in archery in the ancient world, in both the Assyrian empire and New Kingdom Egypt (Balfour, 1897, pp. 211, 213; Longman, 1895, p. 49). It is in New Kingdom Egypt that artifact and textual evidence for the composite bow largely stops. As such, it is not surprising that a number of scholars believe that prior to the Hyksos invasion of Egypt the existence of the composite bow cannot be proven (Spalinger, 2009, p. 15; Cotterell, 2005, p. 57; Credland, 1994, p. 30; Hamblin, 2006, p. 90). It is also at this point that the development of the composite bow becomes entwined with that of the light, spoke-wheeled chariot. Indeed, the most commonly quoted refrain with regards to the dating of the composite bow, if it is mentioned at all, is that the composite bow and chariot "were introduced to Egypt during the Hyksos period" (Spalinger, 2009, p. 15; Cotterell, 2005, p. 57; Albright and Mendenhall, 1942, p. 229; Drews, 2004, p. 49).

This repeated refrain, while most likely correct, also in large part side-steps the issue of composite bow dating, replacing it with a fact that is often presented in such a way that it implies the possibility of causation. Drews however expands on the origins of the composite bow with slightly more detail in his work *The End of the Bronze Age*, stating that the development of the chariot made the "pre-existing technology of the composite bow more effective" (Drews, 1993, p. 105). Drews does not provide any direct support for this claim, but does agree with Littauer and Crouwel that "by Hammurabi's time the two-wheeled chariot was beginning to show up on the roads of Mesopotamia and Syria" thereby indirectly supporting a date of at least 1792 BCE (Drews, 2004, p. 49; Littauer and Crouwel, 1979, pp. 50-52). For the majority of authors however, both limited space and the relatively small amount of evidence with regard to a date of inception has meant that the question of the development of composite bow technology is an issue that remains largely unaddressed. The continued association of composite bow and chariot and its implied possibility of causation (even if unintended) will be investigated in greater detail in Chapter Five, as it presents the possibility that the depiction of chariot archery could act as a potential proxy for bow profile with regard to iconographical analysis. In sum, the association of the composite bow with the invasion of the Hyksos pushes the date of inception of composite technology back to between 1900 BCE at the earliest and 1700BCE at the latest, and that this range of dates is accepted by a number of scholars with regard to the origins of the composite bow (Spalinger, 2009, p. 15; Westermann, 1928, p. 366; Credland, 1994, p. 30; Drews, 2004, p. 49).

The first scholar to date this development earlier than that associated with the Hyksos was Yadin, who claims in his two volume work *The Art of Warfare in Biblical Lands* that the victory stele of Naram-Sin was "the first pictorial representation of the composite bow" (Yadin, 1963, p. 150). Yadin's appraisal is based solely upon an examination of bow profile, with the understanding that a recurved bow profile would place sufficient stress upon the constituent materials as to make a bow of all wood construction untenable, pushing claims to the date of inception of composite technology to approximately 2250 BCE. The issue of bow profile will be important in the development of a new methodology of iconographic evaluation, and will be examined in greater detail in Chapters Four, Six and Seven alongside the variable of bow length, both of which directly relate to degree of materials stress (Kooi and Bergman, 1997, p. 129; Credland, 1994, p. 21; Galilie, 2000, p. 159).

A number of other authors also follow Yadin's claim that the Naram-Sin stele depicts a bow of composite construction, also based upon bow profile (Gabriel, 2007, p. 27; Gabriel and Metz, 1991, p. 9; Ebeling and Meissner and Ebeling, 1978, p. 339; Rausing, 1967, p. 83; Roberts, 1993, p. 47). As a group, the linking of the composite bow to the victory stele of Naram-Sin and their dependence on examination of bow profile represents the opposition to scholars following solely artifact based evidence.

Moving from the Near East, Selby, in his work *Chinese Archery* dates the inception of the composite bow in China to somewhere between 1700 and 1000 BCE based upon the shape of character used to depict the character for the word "bow" on extant oracle bone artifacts (Selby, 2006, pp. 32-33). While these dates correlate to some extent to the Hyksos, the idea of coeval development and its potential implications will be investigated in more detail in Chapter Five.

Gabriel, while linking the composite bow to the Naram-Sin stele actually believes that composite technology was developed earlier at approximately 2500 BCE, but calls the Naram-Sin stele the first visual representation, sentiments echoed by Archer (Gabriel, 2007, p. xiv; Archer, 2010, p. 61). Rausing takes a somewhat similar position, but pushes back the date to the "early or middle Neolithic period of China" based somewhat tenuously upon laminate bow artifacts dating to approximately 2600 BCE in Japan (Rausing, 1967, pp. 138-139). John Simpson in *The Oxford Encyclopedia of Archaeology in the Near East* similarly argues for the development of the composite bow in the fourth millennium BCE. The earliest assertion with regards to the dating of composite bow technology however goes to Collon, who claims that a Halaf potsherd dating to 4980 BCE depicts a bow of composite construction, again based on bow profile and consultation with the Society of Archer Antiquaries (Collon, 1983, p. 54).

Figure 2.5 Double-concave bow of all wood construction, Texas (1200-1500 CE).

Figure 2.6 Composite bow with segment profile (19th century?).

Figure 2.7 Unstrung self bow with reflexed profile (19th century?).

Scholars linking the composite bow to the Naram-Sin stele in essence make a twofold claim that: first, the stele depicts a bow with recurved limbs and double-concave profile and that second, this profile unto itself is sufficient proof of existence for composite construction. While there is evidence that recurved limb tips positively identify with composite construction, the correlation is not exclusive to composite construction, as seen in figure 2.5 (Miller, 1986, p. 182; Collon, 1983, p. 53; Rausing, 1967, pp. 38-39; Hamblin, 2006, p. 90). Rausing correctly points out that that bow profile is independent of construction given sufficient bow length a point shown by figures 2.5-2.7, a topic which will be expanded upon in Chapter Three when discussing ancient evidence.

Two scholars delve further into the question of dating in general and iconographic analysis in particular. The first of these is Hamblin, who points out that the examination of bow profile has been done in an inconsistent manner (Hamblin, 2006, pp. 86-92). Hamblin similarly questions that if the composite bow was in existence prior to the start of the second millennium BCE, why did this not result in its widespread adoption in a manner similar to that of the light, spoke-wheeled chariot (Hamblin, 2006, p. 94)? The second of these concerns is addressed in part in Chapter Five, which evaluates the need for a short bow (mandating composite construction) within the confines of a chariot, and again in Chapter Six which reveals the exact amount of performance improvement resulting from composite construction.

The second scholar is Rausing, who was the first (and to date the only) scholar to claim that bow profile *unto itself*, is inadequate with regard to determining bow construction, a point illustrated in figures 2.5-2.7 which according to conventional wisdom should not exist (Rausing, 1967, p. 20). The reason for this is that, given sufficient length (thereby lowering mechanical stress), a bow of all wood construction can be made in any of the profiles outlined previously as a part of the discussion on bow nomenclature. While a highly reflexed double concave bow would need to be exceptionally long to be viable of all wood construction, a mild reflex is possible as seen in figures 2.5 and 2.7. Likewise, a composite bow need not take on a double concave profile as seen by figure 2.6. Indeed, it was noted during testing in Chapter Six that changing the degree of reflex or deflex in a bow does *not* result in a change in strung profile, meaning that the unique curves of a double-concave (or double-convex) bow must be built into the design rather than resulting from the application of a sinew backing. Rausing's insight into bow length will be examined again later in Chapter Seven, where it will form the basis as a substitute for bow profile in iconographic analysis.

CONCLUSION

The current chapter has developed revised nomenclature systems for both bow construction and bow profile. While the primary benefit of these systems is to ensure clarity throughout the remainder of the thesis, as the most complete systems of their kind they also have the potential to increase uniformity of bow terminology (Randall, 2015, pp. 43-46). Along similar lines, major authors within the field of archery in the ancient world are identified. As a part of this process bow limb mass, bow profile and material properties were singled out as likely candidates for further evaluation with regard to the increased relative performance of composite construction in Chapters Four and Six. Additionally the possibility that the impact of one or more of these variables may vary with draw weight was noted, a point which will be examined later during physical testing. Finally, bow length was identified as a possible substitute for the iconographic evaluation of bow construction, a possibility that will be evaluated at the end of Chapter Five.

Thankfully, potentially conflicting evidence with regard to bow design and performance can be tested either directly in the case of the amount and reasons for performance differences, and the potential for bow/railing interference in chariot archery, or indirectly in the case of developing an improved methodology for iconographical analysis. Proper test design must of course take existing evidence into account. While recent efforts have already been examined herein, these efforts were based first upon the examination of ancient evidence in textual, artifact or iconographic form. As such, our attention must next turn to a brief examination of historical source material.

CHAPTER THREE

ANCIENT SOURCES

With the current state of research within the field of ancient archery outlined, attention can now turn to a variety of source material from Egypt (3200-1323 BCE), Mesopotamia and Elam (3800-1850 BCE), Siberia (2250-2000 BCE) and Europe (5500-2070 BCE). It is in no way the intention to describe every possible textual reference, artifact and image that relates to archery in the ancient world. Rather, the thesis will focus on sources most often used by scholars to either affirm or deny the existence of the composite bow, aided by representative examples to provide sufficient evidence that the resulting conclusions are valid within a broader context. Additionally, it should be noted that at several points throughout the thesis the author will refer to artifacts and images that are not associated with the ancient world at all. These later examples, drawn from later Medieval Europe, both pre and post-Columbian North America and the occasional reference to modern archery are introduced on a purely comparative basis to illustrate that a given design, practice or draw weight is both possible and has existed historically rather than remaining purely theoretical, or only possible with the advent of modern materials such as fiberglass or carbon fiber. Sources within this chapter are divided first by type, then by region and finally by *reverse* chronological order. It should be noted that not all sources are given equal coverage due to differences in their applicability to this study and amount of available information.

ARTIFACTS

Physical remains of bows from the ancient world are rare, as the constituent materials of wood, bone, horn, antler and most particularly sinew are all subject to physical degradation. The few examples which have fortunately survived offer a wealth of information to modern scholars (Whittaker, 2010, p. 199). Visual and x-ray analysis reveal material composition, including such details as composite, laminate and joined construction and the types of materials used. This often includes the species of wood (Insulander, 2002, p. 52; Soar, 2005, pp. 2, 4; Zammit and Guilaine, 2005, p. 63; Cartwright and Taylor, 2008, p. 77; Western and McLeod, 1995, p. 88). Exact measurement of physical dimensions and profile allow for the possibility of modern recreations and data for mathematical models which, if carefully done, can provide an accurate estimate as to draw weight, and given examples of arrows typical to the period and culture, arrow velocity and estimates on maximal range. Close examination of wood grain can at times even provide information as to the size of the tree or limb from which a given bow was made, details which provide clues to resource usage for a particular culture (Soar, 2005, p. 2; Hamm, 2002, p. 194). Destructive testing can also reveal tree species and the type of animal used for sinew, horn, antler, baleen or bone in cases of composite construction, and also opens up the possibility of C14 dating (Thomas and Kelly, 2006, pp. 184-5; Grant et al., 2008, pp. 102-3).[8]

EGYPT

The largest collection of complete bow artifacts (both composite and of self construction) found to date was recovered by Howard Carter during his excavation of the tomb of Tutankhamen (1332 - 1323 BCE) (McLeod, 1970, p. 2; Griffith Institute, 2004). The recovery of 27 composite bows is extraordinary in its significance. Only 10 other partial remains of composite bows have been discovered in Egypt, all dating to between 1600 and 1200 BCE. All of the composite bows recovered from Tutankhamen's tomb consist of a wood core with a sinew back (the side facing away from the archer) and a horn belly (the side facing toward the archer), save four, which consist solely of a wood core and sinew backing (McLeod, 1970, p. 32). McLeod goes on to state that all but three of the bows (bows 370jj, 596n and 596o as indexed by Carter's notes) have an angular profile. McLeod does not describe the profile of these bows, and no pictures of these particular artifacts exist other than them being bundled together in a jumbled mass in their original positions as found in the tomb. McLeod may have been basing his interpretation on the fact that the term "angular" does not appear on Carter's original note cards for these artifacts, which are also sadly devoid of sketches. A careful examination of the accompanying descriptive text written by Carter however shows that the three bows in question are either similar or identical to the construction of other bows in the same grouping. Working back through the associated note cards shows that the bows referred to as being similar or identical are in fact angular (Griffith Institute, 2004).[9] As such, while it is certainly possible that the three bows described by McLeod have a different profile, there is no evidence to support this conclusion, and it is possible that Carter simply failed to write the term "angular" on every card, particularly if dealing with bows of a consistent profile. As the bows are were found in a mortuary context, it should be noted that while the majority of weapons would have been usable, some were purely ceremonial. Most notably bow #48h was partially encased in gold, likely making it unsuitable for actual use (McLeod, 1970, p. 12). Another (bow #370ll) is a mere 34cm in length, potentially making it functional as a toy, but not for hunting or war (McLeod, 1970, p. 23; Leibovitch, 1938, p. 148). A number of other bows (#48f, #48g, #48i, #48j, #48k, and #370ff) recovered from the tomb were highly decorative, including details such as inscriptions and extensive decoration done in gold leaf and even small inlaid chips of blue glass (McLeod, 1970, pp. 3-17; Griffith Institute, 2004). While bows #48h and #370ll would not have been usable, their profiles remain

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[8] Dendrochronology, or the dating of wood by tree ring analysis, is not only destructive but is unlikely to yield usable dating information due to the fact that bows are both narrow in cross-section and are built lengthwise with the grain of the wood (Grissino-Mayer, 1999, p. 4; Kuniholm, 2001, p. 37).

[9] Items #370jj-1, #596n-1 and #596o-1.

consistent with the other composite bows found both within the tomb and from other sites (McLeod, 1958, p. 397; Blyth, 1980, p. 34; Howard, 2011, p. 8).

Of the composite bow artifacts from Egypt which do not come from Tutankhamen's tomb, all are in worse condition than those recovered by Carter, and most remain undated (McLeod, 1958, p. 397). Two fragmentary composite bows were however recovered from the tomb of Ahmose Penhat, "Attendant and Fan-bearer" to Thutmose I, and can therefore be dated from between 1526-1508 BCE. Another artifact, intact save for a missing grip, dates to either the end of the 17th or the beginning of the 18th dynasty and thus can be dated to roughly between 1600 and 1500 BCE (McLeod, 1962, pp. 15-16). In addition to the above artifacts, a selection of non-composite self bows has also been recovered in Egypt. Typically double convex in profile, the earliest of these (with the exception of the Den-Setui artifact) date to the 11th dynasty, or roughly 2000 BCE (Rausing, 1967, p. 70; Donato, 1994, 42).

The oldest bow artifact from Egypt is of joined construction, and consists of a pair of shaped Oryx horns mated together with a wooden plug, and recovered from the tomb of Den-Setui, fifth king of the first dynasty, Egypt (Rausing, 1967, p. 70; Baker, 1992, p. 77). Dated to between 3200 and 2950 BCE, the bow consists of at least two separate materials, but as the wooden plug does not make up any part of the working portion of the limbs, it is best categorized as a segment bow of joined construction.

SIBERIA

Moving from Egypt to Siberia, a series of sixteen partially intact bow artifacts have been recovered from graves in the Pribajkalja region northwest of Lake Baikal. Consisting of two, or in one case three, pieces of overlapping antler, these bows of joined construction have been identified by varve-dating to between 2250-2000 BCE (Michael, 1958, p. 12; Rausing, 1967, pp. 119-120; Mörner, 2014, p. 73; Ridge, 2016). These artifacts have received relatively little attention even within the field of history of archery, probably due to the fact they were recovered from a location which is not typically associated with composite construction. The importance of these artifacts however exceeds the meager scholarly attention they have garnered thus far as they represent the oldest known bow artifacts which are certain to be of composite construction. While only the belly laths remain, the fact that other layers at one time did exist is assured, as unlike wood, horn or baleen, a bow *cannot* be constructed solely out of antler, as it would snap under tension without being either glued or bound to a sinew backing and/or a wood core (Collon, 1983, p. 53; Elmy, 1968, p. 20; Gibbs, 1984, p. 32). While these artifacts could potentially represent a technological anomaly, later iconographic analysis done in Chapter Seven will show that a transition from self to composite construction occurred at least several centuries prior to 3000 BCE. In addition, the location of the find, combined with iconographic evidence from Mesopotamia, Elam and Europe is indicative that composite construction was potentially more widespread in the second and third millennia BCE than commonly believed.

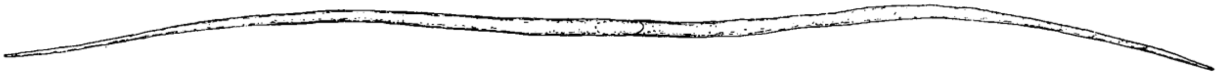

Figure 3.1 Antler belly laths dating to the end of the third millennium BCE, Lake Baikal Region, Siberia.

MESOPOTAMIA AND ELAM

In Mesopotamia and Elam, no extant bow artifacts have been found to date. Woolley, in charge of the excavation of the royal cemetery at Ur (circa 2300 BCE) however recovered what he believed to be decorative copper finials from a bow (Woolley, 1934, p. 226). While similar in appearance to finials shown in contemporary and later artwork of angular profile, exact identification remains unverifiable as no trace of the wood to which the finials were (presumably) attached remains. This is despite the discovery of numerous bundles of artifacts of approximately arrow length (50-70cm) having both metal heads and nocks (Woolley, 1934, p. 49). Additionally, to date no iconography depicting bow use has been recovered from Ur, a point in marked contrast to the spear and javelin use shown on the Battle Standard of Ur (2685-2645 BCE) (Moortgat, 1969, pl. 260).

Finally, the addition of copper finials is, unto itself, insufficient to attribute composite construction according the definitions outlined in Chapter Two as they would be decorative rather than functional and as such would not result in an increase in bow performance or materials strength. As such while potentially indicative of archery, the belief that the copper finials could potentially be associated with a bow remains problematic. Finally, while a number of traditional bows of a recurve design have inflexible (static) wood or bone ears, the addition of comparatively high-mass bow limb tips made of metal would unduly reduce arrow speed, a factor dealt with in more detail in Chapter Six.

EUROPE

Excavation of a burial mound in Northern Poland in 1980 contained what may be the burnt remains of a composite bow (Klochko, 1987, p. 16). As a part of the excavation, a line of charcoal and ash dating to the Early Bronze Age of the region (2310 - 2070 BCE) was found in the shape of a strongly reflexed unstrung bow as a part of the recovered grave goods. This particular find, while indicative rather than conclusive of composite construction, is important for its geographical and cultural separation from the previously discussed artifacts in both Egypt and Siberia. Straddling the demarcation between the Lausitz Culture and the Nordic Bronze Age sphere of influence, the find lends support to the possibility that composite construction technology may have been more widespread than previously believed. Measuring 90cm from tip to tip, the outline shows what appear to be ears from a static recurve design, with a total reflex of 25cm, too much recurvature for a bow of self construction of this length. Analysis of the charred remains show that while the main body of the bow contained a core made of coniferous wood, the ears consisted of deciduous wood.

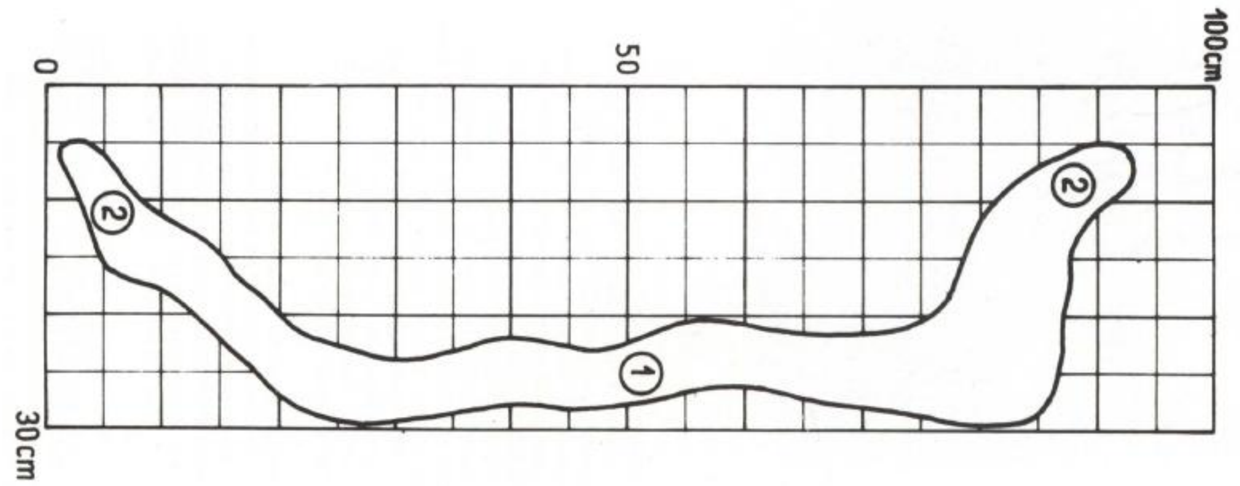

Figure 3.2 Burnt remains of grave good, consistent in size and shape to be a highly reflexed composite bow.

Certainly the size and shape are indicative of a composite bow, and the use of a different wood for the ears of a bow with a static recurve design would be typical, but analysis of the charred remains could neither confirm nor deny the presence of horn, antler or sinew (Klochko, 1987, p. 17). This failure to identify any non-wood material from the burnt remains precludes the possibility of confirming composite construction. Depending on the dimension of the original un-burnt item the artifact, if it indeed was a bow, could have been a non-functional ceremonial offering or perhaps even a short bow of low draw weight of laminate construction similar to the laminate bow recovered from Tuva (Godehardt et al., 2007, p. 115; Čugunov et al., 2003, p. 135).

Other, partial artifacts of an earlier date also exist, although they were found outside of the region typically studied by ancient historians. Of these several partial, broken and nearly intact bow artifacts have been found in Germany and Switzerland dating to the Mesolithic circa 6000 BCE (Burov, 1981, p. 376). Other partial bow artifacts have also been found in Denmark dating to circa 7000 BCE and in England dating to 2600 BCE but none show any clear indication of composite construction (Zammit and Guilaine, 2005, p. 63; Rausing, 1967, p. 40; Soar, 2005, p. 5; Rausing, 1967, p. 45). Finally, a self bow has been recently recovered from a Neolithic site in Spain. Dating to 5200-5000 BCE, the Spanish artifact appears to be the oldest intact bow artifact yet found in Europe (Barcelona, 2013). All of these artifacts however are definitively of self, rather than composite construction, limiting their usefulness to the current thesis.

TEXTUAL SOURCES

In addition to physical artifacts, a number of references are made to bows in ancient written sources. Unfortunately, the majority of these sources provide no information with regard to bow construction and the majority date centuries if not a full millennium or more *after* the inception of composite technology and so are of limited use to the primary focus of the thesis, with the discussion of Odysseus' bow being the most notable example (Homer, *Odyssey*, 21). That being said, a number of details can be gleaned from these sources that, taken together, provide evidence of typical bow ranges in the ancient world from which a potential range of draw weights can be inferred. The results indicate that bow draw weights remained consistent at approximately 23kg in draw weight, and that while bows of "heroic" draw weights most likely did exist, such weapons were the exception and in some cases, such as with Amenhotep II, are almost certainly the result of political propaganda (Spotted-Eagle, 1988, pp. 15-16; Rausing, 1967, p. 29; Decker and Klauck, 1977, p. 40). Finally, the source material provides insight into the culture from which it came, such as the social distancing of rulers in both Egypt and Mesopotamia from both the masses and nobles alike.

MYCENAE, GREECE AND ROME

As previously mentioned in Chapter Two, a number of sources allow for the estimation of range of the "average" composite bow as used in the ancient world, or at least in the ancient world from 700 BCE to 700 CE (McLeod, 1965, p. 4). Herodotus, Thucydides, Statius, Xenophon, Polybius, Strabo, and Vegetius all provide examples in which a known distance can be identified or reliably estimated (Herodotus, 8.52.1, 9.22-23; Thucydides, 3.20.3; Statius, *Thebaid*, 6.351-354; Xenophon, *Anabasis* 1.8.17-19, 4.3.1-6, 4.3.17-18; Polybius, 6.31.10-14; Strabo, *Geography*, 14.1.23; Vegetius, *Epitoma rei Militaris*, 2.23). The usefulness of this "average" range of between 150-250m in practicality likely extends across a much greater span of time, as for the vast majority of human history draw weights have remained stable at between 18-23kg and the same bows were used for both hunting and for war in antiquity (Spotted Eagle, 1988, pp. 15-16; Baker, 1992, p. 79; Rausing, 1967, p. 29). Cross-referencing of these ranges, outlined previously in Chapter Two by McLeod, are consistent with test ranges of modern composite bows made of traditional materials as well as the author's own personal experience with flight (long distance) archery (McLeod, 1965, p. 13; McLeod, 1972, p. 81; Baker, 1992, p. 115). Taken together, this strongly supports that the ranges reported in Greco-Roman sources are generally accurate, and that these distances were achieved with bows that were not significantly above average in draw weight for both the ancient and modern archer (perhaps topping out at 25kg in draw weight).

Several sources are similarly useful with regard to specifically mentioning either a bow's material composition or profile. Homer mentions bows on several occasions, but his use as source material must be taken with caution for while at least some of his information is drawn from oral tradition (which has its own potential problems with regard to validity), other information clearly dates to his own time (Snodgrass, 1974, p. 114; Folely, 2007, pp. 1-2; Burgess, 2001, p. 75; Frazer, 1993, p. 246).[10] The bow of Pandarus the Lycian could potentially be of composite construction, and is specifically mentioned to be made of ibex (*ἰξάλου* αἰγός) horn (Homer, *Iliad*, 4.105; Balfour, 1921, p. 291; Luce, 1975, pp. 109-10). Given the natural curvature of ibex horns, if Homer's description is indeed accurate Pardarus' bow could not be made of joined construction utilizing only horn and instead would have required the use of wood and/or sinew, thereby making his bow composite. That being said, a literal understanding of description of how the bow was made is indicative of joined, rather than composite construction, leaving us with no firm conclusion as can be seen in the text: "the worker in horn had wrought and fitted together (the horns), and smoothed all with care (*καὶ τὰ μὲν ἀσκήσας κεραοξόος ἤραρε τέκτων / πᾶν δ᾽ εὖ λειήνας χρυσέην ἐπέθηκε κορώνην*)" (Homer, *Iliad*, 4.110; Shewan, 1927, p. 176).[11] The bow of Odysseus is also generally accepted to be of composite construction given the statement that Odysseus examined the bow "lest worms might have eaten the horns" *(κέρα ἶπες ἔδοιεν*), although this point does not remain uncontested as it again could apply to a joined construction (Homer, *Odyssey*, 21.395; Rose, 1934, p. 343; Harrod, 1981, p. 429). While not necessarily indicating a particular method of construction, Herodotus mentions that the Arabians carried long bows which had a reflexed profile (τόξα δέ παλίντονα, literally "a bow bent backwards") when unstrung (*Histories*, 7.69). In the same passage, he describes the bows used by the Ethiopians as being both quite powerful and that they were made of palm-wood. Approximately 50 species of palm are native to Africa and some species of palm located in both Asia and South America continue to be used for bow-making in the modern day making Herodotus' assertion possible although its use, if correct, did not apply to Egypt which preferred acacia for bow-making (Johnson, 1998, pp. 16, 19, 105; Western and McLeod, 1995, p. 79; Mason, 1896, p. 868).

EGYPT

Several sources from Egypt deal with bow use as well as chariots (the latter of which will be discussed in greater detail in Chapter Five). While chariot use is somewhat ancillary to the performance of the composite bow, it is key with regard to assessing the importance of bow length with regard to composite construction, an issue which directly relates to the adoption of the chariot as a mobile archery platform. All of the sources date to the New Kingdom period, and when examined with care, provide some supplementary support for differing positions currently held in the field.

Source material mentioning chariots show that they were a both source of prestige and critical to New Kingdom warfare (ANE, EA 15; RA2, A.0.89.2; RAs, A.0.101.1). Official letters also show that they required regular maintenance that required skilled labor (ARM, 5.66). Finally, they

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[10] There is some controversy around this issue and a vast body of scholarship, but since the Homeric period is not the focus of the present study a detailed discussion has not been included.

[11] ἀραρίσκω is translated as 'join' or 'fit together' (Liddell, et al., 2009)

were very expensive unto themselves, but also incurred additional expenses related to the large numbers of horses needed to pull them (Papyrus Anastasi I). As a result of both the cost and prestige associated with chariot use, it was seen as a vehicle of both transport and war associated with the elite and very wealthy, including the Pharaoh.

The role of the Pharaoh must be properly understood within these sources, however. As the living manifestation of a god, the Pharaoh was never shown to have human failings of doubt or shown to have less than ultimate strength and skill (Decker, 1975, p. 21). Indeed, the element of power inherent in the position of Pharaoh made any open and fair competition impossible in ancient Egypt (Poliakoff, 1987, p. 108; Craig, 2002, p. 4). As such, accounts of archery featuring the Pharaoh were written such that the ruler's power was emphasized. The result can be seen in the portrayal of the Pharaoh Amenhotep II (1427-1401 BCE) shooting a bow of heroic draw weight whose arrows transfixed copper ingots instead of targets of mere wood (QT, 17; QT, 19). This heroic portrayal is mirrored in artwork covered later in this chapter, but the truth is that most likely the description was at best hyperbole, as experimental testing with a modern bow 22kg in draw weight showed that shooting at a copper ingot resulted in arrow penetration of only a few millimeters (Decker and Klauck, 1977, p. 40). Finally, the Pyramid Texts represent a collection of works, some of which pre-date the New Kingdom period (the oldest sections on question are attributed to between 2353-2323 BCE) that mention a number of different types of bows. Most particularly, the texts recovered from the tomb of Queen Neith (2246-2152 BCE) dating to the Middle Kingdom specifically reference two different bow profiles: "pillar" and "recurved" (Pyramid Texts, 219-220). While no further studies have been done on the matter, the author believes that the term "pillar" would refer to a self bow with a segment profile when braced and no appreciable reflex or deflex when unstrung (hence making it straight like a pillar). Similarly, the author believes that the term "recurved" refers to a double-convex bow of self construction. Both profiles were known during the Middle Kingdom and survive in both art and surviving artifacts. While the term "recurve" in modern parlance would typically indicate a double concave profile, both the double-convex and double-concave profiles would similarly require steam or heat bending to maintain their profiles, making the term appropriate in a generic sense (Hayes, 1990a, 279; Comstock, 1993, pp. 155-156; Schleining, 2006, pp. 141-142).

MESOPOTAMIA AND ELAM

Texts from the Mesopotamian region mention both archers and chariots which predate the New Kingdom period in Egypt. The information revealed beyond the existence of both of these innovations however remains minor, and subject to potential interpretation. The Law Code of Hammurabi (1754 BCE) contains a ruling that a "bow-maker is to be paid [x] barleycorns of silver" (Hammurabi, 274). The text is damaged, but it appears to imply a set rate per piece of work rather than a daily rate of pay. It similarly fails to identify what kind of bow the finished product would represent, and indeed even the rate of pay remains impossible to discern.

The approximately contemporary Enuma Elish creation story describes the monster Tiamat as being slain by Marduk with a bow; the weapon was subsequently raised to godhood (CAG, K 3449; Jacobsen, 1976, p. 182). The bow then was set to “hang in the heavens,” leading it to be associated with the rainbow in later biblical literature, while the bow of the god Anu (also attributed to “hang in the heavens, *sans* deification) is generally tied to the curving sweep of the milky way (Kraeling, 1947, p. 284; Carrier, 1889, p. 214) Again, no detail is provided about either of these bows, their profile or construction, but a single cylinder seal has been found belonging to a bow-maker dating to between 1953-1921 BCE, indicating that the profession had by that time already been designated to specialized workers (R4, E4.1.1.2010). Finally, much like in New Kingdom Egypt chariot use is seen to be critical to the military, and chariots are mentioned in formulaic greetings in correspondence between rulers (ANE, 85, 94, 111; RA2, A.0.75.8).

The funerary text of Ur-Namma (2112-2095 BCE) describes the inclusion of both chariot and bow (with arrows) as part of the grave goods. Sadly, not only is no detail provided with regard to the bow, the text remains ambiguous if the bow and chariot were meant to be used together or separately. Gudea Cylinder A (circa 2125 BCE) similarly associates the chariot and bow with slightly less ambiguity, as the quiver of arrows is definitively placed within the chariot so that the arrows are fanned out like sunbeams or "rays of light" (Gudea, A: 152-172; Jacobsen, 1987, pp. 395-396). The association however remains unclear if this pairing was or was not typical for the period, nor does it reveal if the arrows were meant to be actually shot from the chariot. Finally, the text in question specifically describes dedicatory objects for a temple and so the pairing could be symbolic in nature (Lambert, 1973, p. 276).

Earlier texts mention either bows or chariots separately, but not in conjunction with each other. Another chariot dedication was performed by Enmetama (2450-2400 BCE). While the chariot's name "Ningirsu's chariot, that heaps up (defeated) foreign lands" strongly implies a military role for the chariot in Mesopotamia at that time, it does not seem to be yet by associated with bow use (PI, La 5.4). A contemporary inscription describes a battle with Eanatum (2450-2400 BCE) where he was shot by an arrow, but no mention of a chariot is made (PI, La 3.1).

ICONOGRAPHIC EVIDENCE

In contrast to the relative dearth of textual sources and the small number of surviving artifacts, images of bow use either by infantry or by chariot forces is comparatively plentiful, consisting of alabaster reliefs, wall paintings, cylinder seals and rock art. Seals, or engraved cylinders of stone or other hard material, were often used throughout the ancient Near East (3300-300 BCE) and would be rolled across clay tablets as a kind of signature forming a sealing or an impression (Collon, 1990, p. 11). Typically, these cylinders were engraved with a scene or an image (a number of which depict bows either being carried or in use), at times accompanied by an inscription (Collon, 1997, p. 13). As these seals carried the authority of the bearer, they were typically used by the elite or administrative bodies throughout Mesopotamia Elam, and Anatolia, and their ownership and material composition (with harder materials being considered more impressive) at the time carried a certain level of prestige (Gorelick and Gwinnett, 1990, pp. 49, 53).

In contrast, rock art occurs throughout both prehistory and the ancient world. Examples include an array of styles, such as bas-relief, the pecking of designs into the top layer of stone by percussion, and painting with one or more different types of pigment. The current thesis looks at examples from Europe, Egypt and the Ancient Near East, and date from between 8500-1200 BCE. All depict a variety of different bow profiles, and many have been claimed by one scholar or another as representing composite construction (again, based solely on their profile). Many of the examples from within a given region show differing profiles yet overlap in time. As a whole this is strongly indicative that throughout history and into prehistory bows did not show absolute uniformity with regard to profile, and that bows with differing profiles (and at times, differing construction) often coexisted, a position that is contrary to Hamblin's assertions with regard to iconographic bow evaluation (Hamblin, 2006, pp. 92-4). Dating of these sources however is also the most problematic, for while graphic representations can often be placed chronologically by style, the dating of older carvings can at times come down to the rather imprecise practice of erosion analysis (Gamble, 2001, p. 5; Nash and Chippindale, 2002, p. 41). Additionally, the depiction of weapons within artwork can take on a number of symbolic connotations such as a sign of leadership, rank, or prowess in battle, hunting or even political or sexual potency (Topper, 1997, p. 295; Craig, 2002, p. 153; Cifarelli, 1998, p. 224; Parker, 1987, p. 75).

The evaluation of artwork in general however presents its own array of unique problems. Representations of both figures and items can, depending on the period and culture involved, be highly stylized, making identification of details uncertain (Manhire, 1985, p. 161). In such cases, proportionately less information can be gleaned from a given image, and the information that is gathered is increasingly suspect. As an example, the author has found that Egyptian artwork tends to over-estimate both bow and (even more so) string length when bows are shown at full draw but not when depicted at brace, a trend not noted in previous research. This point shall be a topic discussed at greater length later within Chapter Five. Even the evaluation of relative length between objects or between an object and the figure holding it can be skewed due to constraints of the area available, particularly when the object would normally extend significantly beyond the boundary of the base figure, an issue common across a number of cultures, but most often present when evaluating images presented within a tightly confined space. The possibility for anachronistic representation is also present. Simply put - the style of a weapon, hairstyle or details of clothing shown in a given piece of art could be contemporary to the time of its creation, or it could show a much earlier style preserved as a part of artistic convention. Rock carvings and cave paintings as a body of work are also notoriously difficult or at times impossible to date (Beckensall, 2002, p. 41).

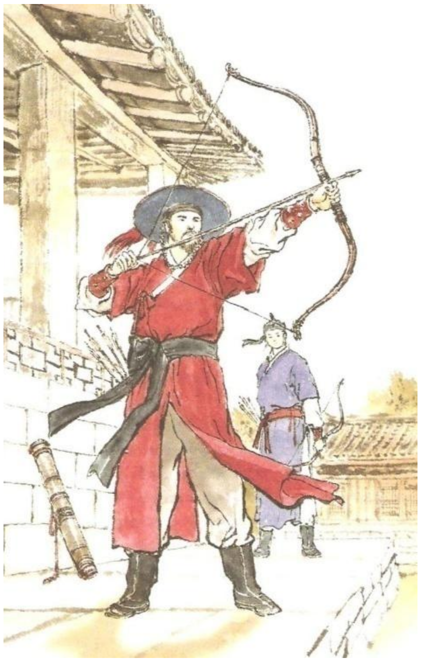

Figure 3.3 Book art showing bow at full draw. Note how little bend there is to the bow limbs compared to the length of the string.

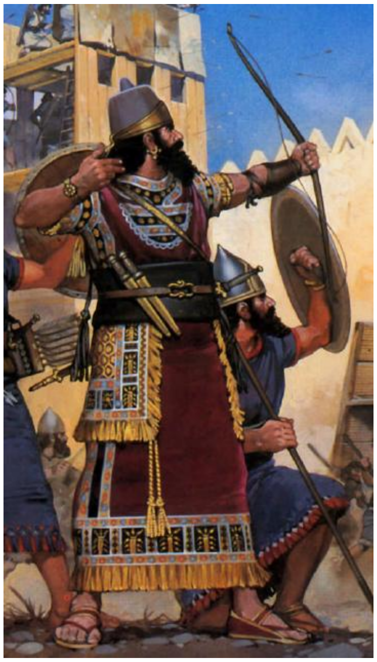

Figure 3.4 Detail of cover art of *The Ancient Assyrians*. Note the string, which is depicted so slack that it is actually flapping.

A final source of error must also be taken into account - poorly executed artwork. Bows in particular are difficult to accurately represent when at full draw unless the artist has considerable familiarity with archery, and often reveal a mismatch between bowstring length compared to the arc length of the bow (Randall, 2011, 106).[12] Even works specializing in early military history at times do not always account for these issues when depicting bows, including a case where a bowstring is shown erroneously flapping loosely upon release (Healy, 1991, cover).

While weapons depicted in art can indeed be interpreted symbolically, the currently thesis will focus more on extracting literal information with regard to visual representation. As bows were commonly used throughout the period under examination, an evaluation of bow profile is perhaps the most basic and most reliable piece of information which can be determined, particularly when fine detail, such as the exact angle or length of bow limb tips, is not needed (Lewis-Williams, 1983, p. 8). The author's evaluation of such is not controversial in this regard, and matches that of previous research although as the use of profile as an indicator of construction has been proven to be flawed previously in Chapter Two, the identification of

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[12] Despite vigorous protest by the author, the editors did not see fit to replace the image prior to publication.

profile is done herein to show diversity in bow design within (and across) time periods and cultures, a point which is not accepted by all scholars (Hamblin, 2006, pp. 92-94). Further, the thesis at times will cross-references different bows within a given artwork and occasionally across works of art within the same culture and time period as a means of correlating a bow's profile when shown both at brace and at full draw.

The second, and for the purposes of determining the likelihood of composite construction the most important piece of information utilized is the comparison of relative bow length to figure height, which will form a major component of Chapter Seven. To date this measurement has only been examined sporadically by both Rausing and Hamblin, but when combined with the results of physical testing performed in Chapter Six, provides a reliable method by which (with certain restrictions) composite construction can be determined (Rausing, 1967, p. 20; Hamblin, 2006, pp. 92-94). The use of relative length does of course require that a given work of art has a moderate degree of proportional accuracy, but this accuracy does *not* however need to apply to a scene as a whole. Rather, proportional accuracy only need be maintained for a given figure and any objects either worn or held in hand (in this case a bow). This sidesteps problems in works with hierarchical proportion where figures are sized according to their social status or importance, a common occurrence in both Egyptian and Mesopotamian art (Spalinger, 2009, p. 77; Bleiberg, 2005, p. 266; Black and Green, 1992, p. 93).

While some societies, such as Byzantine, are well-known for having a distinct lack of realism in representations of visual art, the cultures representing the primary focus of the thesis (ancient Mesopotamia, Elam and Egypt) have an established reputation for proportionality (Parani, 2005, p. 148; Robins, 1994, p. 122; Kantor, 1966, p. 147). Nevertheless, even in such cultures some degree of artistic convention remains and must be accounted for, such as the custom in both Egyptian and Mesopotamian art of not covering the subjects face. As such, to minimize the potential for errors whenever possible iconographic interpretations of relative length have been cross-checked against existing bow artifacts, and within the thesis such cases has been found to be highly accurate. Finally, it should be noted that every image will benefit from the author's own expertise as both an archer and bowyer. In such cases where a bow in its literal depiction would be non-functional (most often occurring due to the artistic inability to accurately render an oblique perspective) an interpreted evaluation will be performed.

Given the potential problems with evaluating iconographic evidence outlined above, it should not be surprising that the differences in opinion discussed previously in Chapter Two have emerged. Interestingly, these differences in opinion remain focused almost entirely on one of two points. The first is that diverging representation of bow profile within a given period and culture are representative of artistic inaccuracy or inconsistency rather than signs of the concurrent use of bows of differing design, a point that will be proven to be false later within the current chapter (Hamblin, 2006, pp. 92-94). The second centers on the current, almost universal method of construction evaluation, namely the comparison and interpretation of bow profiles as a means of determining bow construction; a premise already shown to be incorrect previously in Chapter

Two (Hamblin, 2006, pp. 86-87; Yadin, 1963, p. 81; Gabriel, 2007, p. xvi; Collon, 1983, p. 53; Rausing, 1967, p. 20). As the thesis will focus on the complimentary use of physical test results and proportional length, the results herein do not rely on taking sides in either point of contention. Rather, the use of basic iconographic information that requires minimal interpretation, cross-referenced against physical artifacts to ensure accuracy and combined with results of physical testing seeks to minimize room for potential error, and thereby provide a system for the evaluation of bow construction with a high degree of accuracy.

At this point however it is not the intention to present an in-depth analysis of the various images which have been claimed to represent the composite bow (which remains the focus of Chapter Seven), nor will an image of every claim be presented. Indeed, as the existing methodology of bow profile has already been shown to be insufficient, arguments regarding composite manufacture at this point are somewhat meaningless. That being said, unless otherwise noted, all of the imagery presented in the current chapter has been claimed to represent composite construction at some point. As such, a representative selection of images from different areas to which composite construction has been claimed will be briefly presented, with larger trends expanded upon later within the chapter such that iconographic evidence can be tied together with artifact and textual sources.

EGYPT

It should first be noted that all of the art presented in the current section is funerary art. As tomb paintings and associated goods were a luxury, they were only available to the affluent of ancient Egyptian society, and as such may present a skewed portrayal of bow use (Wilkinson, 1982, p. 26). Given that the presence of the composite bow in New Kingdom Egypt has already been established via artifacts, the artwork from this period presented herein will focus on what additional information can be gathered rather than on potential bow construction, and to what level of accuracy Egyptian artwork portrays bows with regard to comparative length, a major point of evaluation that will be covered in further detail in Chapter Seven.

An excellent example of such artwork is figure 3.5 depicting an archery lesson in progress dating to the reign of Thutmose III (1479-1425 BCE) (Commission des monuments d'Egypte, 1821, pl. 45). The profile of both bows is clearly double-convex. The accompanying inscription further states that the bow should be drawn "to the ear" (QT, 16). The presence of such bows, which correspond to self rather than composite construction, shows that the introduction of the composite bow did not completely replace bows of self manufacture. Additional support can be found in the presence of a number of self bow artifacts in the tomb of Tutankhamen (Griffith Institute, 2004).

The entreaty of “draw to the ear” however is clearly and commonly violated in depictions of the Pharaoh throughout the New Kingdom period, as can be seen in figures 3.6 and 3.7, which both depict the bows being draw to the back of the head if not the back shoulder (Griffith Institute, 2008; Breasted, 1903, pl. 2). Such "heroic" overdraw is physically possible given long enough arrows, a flexible enough bow and a draw weight that does not come close to the archer's physical limits (Elmy and Wood, 2000, p. 41). That being said, accuracy would suffer, as this style of draw does not provide a natural anchor point such as the aforementioned ear, or the corner of the mouth to ensure consistency. Further, figure 3.7 taken from the second pylon of the Ramesseum in particular shows a physically impossible scene - the bow is held in the left hand and drawn with the right, but the bow string appears to pass *behind* the figure's face and torso, indicating a left, rather than a right-hand draw. Such depictions are typical in Egyptian art, as it not only symbolically emphasizes the Pharaoh's power, but also his importance by never obscuring the Pharaoh's face (Wilkinson, 1991, pp. 90-91; Topper, 1997, p. 295).

Figure 3.5 Tomb of Min (1479-1425 BCE) at Sheikh Abd el-Gurhah (TT109). Note the double convex, profile to the bows.

The comparative lengths of the two weapons already discussed in figure 3.5 are similarly illuminating. As Egyptian art follows a canon of proportions based upon the height of a human figure, the space allotted to any given scene was laid out with a grid pattern to which the figures were to be fitted (James, 1985, p. 13; Benzel et al., 1998, p. 43). This system of proportionality did undergo minor change during the 26th dynasty (664-525 BCE) with the height of a human figure shifting from 18 units to 21 units, but this change occurred after the period under investigation within the thesis and as such it has no impact on the iconographical evaluation herein (Robbins, 1994, p. 122, Benzel et al., 1998, p. 43). As can be seen in figure 3.5, the adult figures are of equal height, while the leftmost figure represents a youth - drawn to the same proportions as the adults only smaller. Presuming an adult height of 170cm (a decision discussed in greater detail in Chapter Five), the double-convex bow at the right of figure 3.5 measures 181cm from tip to tip, and 204cm along the arc. In contrast, the bow on the left measures 125cm from tip to tip and 159cm when measured along the arc. Interestingly, the bows show that tip to tip length is consistent for both depictions with bow artifacts from ancient Egypt but the lengths along the arc are overstated when depicted at full draw (Griffith Institute, 2004; McLeod, 1970, p. 12; McLeod, 1981, p. 39).

Figure 3.6 Tutankhamen depicted on chest lid (18th Dynasty).

Figure 3.7 Ramses II (1279-1213 BCE). Note that the bowstring impossibly does not cut across the front of the Pharaoh.

Prior to New Kingdom Egypt, depictions of angular bows cannot be found, but bows with double-convex and segment profiles remain, as can be seen in figures 3.8 and 3.9. Notable however is that these two images depict a relative bow length compared to figure height that is shorter than seen in New Kingdom art. Artifacts from the Old and Middle kingdoms show that indeed, the average length was in general shorter (at approximately 140cm), however longer artifacts of up to 175cm have also been recovered (Cartwright and Taylor, 2008, pp. 78-79; Western and McLeod, 1995, pp. 79-80). All else being equal, a shorter bow length would mean an increase in materials stress, a point expanded upon later in Chapter Six (Middleton, 2007, p. 44; Galilie, 2000, p. 159). In an all wood bow, this would likely result in breakage. To compensate, it appears that draw length was correspondingly shorter prior to the New Kingdom for these weapons, as can be seen in figure 3.10 dating to 2050 BCE and depicting double-convex bows identical to those shown in figures 3.8 and 3.9, only at full draw (Porter and Moss, 1934, pp. 149-150; Newberry, 1893, pl. xiv). This shortening in bow and draw length matches physical findings in Chapter Six, and illustrates that relative bow length to figure height as a method of evaluation of bow construction, used unto itself and unconditionally, can potentially lead to a false positive result. As such, draw length must also be taken into account, a point which is incorporated into the in-depth iconographic analysis performed in Chapter Seven.

Figure 3.9 Model of Nubian archers, tomb of Mesehti, circa 2000 BCE.

Figure 3.8 Funerary stele of Min-oḳre, Thebes (2100-2000 BCE).

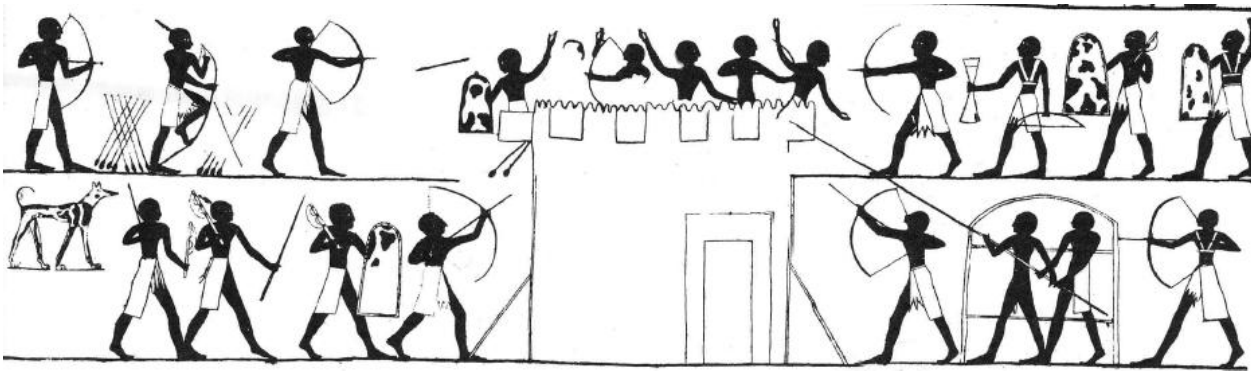


Figure 3.10 Wall painting, tomb of Khety (2050 BCE). Note the use of shorter draw lengths.

EUROPE

Several rock carvings showing what have been claimed to be composite bows have been found in Europe and Russia. Thus far the carvings have attracted little attention with regard to their potential value in the history of archery, likely because they are located geographically outside the ancient Near East which to date has been the primary focus of attention with regard to the question of composite construction (Yadin, 1963, p. 150; Gabriel and Metz, 1991, p. 9; Hamblin, 2006, pp. 92-94; McIntosh, 2005, p. 188). The images shown in figures 3.11-3.13, which are located on the headlands of Lake Onega in Russia near the White Sea, have been identified by careful examination of micro-erosion to date to between 2500-2000 BCE (Raudonikas and Zemljakov, 1938, p. 57, Rausing, 1967, p. 50; Bednarik, 1993, p. 459). Thus far, the only scholar to claim that these carvings represent bows of composite construction is Rausing due to their short length compared figure height. The petroglyphs show representations of people holding what are perhaps bows, and are highly stylized in nature. One (shown in figure 3.13) appears to have been shot by multiple arrows. The bows, if they indeed are bows, each have a different profile with figure 3.11 holding what appears to be a double-concave bow with substantial "ears." In contrast, the bow held by figure 3.12 appears to be double-concave with a set-back grip mirroring the archetypical profile seen in depictions of later Scythian weapons. Finally, figure 3.13 holds a bow with a segment profile. This evaluation however follows Rausing's assumption that the figures are indeed holding bows. Figure 3.13 in particular, which appears to be arrow-riddled, raises doubts as to this evaluation. If the figure shown in 3.13 is indeed holding a bow, then what of the two arrows protruding from said bow? Indeed, when looked at without preconception, the bow could just as easily be a shield, with two of the many arrows protruding from the body having been blocked. In short, the figures are so stylized that it is difficult to be certain that the figures depict bows at all. If the figures do in fact depict bows then the best that can be said is that like Egypt, bows with different profiles appeared to have co-existed at the same time within the Lake Onega region.

Figure 3.11 Rock carving (2500-2000 BCE), Lake Onega, Russia.

Figure 3.12 Rock carving (2500-2000 BCE), Lake Onega, Russia.

Figure 3.13 Rock carving (1500 BCE), Lake Onega, Russia.

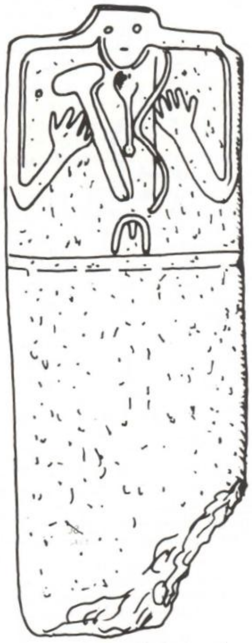


Figure 3.14 Stele (3000-2500 BCE), Poland.

Similar problems exist with most other iconographic evidence in Europe. Both a stele from Poland (figure 3.14) and a rock carving from Germany (figure 3.15) purportedly depict composite bows (Klochko, 1987, p. 19; Rausing, 1967, pp. 38-39). While the styling and level of detail on both of these carvings are fairly evocative of a bow with an angular profile, the identification of both depictions remains in question. Figure 3.15 is particularly problematic, as the scene offers no recognizable context from which the conclusion that it represents a bow can be drawn. With no figure or arrow, the lines could be practically anything, and is perhaps best described as a "sine-wave" pattern divided by a median line. The stele fairs slightly better, as the face and arms at least indicate a figure, and positioning lends credence to the interpretation that this figure "holds" a total of three objects. The precise determination of each of these objects however, the rightmost of which closely resembles a bow with an angular profile, remains impossible.

Finally, a rock painting from the Spanish Levant depicting a hunting scene dates to between 8500 and 5500 BCE, an exceptionally wide range of dates that sadly cannot be narrowed down further (Chippindale and Nash, 2002, p. 41; Dams, 1984, p. 130; Wilkinson, 2003, p. 55). The scene depicts two huntsmen holding bows and presumably shooting at a deer. Several marks which resemble arrows mark the "ground" before the animal. The animal is the most prominent figure in the scene, likely an expression of its relative importance (Topper, 1997, p. 298). As the most recent plausible dating for the scene just barely overlaps the introduction of pottery to the region, a technology commonly viewed as a prerequisite for the development of composite technology, claims to composite manufacture are tenuous (Jameson, 1999, pp. 359-360; Zammit and Guilaine, 2005, pp. 107-108; Rausing, 1967, p. 156). The shapes of the bows depicted however are of importance, as they differ markedly in profile. The upper figure holds a bow with a segment profile, but the lower figure is shown with a clear depiction of a bow with a double-concave profile and set-back grip. Unlike the petroglyphs from Lake Onega the figures and more importantly, the bows, are depicted much more clearly.

While no scholars (including the author) lay any claims to composite construction for figure 3.16 the scene is important for two reasons. First, it further reinforces the concept that bows with differing profiles co-existed for periods of time which has been previously discounted by Hamblin (Hamblin, 2006, pp. 86-87). Second it again illustrates that bow profile, the primary mean of identification of bow construction used to date, is insufficient (Hamblin, 2006, pp. 92-94; Yadin, 1963, p. 81; Gabriel, 2007, p. xvi; Collon, 1983, p. 53; Rausing, 1967, p. 20).

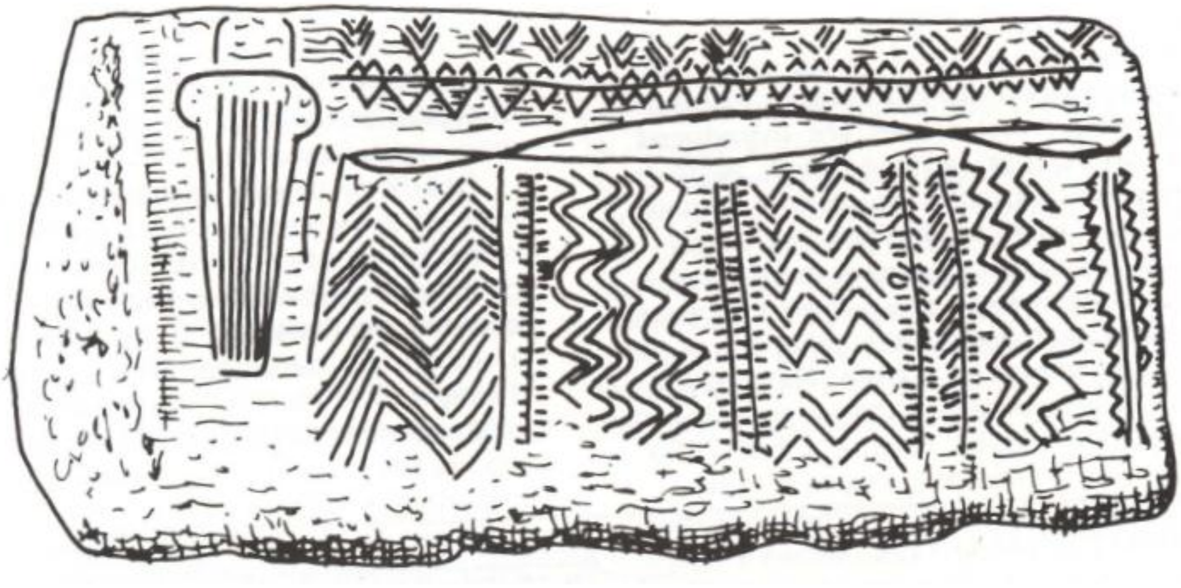


Figure 3.15 Rock Carving (2500-2100 BCE), Gölitsch, Germany.

Figure 3.16 Rock paining (8500-5500 BCE), Spanish Levant. Note the depiction of differing bow profiles.

MESOPOTAMIA AND ELAM

By far the greatest amount of attention with regard to the origins of the composite bow has focused on the Mesopotamian region. As the current chapter is intended to be a review *in brief* of the available evidence only a select number of images about which claims of composite construction have been made will be discussed with the purpose of identifying trends. Evidence from the region consists of several different categories of objects, most notably cylinder seals, cliff-side bas reliefs, freestanding stele and two potsherds, one from Tepe Jowi, and another from Arpachiya. As the composite bow is believed to have been brought into Egypt by the Hyksos by 1782 BCE, the examination of ancient artwork herein should similarly begin at either this date or shortly before (Booth, 2005, p. 6; Gabriel, 2007, p. 87).

Mesopotamian art in many ways follows conventions found in Egyptian art: scenes are organized into registers, proportional hierarchy is at times used to depict important figures such as kings and gods, and proportionality is based on the height of the human figure as well as a lack of depth or illusion of perspective (Kantor, 1966, p. 147; Tomabechi, 1983, pp. 124-125). A number of cylinder seals have been recovered which date to the early third millennium BCE, filling the gap between Egyptian evidence and the more famous stele of Narman-Sin. As artwork in miniature, seals, much like other smaller works of art in many ways magnify the potential for proportional distortion - particularly with regard to elements which extend (or should extend) significantly above or beyond that of any depicted figures as the depiction of people often takes up the entire vertical expanse of the register (Kantor, 1966, p. 147). Thankfully this distortion is typically avoided with bows as the unlike a spear, the weapon rarely projects above the figure even when shown at full draw, and similarly does not project beyond a figure's outstretched arm, thereby avoiding a similar distortion in the horizontal direction.

The first of these seals comes from Sippar and dates to 1850 BCE (Collon, 2005, p. 47; Werr, 1980, pp. 41, 63). The seal is quite small (figure 3.17 is shown twice actual size), and has lost a good deal of its finer detail but the bow held by the central figure is still easily discernible. The bow is carried in the left hand, is quite short, and has what appears to be an angular profile. Similar imagery can be seen in slightly earlier seals from Akkad (figures 3.18 and 3.19). These three seals all feature similarly short bows, although those from Akkad have a double concave, rather than an angular, profile (Hamblin, 2006, p. 92). In particular, the seal shown in figure 3.19 has retained all of its fine detail and has an exceptional level of realism, particularly compared to the somewhat "stretched" stylistic appearance of figure 3.18. Hamblin references both of the seals from Akkad, briefly mentioning the recurved tips on both bows, but makes no particular claims as to whether they indicate composite construction or not, yet expresses the opinion that "Akkadian artists were not overly concerned with accurately representing the weapons they saw" based upon differences between the bow profiles shown in figures 3.18-3.20 (Hamblin, 2006, pp. 92-93).

Figure 3.17 Seal Impression, Sippar, 1850 BCE.

Figure 3.18 Seal Impression, Akkad, 2200-2159 BCE.

Three additional cylinder seals show depictions of bows being drawn or otherwise in use (figures 3.20-3.22). Figure 3.20 closely resembles figure 3.18 stylistically, with its depiction of gods and stretched appearance of the figures. The bow is again quite short, and appears to be possibly angular in profile. Figures 3.21 and 3.22 show bows in use. Figure 3.21 again has a stylistically stretched appearance. The bow is clearly double-concave with pronounced ears, but the bow is shown only drawn to the chest, an anchor point supported by the position of both the elbow and shoulder of the left (draw) hand. Figure 3.22 shows a bow with a similar profile but the seal is so worn that the draw point remains unclear. Given that several of the seals are executed somewhat poorly (figures 3.20-21), are significantly worn (3.17, 3.22) or are stylistically somewhat abstract (3.18, 3.20-21) the bows all show a remarkable degree of consistency in bow profile (double-concave or angular) and comparatively short in length across a period of approximately four centuries.

Figure 3.19 Seal Impression, Akkad, 2200-2159 BCE.

Figure 3.20 Seal Impression, Kish, 2334-2193 BCE.

Figure 3.21 Seal Impression, 2334-2193 BCE.

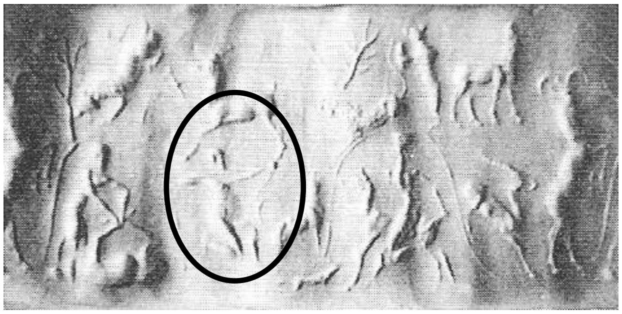


Figure 3.22 Seal Impression, 2334-2193 BCE.

Bow depictions found in monumental structures maintain a similar level of consistency. The bas relief of Darband-i-Gawr (dated by Strommenger on the basis of stylistic analysis to circa 2200 BCE) and the victory stele of Naram-Sin (2254-2218 BCE) both depict short bows at rest held in the left hand just as in found in figures 3.17-19 (De Morgan, 1900, pp. 144-145; Edmonds, 1925, pp. 63-64). The two scenes also show what appears to be a recurrent layout; both depict figures with one foot raised, crushing defeated enemies underfoot. A number of details however vary between the two images, including the depiction of the bows. While the Darband-i-Gawr relief shows a bow with an angular profile, the Naram-Sin stele depicts a double-concave bow with substantial ears. Hamblin points to this difference as a prime example of inconsistencies in Yadin's argument that the composite bow existed by the time of Naram-Sin, which both Hamblin and others ascribe is depicted in both images (Hamblin, 2006, p. 92; Meiroop, 1999, p. 219; Meissner and Ebeling, 1978, p. 339). It is true that the Darband relief shows a bow with a different profile. It is also true that the Darband relief has not been regularly incorporated into the larger analysis of bow profile on a consistent basis, likely in part to the fact that while the first images of the site were published in 1925, the first real archaeological investigation was only done in 1960, and therefore was not well-known at the time Yadin and Rausing published their works later in the same decade (Strommenger, 1963, p. 83; Hamblin, 2006, p. 86; Edmonds, 1925, pp. 63-64). The critique is potentially valid if the Darband relief also depicts Naram-Sin, although the co-existence of bows with different profiles elsewhere as shown earlier herein lessens the impact of the claim substantially.

Not everyone however agrees that the Darband relief depicts Naram-Sin. Strommenger points out that while the Darband relief is certainly done in the Akkadian *style*, no names, dates or inscriptions accompany the image, making precise identification impossible, although it has also been attributed to a Lullu King (Strommenger, 1960, pp. 84, 88; Orthmann et al., 1975, pp. 202-3; Houtsma et al., 1993, p. 538). Again, it can be said that two different profiles of bow appear to co-exist and that both styles are quite short. Hamblin further argues that a figure in the lower register of the Naram-Sin stele (not shown) depicts yet another profile of bow (Hamblin, 2006, pp. 86-87). As the author will actively refute this point later in Chapter Seven in detail the issue will be set aside until then.

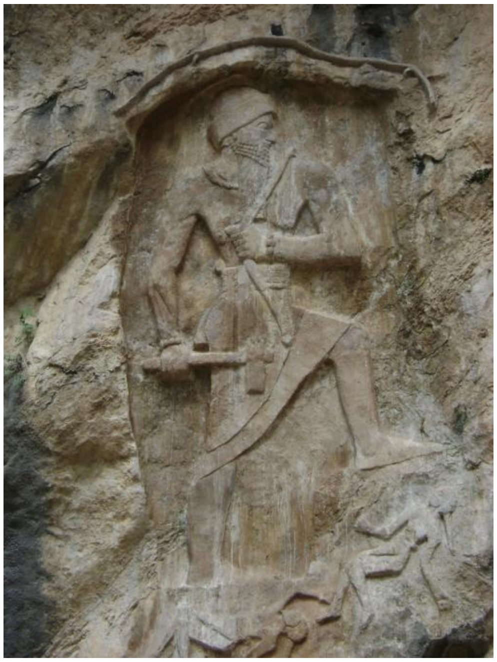


Figure 3.23 Darband-i-Gawr bas relief, 2200 BCE.

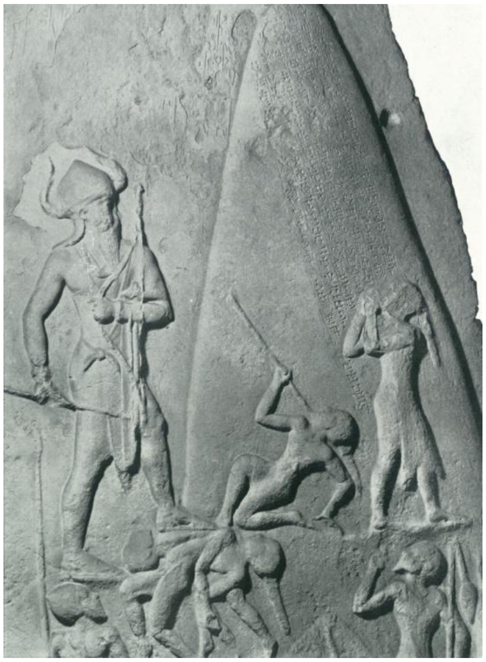


Figure 3.24 Victory Stele of Naram-Sin, 2254-2218 BCE.

This continuous progression of short angular and double-concave bows does not continue unaltered. Prior to approximately 2400 BCE a change in bow profile can be observed. Figures 3.25 and 3.26 both depict bows which appreciably thicker than those seen previously. As both of these figures are shown with the bows at full draw it is difficult to determine their profile at brace, but bow draw appears to have shifted, as both use an anchor point lower than that seen in later art. While the draw point appears to match the ear, the anchor point is instead the nipple, which would equate to a somewhat shorter draw length due to the oblique (rather than full profile) stance taken when shooting, approximately equal in draw length equal to drawing to the corner of the lip. To date, no scholar has examined figure 3.25 with regard to its impact on the field of archery, but Rausing claims that the Lion Hunt Stele depicts a composite bow based upon relative bow length (Rausing, 1967, p. 82; Collon, 2005, p. 192; Amiet, 1972, pl. 1014).

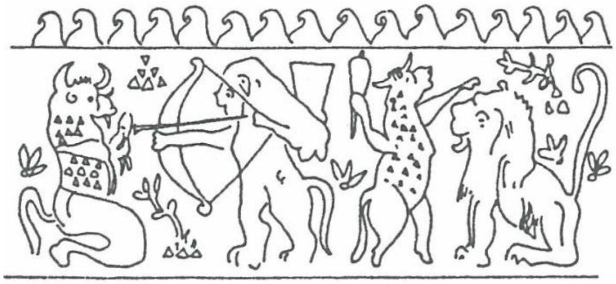


Figure 3.25 Seal Sketch, Susa, 3000-2334 BCE.

Figure 3.26 Lion Hunt Stele, Uruk, 3250-3000 BCE.

These two figures are not isolated. Two additional cylinder seals show the same trends with additional detail. Figures 3.27 and 3.28 show double-concave bows, in this case with limbs of varying thickness. Figure 3.27 depicts a hunt, while figure 3.28 clearly shows a bowyer's shop (Collon, 2005, pp. 155, 163; Wallenfels, 2003, p. 23; Hamblin, 2006, p. 90). From a design standpoint such weapons would be unusable if the images are interpreted literally; the increase in thickness mid-limb would cause the bow to break. An alternative explanation however does exist. If the bows are interpreted as being shown in at attempt at an oblique perspective, then the varying limb thickness could just as easily represent variations in limb *width*. The result would be a bow with a thick, narrow handle which transitions to thin, wide limbs that gradual taper toward the nocks, the same style that can be seen in the Mere Heath artifact, the Sudbury Bow and modern recurves, including those used for testing in Chapter Six (Herrin, 1993, p. 64; Soar, 2005, p. 5; Allely and Hamm, 1999, p. 34).

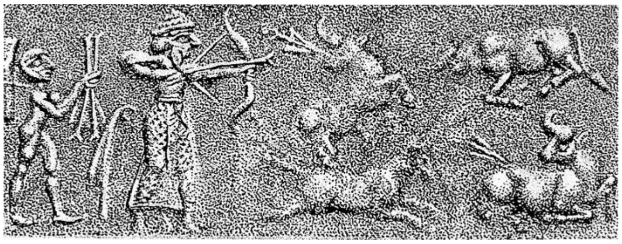


Figure 3.27 Seal Impression, Uruk, 3300-3000 BCE.

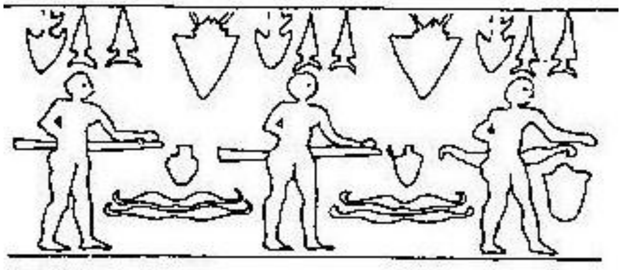
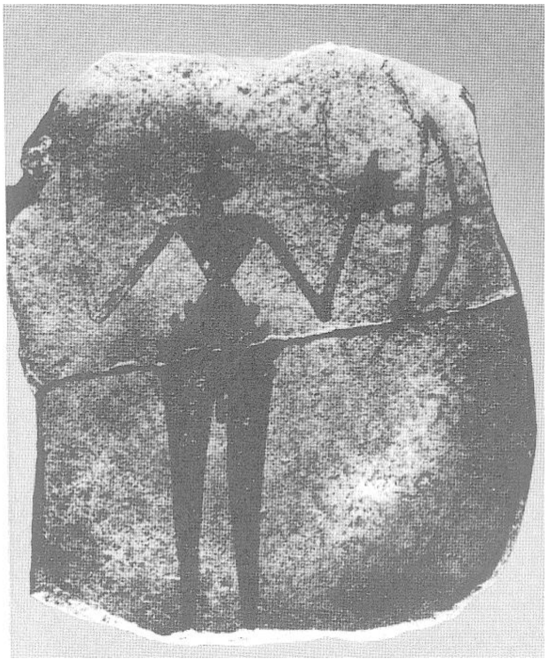


Figure 3.28 Seal Sketch, Uruk, 3500-3000 BCE.



3.29 Potsherd, Tepe Jowi, Iran 4200 BCE.

3.30 Potsherd, Arpachiyah Iraq 4890 BCE.

The two potsherds mentioned at the beginning of the section sadly cannot be relied upon to provide the same level of detail as that found on either the larger works or seals due to their high level of stylistic abstraction, a problem that can often occur in pottery in part due to due curved surfaces but also cramped spacing (Ehrich, 1954, p. 42). Profile for the fragment from Tepe Jowi is clearly discernible as a segment shape, but styling of the figure makes the possibility of proportional analysis unreliable. The potsherd from Arpachiya suffers similarly. The bow (an attribution claimed by Collon who asserts is composite in construction), if it indeed is a bow is double-convex in profile (Collon, 1983, p. 55). The item held by the figure certainly *could* be a bow, a deduction that is supported by the presence of what appears to be a back quiver (with an exaggerated dangling tassel reminiscent of that seen in figure 3.19). The image however could also potentially be a shield or some other implement, and the depiction of both arms fully extended leaves a certain attribution in doubt. Like the claims of composite construction for the European rock carvings already described, the potsherds potentially illustrate diversity in bow profile that extends back into the fifth millennium BCE, but are stylized to the point that they cannot be used for further analysis later in Chapter Seven.

CONCLUSION

Taken as a body of evidence, several conclusions can be drawn. First and foremost, a form of composite bow can be dated to at least the end of the third millennium as shown by the bows recovered from the Pribajkalja region in Siberia (Michael, 1958, p. 12; Rusing, 1967, pp. 119-120). While the Pribajkalja artifacts could potentially represent a technological anomaly, the author will endeavor to show that such is most likely not the case through detailed iconographic analysis done later in Chapter Seven. Archaeological evidence in both Poland and Ur could potentially point to even earlier use, but the finds lack the actual physical remains of a bow making any conclusions at this point speculative (Klochko, 1987, p. 16; Hamblin, 2006, p. 53; Woolley, 1934, p. 461).

Textual evidence provides several points of supplementary information, including bow use in southern Mesopotamia during the reign of Gudea (2125 BCE), and that bow use can be associated with the chariot at the end of the Second Intermediate Period in Egypt (1539-1514 BCE) (QT, 19; CAG, 5.6R.20-30; Gudea, A: 152-172). Later sources from the Greco-Roman period provide evidence that the average effective range in the ancient world for the composite bow was between 150 and 250m, and that this range matches modern data for bows between 18-23kg in draw weight (Strabo, *Geography*, 14.1.23; Vegetius, *Epitoma rei Militaris*, 2.23; Xenophon, *Anabasis* 1.8.17-19, 4.3.1-6, 4.3.17-18; Blyth, 1980, p. 34; Spotted-Eagle, 1988, pp. 15-16). This range in draw weight was common throughout history, and remains the case in the modern day. Finally, while Homer's works provide suggestive evidence for composite construction, they are less useful as they date long after existing composite artifacts from both New Kingdom Egypt and the Pribajkalja artifacts.

Additionally, the advent of composite construction methods in Egypt did *not* result in the complete replacement of self or other bow construction methods, as can be seen in artifacts from the tomb of Tutankhamen (Griffith Institute, 2004, McLeod, 1970, p. 2; McLeod, 1981, p. 38). The continued use of bows of self manufacture centuries after the introduction of composite construction unto itself should not be surprising. Self bows continued to be (and remain) effective weapons (Wilson, 1901, p. 515; Milner, 2005, p. 146;). The use of composite construction in contrast represented a significant increase in cost in terms of materials and construction time in exchange for some degree of increased performance, an issue that will be the focus of Chapter Six (Casson, 1969, p. 63; Healy, 1992, p. 13; Wilkinson, 1982, p. 4). This tradeoff is one that will not always be worthwhile depending on the factors facing an individual culture, including such issues as what number of weapons is needed, and the nature of armor and weaponry utilized by the enemy (Phillips, 1999, p. 576).

Of additional interest is that while the production and use of self bows continued for at least several centuries after the advent of composite construction techniques were introduced to ancient Egypt, the iconographic adoption of the composite bow with regards to the Pharaoh was rapid and universal starting with Ahmose I (1539-1514 BCE). This represents a real but understandable "mismatch" between iconographic depictions and artifact evidence, potentially indicative of the difference between that of the Pharaoh as the living embodiment of a god (and elite troops such as the chariot corps) using only the finest equipment compared to the realities of the average infantryman, where well made but serviceable equipment of less expensive self manufacture continued to be used by at least a portion of the rest of the army (Hamblin, 2006, p. 3; Spalinger, 2009, p. 251).

With regard to the similar but separate issue of bow profile (as opposed to construction technique), it is clear that the depiction of bows of differing profiles and designs at any given period and culture was not unusual, and differing profiles coexisted across the ancient world in Mesopotamia, Elam, Egypt, and Western Europe. As both bow artifacts and artistic representation have been shown to vary in both length and profile within ancient Egypt, similar diversity in iconography elsewhere should not be considered unusual.

Finally, while it was shown in Chapter Two that iconographic sources cannot be used to determine the method of manufacture solely on the basis of bow profile, shifts in bow profile and length can be seen in both Egypt and Mesopotamia over time. These shifts will be examined in greater depth in both Chapter Five, where bow length will be examined as a function of chariot archery, and in Chapter Seven, where proportional bow length, in combination with draw length will be shown to be a viable method for determining potential composite manufacture. Before either of these points can be addressed however, a better understanding of bow mechanics is needed, and as such shall be the topic of Chapter Four.

CHAPTER FOUR

BOW MECHANICS

This chapter will identify and briefly explain the various factors involved in bow mechanics. A clear understanding of this process will allow the differentiation of which variables potentially apply to the performance differences associated with composite, rather than self, bow construction such that they can be subject to physical testing in Chapters Five and Six. While it is by no means the intention of the author to engage in extensive mathematical modeling, it is precisely because certain aspects of bow related themes are under-researched that some attention must be given to a brief discussion of bow engineering and design. The chapter encompasses a theoretical understanding that can be applied to all bows, thereby providing a baseline of understanding for how bows work in general, a necessary foundation which allows identification of which elements could potentially apply to the performance enhancement typically associated with composite manufacture. As such, the primary goal of this chapter is to form a basis for understanding the testing and analysis which is to follow in Chapters Five and Six. Perhaps even more importantly however, it also forms a foundation of knowledge from which both existing and future literature can be evaluated with regard to the historical capabilities of the bow and arrow as a weapon system. The result is a purely functional overview - intentionally so not because bows, arrows and their use was uniform throughout time and place (which is clearly untrue), but to ensure that the mechanics explained in the current chapter can be applied to bow performance in general regardless of context. As a result, the following section deals with an explanation of the physics of energy storage and release involved in bow use.

This is not to say that all cultures have strived to achieve an "optimum" bow design that focused on increased range. Indeed, each and every design and construction method is a unique solution to a complex set of material, economic, environmental and cultural constraints matched against the varying physical needs of power, accuracy, comfort, and ease of use. As one of the initial problems outlined in Chapters One and Two however deals with uncertainty of how, why and to what degree composite construction can outperform self construction, the conclusions made at the end of this chapter and carried forward into Chapter Six dealing with physical testing are focused primarily on factors influencing energy storage, energy transfer efficiency, and arrow velocity.

From an engineering standpoint, a bow is essentially a double-ended leaf spring (Kooi, 1994, p. 15; Farmer, 1994, p. 680). As the bow is drawn, energy is stored in the bow's limbs in the form of elastic deformation caused by both tension and compression. Upon release, much of this energy is transferred to an arrow through the bow string. The transfer of energy from bow to arrow is not perfect: some energy is spent returning the mass of the bow's limbs (and string) back to their original position, some energy remains in the bow, inaccessible for use, and a measure of additional energy is lost due to a variety of other inefficiencies, including hysteresis, and nock friction (Kooi and Bergman, 1997, p. 128; Klopsteg, 1943, p. 178; Kooi, 1994, p. 17). A very small portion is converted to heat, and another portion is expended by the upper limb of the bow as it overcomes the force of gravity (travelling upward) toward its natural state of rest (Denny, 2007, p. 28).

Although a large number of factors go into calculations which can accurately model arrow velocity, which typically reaches its maximum between one and three meters from the bow upon release, these variables can be broken down into two basic groups: factors influencing energy storage, and factors influencing energy output (Baker, 1992, p. 44; Kooi and Bergman, 1997, p. 128). Rather than introduce mathematical models to describe these factors, this thesis will focus on a clear description of each variable, their influences on bow performance, and some of the limits encountered arising from both materials strength and practical use.

ENERGY INPUT FACTORS

Energy input factors can be broken down into four variables: draw weight, draw length, brace height, and (unstrung) bow profile (Baker, 1992, p. 44).[13] Each of these factors is fairly simple in itself, but also has the potential to affect other energy input and output factors in a positive or negative fashion.

DRAW WEIGHT

Draw weight is the amount of force needed to draw a bow back a given length.[14] Modern bows are typically described by their draw weight (described in pounds) as in a "50 pound (22.72kg) bow." The greater the draw weight, the greater the amount of force needed to draw the bow, and the greater the amount of energy stored. Although bows can theoretically be made in almost any draw weight, a number of practical limitations exist. For common usage today, draw weight most commonly varies from ten pounds (4.54kg) for a children's toy bow with arrows topped with suction cups to 70 pounds (31.81kg) for a very powerful commercially available hunting bow.

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[13] Although any brace height (the distance between the bow handle and the string when braced) greater than zero inherently decreases the amount of possible energy that can be transferred to the arrow, it is directly linked to energy *storage* rather than inefficiency of energy transfer.

[14] Full draw as a measure of distance will depend not only upon the design of the bow, but also the archer and his or her physical anatomy and choice of anchor point.

While both historical and modern bows have been made with higher draw weights, even the above mentioned 70 pound draw weight would be unusually heavy (Baker, 1992, p. 79; Spotted-Eagle, 1988, pp. 15-16). Given that a draw weight of between 45 and 55 pounds (20-25kg) is more than adequate to kill all but the very largest game, it appears that the higher draw weights seen in medieval longbow and Turkish flight bow artifacts do not represent the norm for the ancient world (Baker, 1992, pp. 78-79; Blyth, 1980, p. 34; Godehardt et al., 2007, p. 117).

As mentioned previously, a number of limits exist with regard to draw weight. The most notable limitation is probably that of human capabilities. In other words, while it is possible to make a bow with an exceptionally high draw weight there would be no point in doing so unless a person could actually draw it. Exactly where this limit lies is of some debate and of course will vary with an individual's training and level of fitness or bow-fitness. One bow artifact recovered from the wreck of the Mary Rose has an estimated draw weight of 83.9kg, a feat far beyond the ability of most people living today (Hardy et al., 2011, p. 627; Hardy, 2005, p. 17). An Ottoman flight bow from the Topkapi Palace Museum has an estimated draw weight of 110kg (Karpowicz, 2007, p. 678). Both of these bows represent examples of what is likely the top end of human performance, a potential that can only be reached by years if not decades of practice devoted to increasing one's draw-weight capacity, at times to the point of skeletal deformation (Hageneder, 2007, p. 103; Stirland, 2002, p. 74). While this maximum can be extended through the use of mechanical aids such as those typically used with crossbows, this lies beyond the purview of the current thesis (Popular Mechanics, June 1944, p. 103; Excalibur Crossbow, 2008, p. 7; Payne-Gallwey, 2007, p. 14).

Draw weight is also limited to a certain extent by material choice. As has been noted above, bows of exceptionally high draw weight can be made of a single stave of wood using self construction, composite construction using horn, wood and sinew, and in the case of the windlass-cocked crossbow, steel. The overall length of these weapons however is quite different. The all-wood bow will be by necessity substantially longer (and thicker) than that of the composite bow, which in turn will be longer (and thicker) than the steel brace used on the crossbow. The reason for these differences in length and thickness has to do with material properties, including its capacity for elastic deformation, stiffness, and both tensile and compressive strengths.

Bows in particular must deal with material strength under tension (for the outside face, or back of the bow) and under compression (for the inside face, or belly of the bow) (Gürkök and Hopkins, 1973, p. 518). As a bow is drawn, the bow will come under increasing stress and the arc described by the grip and nocks shows increased curvature. The smaller the radius of the arc described when a bow is bent, the greater amount of stress is applied to the bow (Middleton, 2007, p. 44; Denny, 2007, 24; Klopsteg, 1992, p. 9). In the case of a bow, excess stress manifests itself in one of two different ways. If a bow (or more accurately the materials it is made out of) fails under compression it will result in the bow becoming permanently bent, also known as taking a "set" (Baker, 1992, p. 63). Under an excess amount of tension the bow limbs will crack, eventually resulting in outright breakage (Hamm, 1992b, p. 213).

Wood in general tends to have approximately two to three times greater tensile strength than compressive strength, meaning that assuming careful construction, a self bow will take a set before it will break (Klopsteg, 1943, p. 182; Baker, 1992, p. 63; Landels, 2000, p. 106).[15]

This relation between material stress and arc length explains one of two ways in which draw weight can be increased - by making a bow shorter (Strunk, 1992, p. 283, Klopsteg, 1992, p. 9). Draw weight will continue to increase as bow length decreases (assuming that is the only variable changed) until the stress exceeds the material's tensile strength or much more likely its compressive strength, at which point draw weight will level off or even decrease. Increasing a bow's length in contrast will reduce stress on a bow and decrease draw weight. Of course once construction begins, making a bow longer is not physically possible, but from a design perspective two comparable bows can be made showing this to be true.

The second means of increasing or decreasing draw weight is to design a bow with increased or decreased material in the working (bending) portion of the limbs. If a bow is too heavy, the bow limbs can either be made thinner or narrower, thereby decreasing draw weight. Conversely if a bow has a draw weight which is too light, a bow's limbs can be thickened through the addition of a backing, such as a layer of sinew, or a strip of bamboo or wood or a comparable bow can be made with wider and/or thicker limbs (Wescott, 2001, p. 118; Karpowicz, 2007, p. 677; Kooi, 1994, p. 2). Increasing the width of a bow's limbs mid-construction is of course impractical.

The choice to increase either limb width or limb thickness (or both) has different effects on bow performance. If a bow limb is doubled in width, draw weight will also double. Doubling a bow limb's *thickness* however yields an 800% increase in draw weight (Wolfram Alpha, 2013a; Baker, 1992, p. 66).[16] In practice, increasing limb thickness was generally preferred as a design option, as it required a good deal less labor and made more efficient use of material (Hardcastle, 1992a, p. 32).[17] Even here there are limits however, as limb thickness should be less than its width or the resulting design runs the risk of becoming unstable and twist when drawn as seen in figure 4.2 (Kooi, 1994, p. 18; Selby, 2006, p. 90).

Aside from increasing draw weight at different rates, the choice to increase either limb thickness or width has additional ramifications. Increases in limb thickness again increases stress, eventually leading to material failure. Increasing limb width however has no effect on material stress, making it a "safer" option with regard to bow design (Baker, 1992, p. 66). As previously mentioned, this potential benefit is accompanied by increased material wastage. Perhaps even

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[15] The actual ratio of strength under tension to strength under compression varies somewhat by the variety of wood used and how it has been cut.

[16] The exact formula will vary by the cross section of the bow limb, but for a rectangle is (Width x Height^3)/12.

[17] Some cultures however have historically chosen to produce bows with wide, flat limbs including the Eastern Woodland tribes of North America.

more important is the additional cost in production time, as creating wide, flat limbs requires a significant increase in the amount of labor when using traditional materials and tools (Hardcastle, 1992a, p. 32).

DRAW LENGTH

The second energy input factor is draw length, or how far back a bow is drawn. The longer the draw, the more energy is stored. As a double-ended leaf spring, draw length is described by Hooke's Law, which states that the extension of a spring is directly proportional to the force applied (Wolfram Alpha, 2013b; Baker, 1992, p. 46).

Again, a number of limiting factors apply. A bow, just like any spring, can be extended (the limbs bent) too far, resulting in material failure. And again, even if material failure is not an issue the limits of human physiology still apply. As a bow's limbs continue to bend, draw weight increases, eventually reaching the point where an unaided human can bend it no further.[18] Finally, there is a physical limit to how far a bow can be drawn which is determined by the archer's arm length. Simply put, an arrow (if long enough) can be drawn back to a point somewhat behind the archer's ear. Beyond this, it becomes more efficient to move to a higher draw weight than to continue the draw further.

In addition to the physical limits of both the archer and materials of which a bow is made, certain lengths of draw are more common than others. These common lengths are typically associated with an "anchor point," or a reference point to which the bow is draw such that the drawing hand comes to touch a set point on an archer's body, thereby increasing accuracy by setting a consistent draw length (Kidwell, 2004, p. 62). Perhaps the most common anchor point used by archers in the modern day is the corner of the mouth, a position sometimes referred to as the "kisser." Many styles of traditional Asian archery often use a longer draw that uses the ear as an anchor point, as did the archers of ancient Egypt (Wilkinson, 1991, pp. 90-91; Yadin, 1963, p. 201). A number of Native American tribes traditionally use a shorter draw, and instead use an anchor point on the archer's chest (Laubin and Laubin, 1980, pp. 145-146; Gray, 2007, p. 148). In such cases where an anchor point is used, exact draw length will vary slightly from archer to archer, even among archers using the same anchor point, due to anatomical differences.

At times however an anchor point is not used, but instead an archer is trained to draw until a set point is reached upon one's arrow. In such cases, the arrow is marked with ink, or a small notch. The author learned in this manner as a part of the training involved in practicing traditional Korean archery, in large part because the local arrow manufacturers could not supply arrows long enough for the author to use the standard anchor point used in Korean archery tradition, the ear.

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[18] Aside from mechanical aids, additional force can be applied by using one's legs to draw the bow while holding the string in hand. Such foot-bows were not commonly used in most cultures, although they do form a separate category for modern flight archery records.

Finally, an archer's draw length is limited by the length of arrow used. Without the use of some kind of support rest which extends behind the belly of the bow, it is impractical and often dangerous to use a draw length longer than the arrow. Such supports did historically exist in certain cultures and in fact see continued use in the modern day, allowing a certain amount of "overdraw." Turkish archers would at times use a ring or wrist brace that formed a shelf allowing the arrow to be drawn several inches behind the body of the bow (Cotterell, 2005, p. 59; Grayson, 2007, 65). Even here however there is a natural limit, in this case determined by the brace height of the bow, for if the support extends backward toward the archer beyond the brace point of the string it would interfere with the release of the arrow as the string would strike the support.

BRACE HEIGHT

Brace height represents the distance between the bow handle and the string of an undrawn bow. In an ideal, theoretical situation a bow with a brace height of zero would be considered "best" as it could make the fullest possible use of the energy stored in a bow (Baker, 1992, p. 47). The string of such a weapon would slap the handle, and possibly the limbs upon release. Noise concerns for hunting situations aside, such a bow is impractical in real terms as it allows no space for an archer's hand. While it is of course possible to build and use a bow with a brace height of zero, the string slap against the hand, wrist and forearm of the archer would cause inconsistencies in arrow release, creating problems with aiming. It would also be fairly painful to use such a weapon, even at low draw weights.

In real life terms, the minimum brace height for a bow is one which allows the archer to loose an arrow without having the string slap against the archer. This minimum brace height will vary from archer to archer, but could perhaps be a low as 10cm, assuming perfect technique (Baker, 1992, p. 75).[19] For practical use, brace height rarely drops below 15cm and more commonly ranges from 17-23cm, the higher end being more common for compound bows (Alrune, 2007, p. 29; Tomihama, 2011, p. 69).

As previously mentioned, any brace height greater than zero limits the storage of *usable* energy, which should not be confused with total stored energy. Any particular bow will have the same total amount of stored energy at a given draw length regardless of brace height. The amount of energy that can be transferred to the arrow however decreases as brace height increases, as total string travel becomes smaller (Baker, 1992, p. 47). This limit is due to the fact that a bow's limbs cannot travel farther forward than the brace position when strung. This principle can be seen in figure 4.1.

The total amount of energy stored in figure 4.1 at full draw is identical regardless of brace height at a given draw. The bow depicted at a higher brace height, although it has the same amount of energy at full draw has less energy freely available to transfer to the arrow, resulting in decreased

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[19] Lower brace height requires more careful positioning of the archer's wrist and the angle at which the bow is held.

range and lower arrow velocity. The amount of energy "trapped" is represented by the difference between the low brace height shown in the bow on the right, while the bow with the higher brace height is shown in the middle.

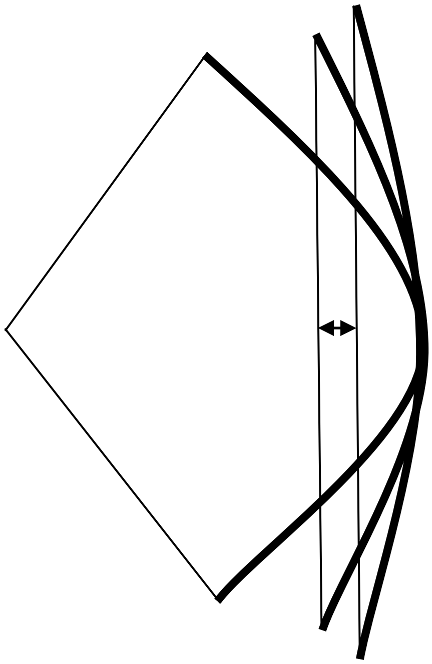

Figure 4.1 Drawing showing the same bow braced (right), at a higher brace height (middle) and drawn (left).

In addition to arrow speed, brace height also affects accuracy above and beyond occasions where string slap against the archer is an issue as a higher brace height is generally more accurate. This increase in accuracy is caused by the Archer's Paradox, or the conflicting forces of the bowstring, which pushes the arrow directly forward, and the width of the bow handle, which forces the arrow off to the side (Denny, 2011, pp. 21-22; Baker, 1992, p. 75; Asbell, 1993, p. 286). Arrows are however not completely rigid and as such the force of acceleration causes the arrow to flex, essentially bending the arrow shaft *around* the handle of the bow as it is released, a phenomenon which can be observed with high speed video. The lower the brace height of a bow, the greater the angle of deflection of the arrow as it leaves the string.[20]

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[20] Many modern bows avoid Archer's Paradox completely by having a deep handle which has a cutout wide enough to reach the center point of the bow where the arrow is held. Such bows are said to be "center-shot," and can use proportionately stiffer arrows.

In theory, this decrease in accuracy can be counteracted by using a more flexible arrow, allowing it to more easily curve around the bow handle. Indeed, numerous arrows with "disproportionately low spine (stiffness)" from ancient Egypt have been recovered (Blyth, 1980, p. 34). Arrows which are too flexible can also cause problems with accuracy as arrows which are too stiff, but carry the additional risk that the arrow may break upon release (Quillian, 2012, p. 44; Massey, 1992, p. 313). Blyth correctly noted the recurring mismatch of bows which average 18.2kg in draw weight and arrows which by modern standards would be appropriate for a bow with a draw weight of 6.8kg (Blyth, 1980, p. 34). While Blyth makes an excellent point with regard to noting the low level of arrow stiffness in Egyptian artifacts, this can be readily explained by the overall low brace height typically found in Egyptian self bows, as can be seen in figure 3.8 (Wilkinson, 1982, p. 17). Indeed the very design of the double-convex bow, with its set-back grip and decurved tips is naturally designed to reduce brace height and minimize bow stress at brace. A lower brace height would have required arrows significantly more flexible due to the increased angle of deflection formed between the string at brace and the sides of the bow stave at the grip.

Brace height then represents a compromise between a small increase in arrow velocity on one hand (mitigated by the need to prevent string slap against the archer’s hand or wrist), and the desire for increased accuracy on the other. As brace height represents a limit to how much of the stored energy can be usefully released, it must also be matched with arrow stiffness (Asbell, 1993, p. 286; Cosgrove, 2000, pp. 228-229).

UNSTRUNG BOW PROFILE

While artwork depicting unstrung bows is uncommon compared to depictions of strung bows in the ancient world, the profile of an unstrung bow has an influence on the amount of energy stored at a given draw length (Denny, 2007, p. 8; Baker, 1992, p. 115). The reason why again involves Hooke's Law. A bow which has a deflexed profile (having limbs which bend toward the archer when unstrung) will need to bend relatively little to reach its brace point, thereby lowering string tension at brace (Wolfram Alpha, 2013b). Low string tension at brace in turn means that the first part of the draw will be relatively easy as the bow limbs will begin the draw having a small amount of proportional spring movement, storing relatively less energy overall.

In contrast, a bow with a reflexed profile (having limbs which bend *away* from the archer when unstrung) will need to bend significantly more before reaching brace, resulting in a higher initial string tension and draw weight. Such a bow will have a higher initial draw weight and therefore store more energy.

From an efficiency standpoint, a bow which has an initial string tension of zero would be ideal, as no energy would remain "trapped" inaccessible for transfer to the arrow. It would also be mechanically safer with regard to material strength and convenience, as such a bow could be left strung indefinitely and not suffer from degradation of arrow speed due to long-term material stress. From a performance standpoint however this view is flawed. Zero (or very low) string tension at brace may be efficient, but results in lower overall arrow velocity.[21]

Finally, as with other input factors, there are both physical and practical limits involved with bow profile. Given that string tension at brace should be greater than zero, the maximum amount of bow deflex, or the degree to which an unstrung bow bends towards the archer when held would be slightly less than brace height. In reality a bow would typically have a profile that would be deflexed at least 5cm *less* than the profile measured at brace.

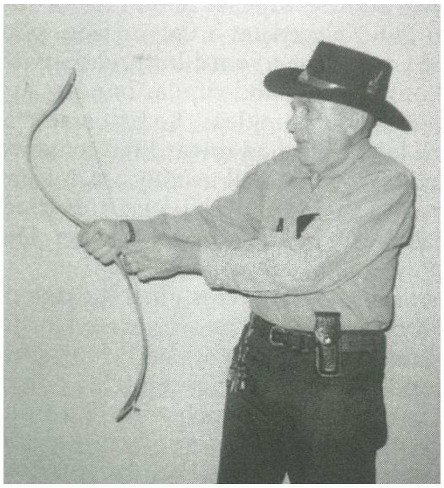

Figure 4.2 Composite bow of horn and sinew, lower limb reversed.

Figure 4.3 Korean bow from Chosun dynasty, unstrung.

The amount of bow reflex, or the degree to which an unstrung bow bends away from the archer when held is again met with both practical and physical limits. First and foremost of these limits are the tension and compression strengths of the materials from which a bow is made. As increasing bow reflex increases not only string tension at brace (and initial draw weight) but also final draw weight, excessive reflex can result in a bow either failing under tension (potentially resulting in catastrophic breakage) or under compression, which would result in the bow taking a set, thereby altering its unstrung profile. Particularly with regard to wood, which is weaker under compression than tension too great an initial reflex during construction will result in at least a partial set if final draw weight exceeds the bow's compression strength, an occurrence with which the author has experience (Kooi, 1994, p. 18; Klopsteg, 1943, p. 182).

The use of additional materials, such as horn, sinew, antler, baleen or modern alternatives such as fiberglass and carbon fiber can increase the degree to which a bow can successfully take a reflexed profile, but even here there are practical limits. Increased reflex also increases the potential for lateral instability and limb twist (Selby, 2006, p. 90; Kooi, 1994, p. 18). While this

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[21] This assumes that low string tension is caused by profile and not by a change in brace height.

instability can be reduced by increasing limb width, even perfectly balanced limbs in a highly reflexed bow can suddenly reverse. The comparison of excessive limb reflex to a watch spring is a good analogy; in theory a watch spring would make a perfect highly-reflexed miniature bow. In practice however attempts to uncoil a watch spring will invariably result in a twisted spring (or in the case of a bow, a reversed limb), as can be seen with the bow in figure 4.2. Korean flight bows perhaps take an unstrung reflexed profile to the practical extreme, to the point that the bow tips can even cross when unstrung, as seen in figure 4.3 (McEwen, 1973, p. 8).

THE DRAW-FORCE CURVE

With an understanding of these four factors, the amount of energy stored in a bow can be graphically represented as a draw-force curve. With draw length shown on the X-axis, and draw weight on the Y-axis, a draw-force curve can be used to graphically compare the energy storage patterns of different bows (Baker, 1992, p. 45; Klopsteg, 1943, p. 179; Godehardt et al., 2007, p. 125). Brace height is indicated as the point at which draw weight reaches zero, while the total amount of available energy stored (and available to transfer to an arrow) in a bow is the total area under the curve at a given draw length (Baker, 1992, p. 45; Waits and Silver, 1973, p. 52).[22] Some indication of a bow's profile can even be ascertained based upon the shape of the draw-force curve, with bows exhibiting a deflex having lower initial draw weights and a concave shape as seen in figure 4.4. Bows with a reflexed profile on the other hand would tend to have higher initial draw weights, resulting in a flatter or even a slightly convex curve.

In the graphs that follow, examples of bows are compared to illustrate the influences that draw weight, draw length, brace height and bow profile have on the total amount of energy stored (again, represented by the area beneath a draw-force curve). Figure 4.5 compares two otherwise identical bows that have different draw weights. The bow with the lower draw weight has a total available energy storage substantially less than that of the higher draw weight bow (half, in this case).

Figure 4.6 by comparison shows a theoretical set of three different bows which have different draw lengths, but identical final draw weight, brace height and profile (Baker, 1992, p. 46). While all three begin at almost the same point, the bow with progressively shorter draw lengths must have draw weights which increase more quickly resulting in increasingly steep draw-force curves. The decrease in draw length is also accompanied by a decrease in total available energy stored. This graphically explains why the range of European crossbows is not appreciably longer than that for a medieval longbow designed for war. While powerful crossbows cocked by a windlass may have a draw weight of 550kg, or between five and six times that of medieval longbow artifacts designed for war, the draw length is much shorter, on the order of less than 18cm compared to the 75-82cm of that of a longbow (Payne-Gallwey, 2007, p. 14). Thus while a

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[22] Baker states that the area under the draw-force curve represents the total amount of stored energy, but this is incorrect as it neglects to account for the energy stored in the bow at brace which is unavailable for transfer to an arrow.

siege crossbow has a significantly higher draw weight, the total amount of energy stored would not be significantly greater than that of longbow, which has a much longer draw length but lower draw weight.[23] It should be noted that the effect of different draw lengths on the *same* bow would be shown by a single curve overlaid with identical lines of increasing length.

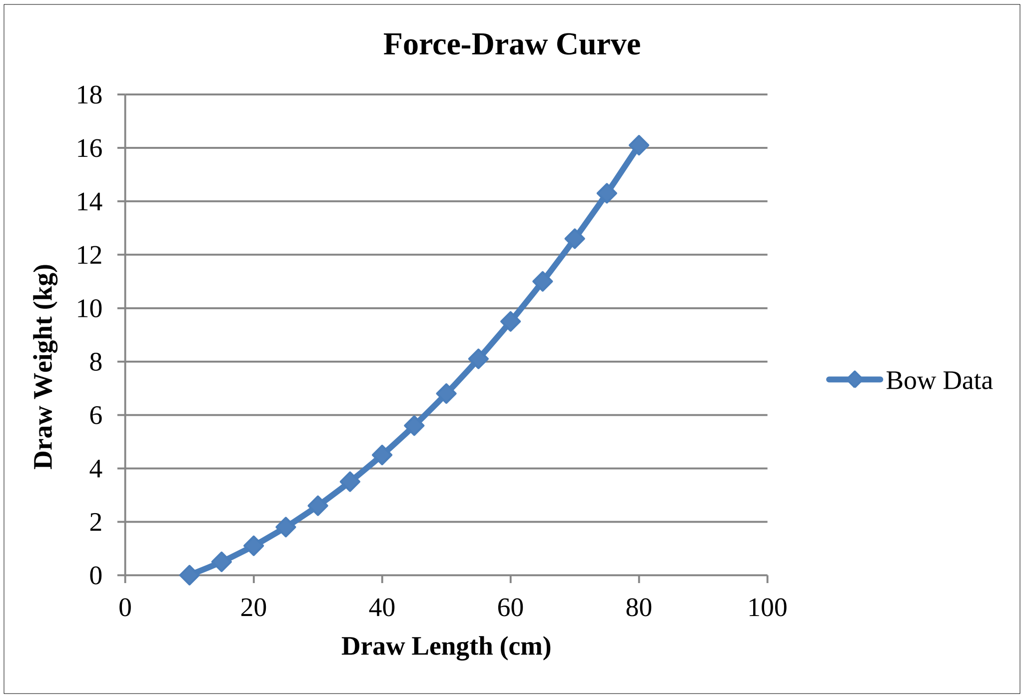

Figure 4.4 A typical draw-force curve.

Similarly, figure 4.7 depicts the same bow strung at two different brace heights. As figure 4.7 depicts the same bow twice, it should not be surprising that the majority of the graphs overlap. The difference in brace heights can still be seen in the additional energy storage however, with the lower braced bow able to potentially transfer more of its total stored energy to an arrow.

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[23] In Asia crossbows with a steel span never came into common use, instead essentially using a powerful full length composite bow strapped to a stock, thereby enabling longer draw lengths.

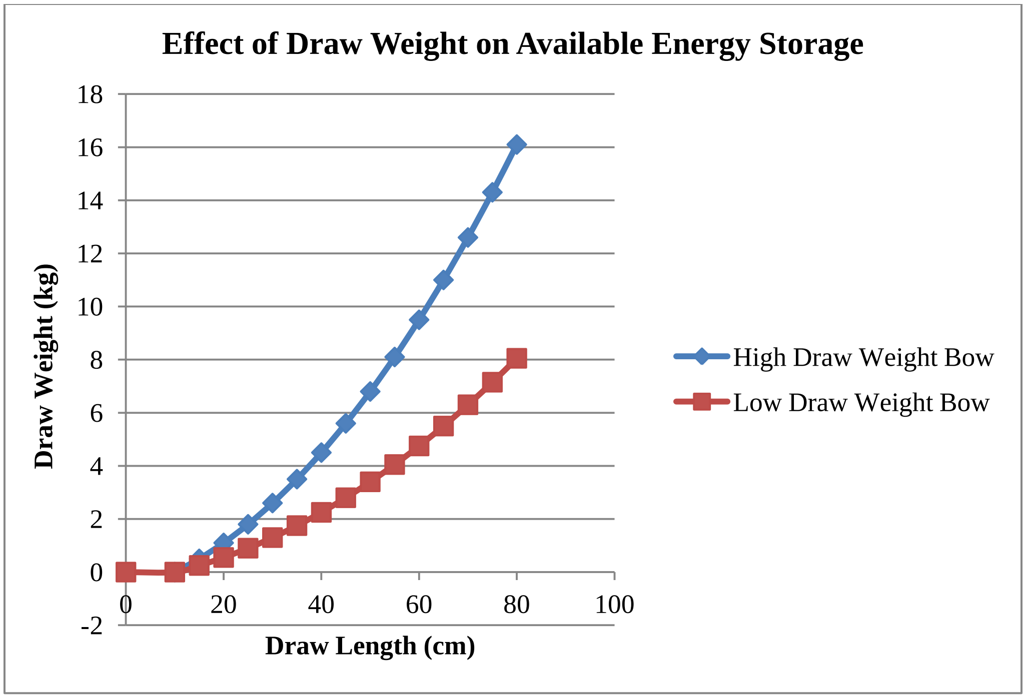

Figure 4.5 The second bow (marked in red) has an identical profile, draw length and brace height, but has half the draw weight of the first bow (marked in blue).

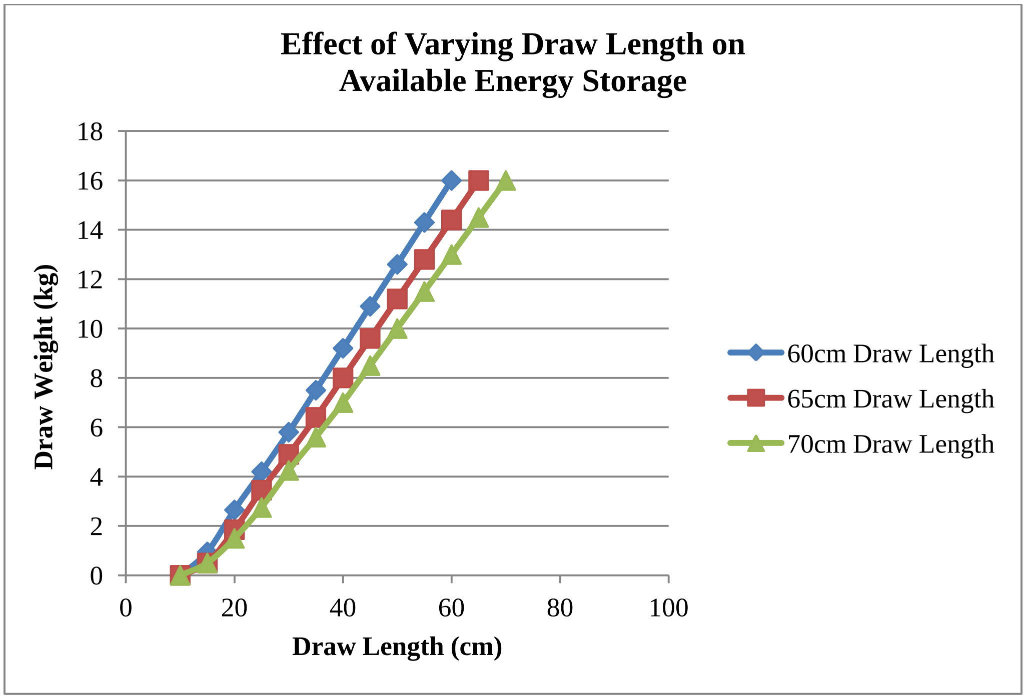

Figure 4.6 Three bows with identical brace heights draw weights and profile but different draw lengths.

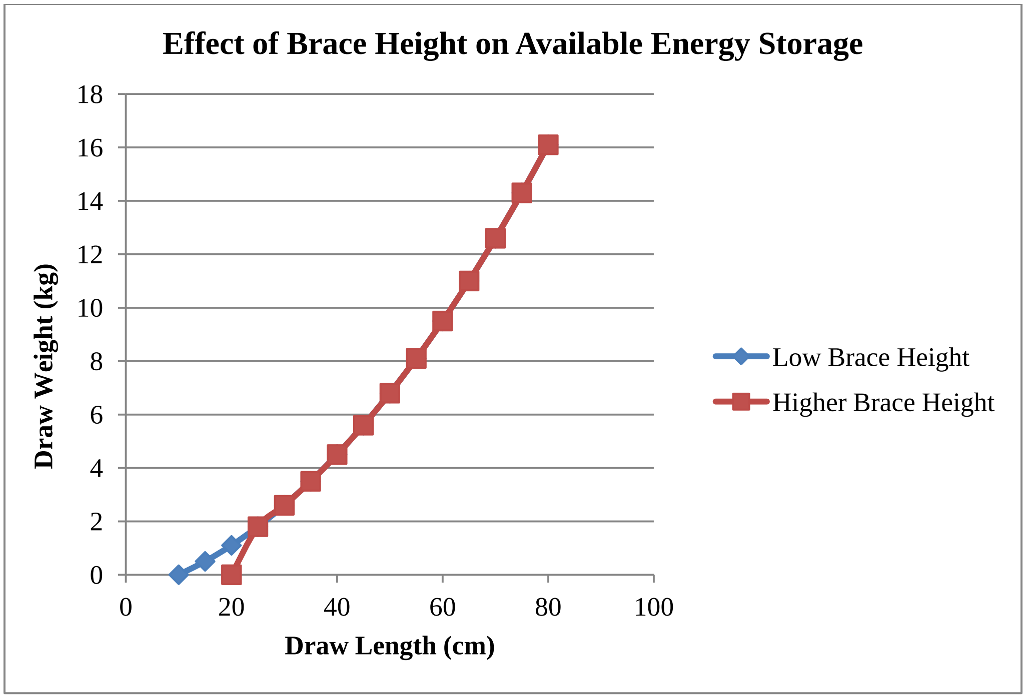

Figure 4.7 The same bow depicted twice, but with two different brace heights.

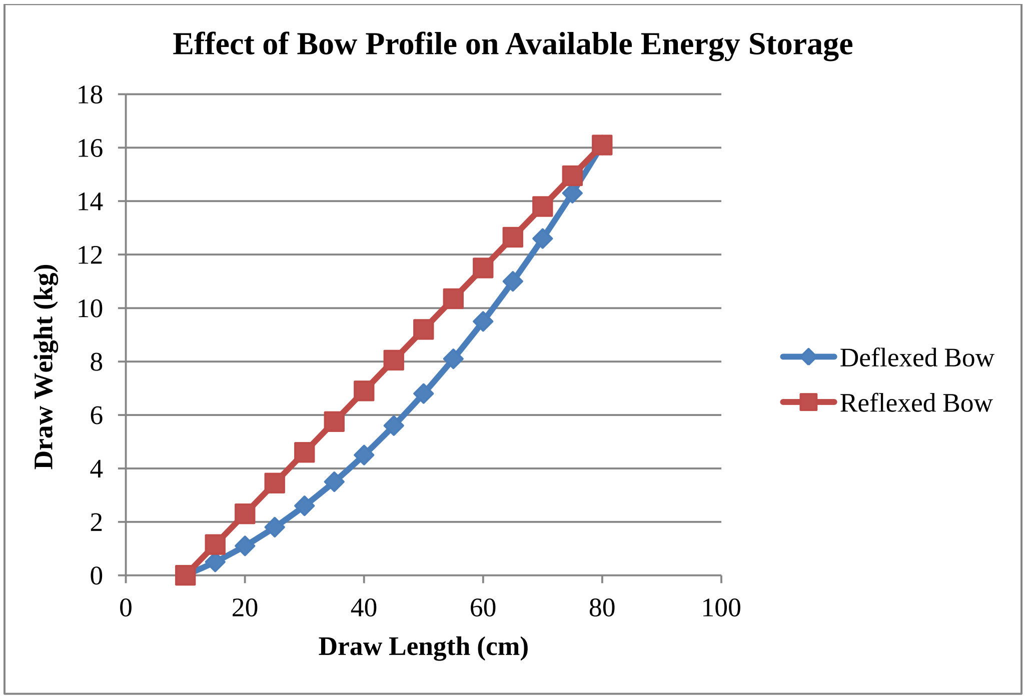

Figure 4.8 Two different bows with identical draw weight, length and brace height but different profiles.

Bow profile can be similarly depicted. Figure 4.8 shows two different bows that are identical save for their profile. The bow with the reflexed profile obviously stores a greater amount of available energy than the deflexed bow. What cannot be seen but is implied is that the higher initial draw weight of the reflexed bow means a higher base level of string tension, which is caused by the proportionately greater amount of distance the limbs must be bent prior to achieving brace. Bergman and Kooi imply that bow profile would not have a significant effect on arrow velocity in large part because they assume equal initial string tension at brace (Kooi and Bergman, 1997, p. 130). Such is not the case: if a bow has a different profile but the same final draw weight its initial string tension (and hence early draw weight) will be different as can be seen in figure 4.8.

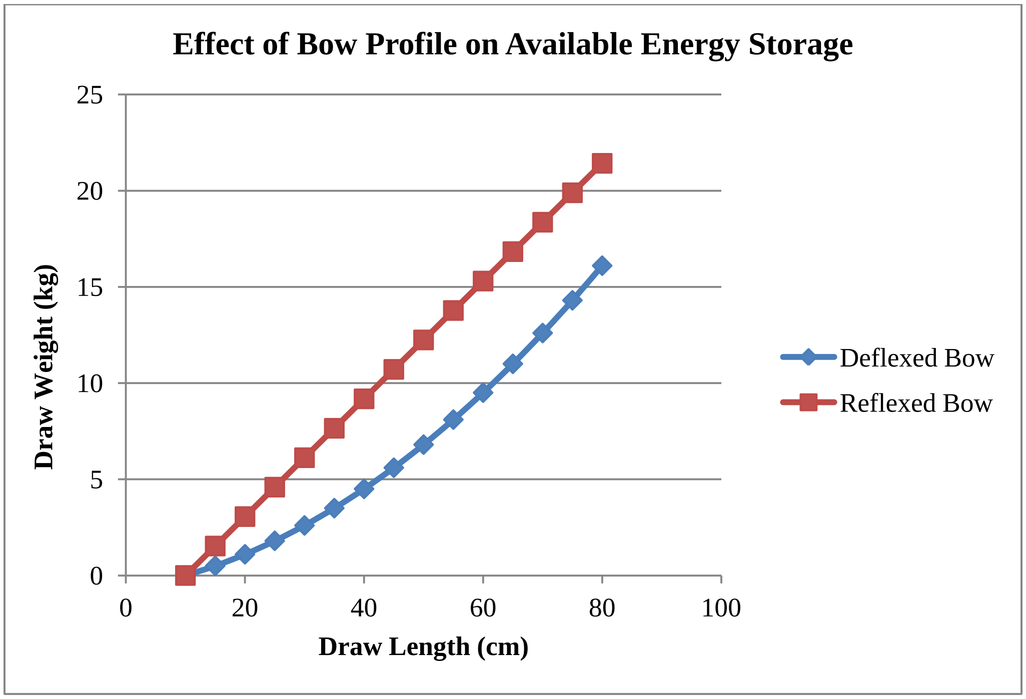

Figure 4.9 The draw-force curve of the same bow with a changed profile.

It is important to understand however that the bows depicted in figure 4.8 are in fact different: unlike figure 4.7 where the same bow is shown at two different brace heights figure 4.8 does *not* show the same bow with a modified profile. If a bow with a reflexed profile were changed, perhaps through steam bending, to have a deflexed profile, both initial *and* total draw weight would decrease.[24] An example of how the draw-force curve of a bow would change if steam bent

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[24] The reverse (changing a deflexed bow to have a reflex) while theoretically possible would probably not be successful in real life as the bow likely has already suffered from partial compression failure already - hence the deflexed profile.

is presented in figure 4.9. Initial draw weight decreases for the deflexed bow due to the decreased limb travel needed to reach brace - as expected by Hooke's Law. Likewise, this initial decrease in draw weight carries forward throughout the draw, leading to an overall reduction in final draw weight as well.

While the previous section provides the reader with a general understanding of energy input factors the exact extent to which bow profile affects stored energy and arrow velocity thus far remains unaddressed. The question of relative performance between bows of self and composite construction will be examined in more detail later with the presentation of data gathered from physical testing in Chapter Six.

FACTORS INFLUENCING ENERGY OUTPUT (INEFFICIENCIES)

Factors which influence energy output include anything that prevents perfectly efficient transmission of available energy stored in a bow to an arrow. These inefficiencies are more varied than the relatively simple input factors. They also, save for hysteresis, cannot be displayed in a draw-force curve. Additionally, a number of inefficiencies such as air resistance, limb and string mass, and gravity cannot be removed during physical testing (Denny, 2007, p. 28; Baker, 1992, p. 45). As a result, these inefficiencies must be mathematically isolated if they are to be dealt with at all. Thankfully the vast majority of these factors either remain constant (e.g. gravity), or their effect on arrow velocity is small enough to be negligible (the effect of air resistance on limb travel). Several of these factors however will be dealt with in some detail including hysteresis, bow mass and string mass.

ELASTIC HYSTERESIS

Elastic hysteresis (also sometimes know as creep), is energy loss due to internal friction (Denny, 2007, p. 28; Baker, 1992, p. 71; Moore, 1936, p. 19). When a bow is drawn, some of the energy converts to heat. Because of this energy conversion, upon release not all of the energy which was used to bring to bow to full draw can be transferred to the arrow. When looking at a draw-force curve, the effects of elastic hysteresis causes the force curve measured upon the let down (release) to be different from, and slightly lower than that of the draw as can be seen in figure 4.10 (Klopsteg, 1943, p. 179; Denny, 2007, p. 28). As the amount of loss increases the longer a bow is left in a stressed position, this additional energy loss can also be described as the gradual loss of plasticity (Cotterell, 2005, p. 162). Such losses may be temporary if the bow gradually regains its original profile after being left unstrung for a period of hours or days, or partially or entirely permanent in which case the bow takes a permanent set to some degree. It is for this reason that storing one's bow strung is not generally recommended, a point known to both the ancient Greeks and Persians if not before (Herodotus, 2.173; Cotterell, 2005, p. 162; Karpowicz, 2007, p. 681).

The amount of hysteresis varies from bow to bow for a number of reasons, including such factors as bow profile, materials choice, draw weight, and environmental conditions such as temperature and humidity (Karpowicz, 2007, p. 681; Miller et al., 1986, p. 181). Taken as a whole, hysteresis can result in a total energy loss of between 1-20% (Baker, 1992, p. 71; Klopsteg, 1943, p. 179). Results of higher than 5% may be skewed however, as they likely represent hysteresis of a bow tested "cold" or when first drawn after being strung. Attempts to replicate original results reported by Klopsteg show that after a bow has been drawn several times, hysteresis dropped to 5% in one case and less than 1% in all others (Baker, 1992, p. 72). The results of this additional testing by Baker were invaluable, as it showed that hysteresis can be removed as a test variable by recording only draw-force results from the let-down of a given bow after having been brought to full draw several times to minimize potential inaccuracies that could result when correlating such factors as draw weight and profile to arrow velocity.

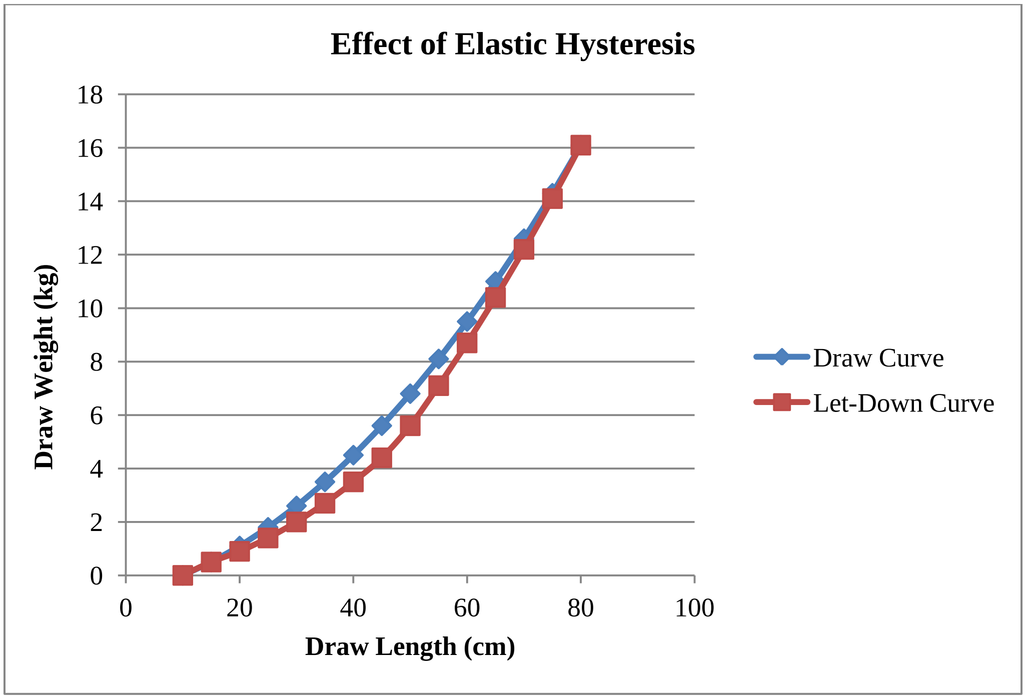

Figure 4.10 The draw-force curve of the same bow when drawn (blue) and upon let down (red).

BOW LIMB MASS

Bow limb mass is another source of inefficiency. Simply put, the more energy that is spent accelerating and returning a bow's limbs to brace position, the less energy is left over to transfer to an arrow (Baker, 1992, p. 45; Kooi and Bergman, 1997, p. 129; Kooi, 1994, p. 21). It is however important to differentiate between bow mass and limb mass, as this inefficiency is limited to the portions of the bow which actually move and as such the mass of a bow's grip can be disregarded. Evaluation of limb mass is however not as straightforward as might be expected for total mass is not nearly important as mass placement, for the farther a given point on a limb must travel from full draw to return to the brace point, the more energy it takes to move. Points farther along the end of the bow limb must naturally travel farther upon release. A "perfect" bow, which can only exist theoretically, would then have a limb mass of zero. The degree to which limb mass affects arrow velocity and how this may change with increasing draw weight will be investigated during physical testing in Chapter Six.

It is however possible to minimize bow limb mass and optimize mass placement along a limb for a given bow. As explained in the discussion on draw weight, doubling a bow's width will double draw weight while doubling its thickness will increase draw weight by a factor of eight (Wolfram Alpha, 2013a; Baker, 1992, p. 66). Reaching a given draw weight with as little mass as possible will therefore lead to maximization of arrow velocity. Minimal mass naturally requires that bow limbs be narrow and thick (as increasing thickness yields greater gains in draw weight), yet not so thick that bow limbs become unstable and prone to twist or that the resultant draw weight exceeds the compression strength of the bow limbs.

The placement of mass within a bow limb also needs to be considered, for ideally the far end of a bow limb (which must undergo the greatest amount of movement) should be relatively less massive than that of the area of the limb close to the handle (which moves relatively little). Optimization of bow mass *within* a limb then tells us that a bow limb should narrow as it moves farther out from the handle, as increasing thickness would have relatively less effect on mass. The result is a bow with limbs that have a pyramidal silhouette when viewed from the front or back, a design which also minimizes the likelihood that a limb might twist and reverse when drawn (Baker, 1992, 67; Kooi, 1994, p. 18; Verma and Keller, 1984, p. 569). As limb mass and mass placement will vary by materials choice, limb shape (notably the inclusion of non-bending reflexed limb tips commonly referred to as "ears"), limb cross-section and finally bow draw weight, complete modeling lies beyond the scope of this thesis.

STRING MASS

String mass has the same effect on arrow velocity as limb mass, namely that increased string mass decreases arrow velocity. Also like limb mass, from a theoretical standpoint efficiency of energy transfer can be maximized with a string mass of zero (Baker, 1992, p. 73; Kooi, 1994, p. 7). Thankfully, mathematical modeling of string mass is less problematic than for bow limbs as there are fewer variables to contend with. B. W. Kooi, in his work *The Design of the Bow* determined that one third of string mass can be added to arrow weight when attempting to model arrow velocity, and an additional third can be added to each limb tip, upon which string mass can be mathematically treated as if it were zero (Kooi, 1994, p. 7). For the purposes of this paper, string mass is only of concern during physical testing, where it was effectively removed as a variable by ensuring that string mass remained identical between bows.

STRING STRETCH

At first glance it would appear that string stretch would be good for a bow, helping to accelerate the string upon release. In reality however string stretch actually hurts bow efficiency, as it slows the acceleration of bow limbs as they return to brace, absorbing energy that would otherwise be transferred to the arrow (Denny, 2007, p. 16; Baker, 1992, p. 74). Efficiency of energy transfer from bow to arrow is therefore maximized when string stretch is zero. In practical terms string stretch can be kept to a minimum through the use of materials with low elasticity. String stretch was normalized during testing by re-using the same string for the different bows used when conducting experimental testing as much as possible.

NOCK FRICTION

Friction between the bowstring and nock of the arrow also contributes a small amount of inefficiency (Baker, 1992, p. 45). Unlike such factors as bow limb and string mass, nock friction can be reduced to a point where it become immeasurable in a practical sense even if it cannot be reduced to zero through careful matching of string width to nock size. Depending on the style of draw being used, having an arrow "loose" on the string can lead to problems with aiming and release, and as such care must be taken to choose a style of draw (determined by how the archer's hand grips the string) so that the arrow is supported at the nock by finger pressure.[25] Again, attempts were be made to ensure nock friction remained constant in testing through the re-use of bowstrings whenever possible.

OTHER SOURCES OF INEFFICIENCY

As mentioned previously air resistance caused by limb travel upon release and gravity also reduce bow efficiency (Denny, 2007, p. 28). As these factors are impossible to remove from the environment except on a mathematical basis, this study shall not seek to isolate their effect on arrow velocity. It should be noted however that as these factors remain constant (in the case of gravity) or nearly constant to the point of being immeasurable on a practical basis (in the case of air resistance to the movement of bow limbs) the effect of both of these factors will have no measurable influence on physical test results performed later herein.

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[25] Several different draw styles exist, although the exact number and nomenclature of different hand positions varies from scholar to scholar.

Choice of arrow also has a profound impact on bow performance, with mass, spine (arrow stiffness), taper, length, height, and curvature of fletching and mass and shape of arrowhead all playing a part in resulting effectiveness (Tomka, 2013, p. 554; Cheshier and Kelly, 2006, pp. 253-4). While arrow dynamics lie beyond the purview of the thesis, it should be noted that identical arrows (with mass varying no more than ±0.25g) have been used in testing throughout the thesis.

ENVIRONMENTAL CONSTRAINTS

In addition to the factors outlined above with regard to design performance, the design of any given bow also faces a vast array of "outside" factors, or environmental constraints. These constraints include, but are not limited to such factors as cultural tradition and inertia, time, cost, material availability, local climate and intended bow use (Belloc and Bowles, 2013, p. 93). While none of these factors will be dealt with extensively herein, several do have an impact on the choice to utilize composite construction.

First and foremost, composite bows typically utilized hide glue as part of their construction, and as such are more sensitive to humidity and can suffer material failure in the form of separation of the various layers when used in conditions of prolonged dampness (Laubin and Laubin, 1980, p. 76; Karpowicz, 2007, p. 11; Klopsteg, 1992, p. 24; Nieminen, 2010, p. 2). As a result, composite construction is inappropriate for locales with a highly humid climate such as a jungle, rainforest or use and prolonged storage onboard a ship.

Cost in time, money and materials is another factor. Materials themselves will of course vary with the local environment and season, as will their relative cost. Above and beyond this however the creation of a composite bow, even in an environment where suitable wood is scarce, represents a significant increase in cost in both materials and time, a factor which could potentially restrict access to bows of composite construction to the upper classes or elite military units. (Godehardt et al., 2007, p. 118; Rausing, 1967, p. 157; Howard, 2011, p. 8).

Finally, how a bow is intended to be used has a significant impact on its design. Target shooters put a premium on accuracy and minimizing hand shock, while flight (distance) shooters place a higher value on initial arrow velocity (Baker, 1992, p. 74; Miller et al., 1986, p. 181; Rausing, 1967, p. 29). Additional constraints face the archer when dealing with both mounted archery and potentially chariot-based archery (Laubin and Laubin, 1980, p. 25; Baker, 1992, p. 78; Credland, 1994, p. 21). Use under either of these conditions will face physical limitations with regard to lower limb length, a subject that will be the primary focus of Chapter Five.

CONCLUSION

The above explanations provide the reader with a basic background to bow mechanics as it applies to energy storage and release. As mentioned previously however, maximizing energy transfer to the arrow typically was *not* the primary goal of archers and bowyers - if such was the case, it is entirely possible that traditional archery would no longer exist as either a sport or hunting medium. The question of how, why and to what degree a bow of composite manufacture can out-perform (in the form of either increased range or arrow velocity), a bow of self construction relies on carefully designed testing using bows of equal draw weight, draw length and unstrung bow profile. Only in this way can the impact of materials be isolated and quantified with accuracy, a problem that will be dealt with in Chapter Six. Indeed, with this basic understanding of bow mechanics, a small number of possible reasons for the improved performance of the composite bow can now be identified as worthy of further testing.

Clearly a composite bow would have a significantly higher draw weight than a self bow if one were to take an existing bow of self manufacture and add layers of horn and/or sinew (Gabriel, 2004, p. 59; Yadin, 1963, p. 7). This belief however fails to compare bows of *equal* draw weight, which can be made in a wide spectrum of strengths using any of the construction methods outlined in Chapter Two, including self, composite, or laminate manufacture (Hardy, 2005, p. 17; Hardy et al., 2011, p. 627; Karpowicz, 2007, p. 679).

String mass, can also be discounted for while composite bows can be made shorter than a bow of self construction, the resulting difference in string mass will be less than 10g, or the mathematical equivalent of decreasing arrow mass by $3^{1/3}$g (Kooi, 1994, p. 7). The mass reduction would indeed have a positive effect on arrow speed, but the difference would minor, and has further been rendered constant during physical testing in Chapter Six.

Brace height can also be excluded, for while personal and cultural preferences have their influence, construction method does not.[26] Draw length is also out of contention, as the English longbow was of self construction and was also typically drawn to the ear in the same manner of many ancient traditions (Hardy, 2005, p. 14; Wilkinson, 1991, p. 90). Given that a number of the double-convex self bows from Egypt are of a similar length to the bow artifacts recovered from the wreck of the Mary Rose, there is no reason why they also could not be drawn to the ear, even if they lack the draw weight of their later European counterparts (Donato, 1994, p. 42; McLeod, 1981, p 36).

This process of elimination then leaves a select group of variables as the only options which can potentially explain the superior performance of composite construction: unstrung bow profile, limb mass, and materials choice. In addition to these factors, the environmental constraint of use

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[26] Modern compound bows however generally use a higher brace height that the majority of traditional style bows.

within the confines of a chariot will be examined as bow length, independent of bow limb mass, is often presented as a benefit of composite construction for chariot use and later, mounted archery (Gabriel, 2007, pp. 73-74; Cotterell, 2005, p. 103; Drews, 2004, p. 49; Rey, 2010, p. 22). As this question has to date remained unexamined it shall be the focus of Chapter Five.

While the effects of bow profile and limb mass are readily understood from the previous explanation, materials present a number of secondary questions. Does the use of composite materials *themselves* (i.e. horn/antler/baleen/bone in combination with sinew and wood) result in improved performance? Or does the choice of improved materials allow for performance gains due to their increased efficiency, thereby allowing a decrease in limb mass? Do the higher materials tolerances of horn and sinew allow a more highly stressed profile than possible with wood alone? Or (most likely) does a combination of these factors come into play, and if so to what degree does each of these affect results and do they vary with draw weight? Additionally, the question of to what degree composite construction increases arrow velocity (and hence, range) remains, a question which potentially colors the expectations of scholars and their research, thereby affecting the field of military history as a whole.

Having established a clear basis for understanding the basics of bow mechanics, the following chapter will deal with the question of bow use within the confines of a chariot cab to determine to what extent composite construction, capable of bow lengths shorter than otherwise possible using self construction, was required for the chariot to be used as a mobile archery platform. The results will provide evidence with regard to the chronological development of composite bow technology and the evolution of military vehicles from the battle cart to the light spoke-wheeled chariot that will be matched with the iconographical analysis done later in Chapter Seven.

CHAPTER FIVE

EXAMINATION OF BOW/CHARIOT RAILING INTERFERENCE

This chapter examines the relationship between the composite bow and the chariot. More specifically it will investigate to what extent bow length impacts bow use from within the confines of a chariot cab. The two inventions of chariot and composite bow were a common, and perhaps defining aspect of warfare in the ancient Near East during the Middle and Late Bronze Age periods and into the Iron Age, creating the first highly mobile archery platform (De Backer, 2009, pp. 585-6; Cotterell, 2005, p. 103; Drews, 1993, p. 97). This association between the composite bow and chariot naturally leads to the possibility that chariot archery could act as a substitute for bow profile in iconography for determining if a composite bow is depicted, a question that will be answered by the results of physical testing. Yet while chariot iconography is fairly well represented, surviving chariots are quite rare, often incomplete, and typically come from mortuary contexts, with all the attendant difficulties of how representative they may therefore be. This dearth of physical (and textual) evidence has led to the linkage of the composite bow and the chariot in a number of works in such a way as to potentially imply causation. This is to a certain extent inevitable in that space in every volume, even in works devoted solely to warfare in the ancient world, is limited. The issue of potential dating of the origins of the composite bow is no exception. As such, a typical passage reads along the lines of "the composite bow and chariot were introduced to Egypt during the Hyksos period" (Spalinger, 2009, p. 15; Credland, 1994, p. 30; Gabriel, 2007, p. 87). The statement unto itself is correct to the best knowledge of current scholarship, but the presentation is potentially misleading in nature.

Some degree of contact between Egypt and Southwestern Asia can be attested, the composite bow and chariot appear to have arrived in Egypt together, and it is widely accepted that both these innovations were introduced to Egypt by the Hyksos (Rice, 2003, p. 34; Shaw, 1991, pp. 31-2; Smith, 1969, p. 277; Wilkinson, 1982, p. 4). Prior to the Second Intermediary Period Egyptians appear to have no knowledge of the chariot, and used bows of self manufacture of either a segment or double-convex profile, although joined bows of horn were also known (Drews, 1993, p. 105; Anglim et al., 2002, p. 10; Hayes, 1990a, p. 279). Exactly when the chariot and composite bow both emerged, and whether they came into being at roughly the same time typically remains unaddressed, but several authors leave readers with the impression that either both the chariot and composite bow either developed simultaneously or that the rise of the chariot in some way caused, or was co-dependent upon the development of the composite bow (Cotterell, 2005, p. 57; Drews, 2004, p. 49; Hamblin, 2006, p. 146). This appears to be a case of unintended consequence, as Drews in *The End of the Bronze Age* goes into more detail stating that the pre-existing technology of the composite bow made chariots more effective (Drews, 1993, p. 105). Such clarification is however often absent, and presentation of the understandably limited coverage on this particular point tends to leave the reader with the impression that there is a degree of causation which may not actually exist. The small amount of additional information provided by Drews does little to answer the question of origins, as he mentions the statement in passing and provides no rationale or supporting evidence.

Certainly the pairing of the composite bow with the chariot resulted in a rapid shift in warfare throughout Egypt and much of the ancient Near East corresponding to the early second millennium BCE, as chariotry suddenly became an important military unit (Casson, 1969, p. 63; Gabriel, 2007, p. 87; Rice, 2002, p. 257). The shift is perhaps most easily seen in Egyptian warfare where the navy, which was considered to be more elite and prestigious compared to other military units during the Middle Kingdom, was superseded by the newly formed chariot corps (Spalinger, 2009, pp. 2, 5; Berlev, 1969, p. 8; Hamblin, 2006, p. 146). The creation of this corps consisting of hundreds of chariots represented a major investment not only with regard to the importation and breeding of horses and facilities for both their training and care, but also craftsmen for the construction and repair of the chariots themselves (Papyrus Anastasi I; Spalinger, 2005, p. 12; ARM, 5.66; Hamblin, 2006, p. 146). Nor were rulers content to leave their chariots behind if the terrain between their current location and their destination did not readily allow their use as several accounts specifically mention having to hack out an appropriate track from one or more mountainsides before their chariots could pass (RA2, A.0.89.2; RA2, A.0.101.1). In time chariots came to be recognized as a sign of power and wealth, so much so that inquiring about the state of one's chariots became standard diplomatic protocol between rulers (ANE, EA15).

Any synergies that came about as a result of the pairing of the chariot and composite bow however shed no light on the question of which came first. While the question of causation can likely never be proven even if such did exist, the possibility that the composite bow was *prerequisite* with regard to the chariot's use as a mobile archery platform is easily testable. Additionally, if the composite bow can be shown to be a necessary before the chariot can be reasonably used as a mobile archery platform, the presence of chariot archery within ancient artwork then has the potential to act as a proxy for the currently flawed system of profile evaluation with regard to the determination of bow construction.

Why then would the chariot require a bow of composite, rather than of self, manufacture? While increased power and/or range certainly would be *useful* it would not be necessary. Another possibility does exist, for composite manufacture also allows for the potential for a shorter overall weapon *length*, a physical feature which could potentially be importance within the confines of a chariot (Hulit and Richardson, 2007, p. 62). Indeed, several authors specifically mention the advent of the *short* composite bow being paired with chariot and mounted archery, lending credence to the possibility that bow length may be of potential importance with regard to chariot use above and beyond any gains brought by reduction in bow limb mass (Credland, 1994, p. 21; Kelekna, 2009, pp. 76-7; Raulwing, 2000, p. 91; Cotterell, 2005, p. 57).

Let us then for a moment presume that there is a case either for causation, or that the composite bow was a prerequisite for the adoption of the chariot as a mobile archery platform. How would this potentially influence the interpretation of evidence, or more directly, the lack of physical evidence for composite construction predating the Hyksos invasion of Egypt? It could easily be argued that the use of a proto-chariot or battle wagon as a mobile archery platform was impossible if it required the use of a bow shorter than would otherwise be possible using self construction (i.e. a composite bow). The train of supposition continues; since the pairing of chariot and bow did not happen until the early second millennium, this could potentially imply that the composite bow did not exist at the time. The argument is a reasonable one, and forms a key point in Hamblin's case for the late development of the composite bow (Hamblin, 2006, 94). The author himself began the present endeavor believing that chariot use may have created a need for shorter bows, thereby facilitating the advent of composite construction. This turned out not to be the case, but the argument sounds so rational that it may cast lingering doubt on the evidence contained later herein to those not specialized in the history of archery unless subjected to further investigation.

While well-reasoned, Hamblin's chain of logic hinges on the presumption that a chariot requires the use of a short bow of composite construction. If incorrect the presumption of causation (or prerequisite existence at a minimum) becomes completely overturned, an issue which has a major impact on both the timing and development of the composite bow and chariot alike. As such, the remainder of the chapter will focus on an investigation of how bow length affects chariot use by means of interference between the bow limbs and the chariot railing as a means of determining the maximum practical bow length useable within the confines in a chariot cab.

Should it be found that the confines of a chariot cab necessitates a bow shorter than otherwise possible using all wood construction, then there is a strong implication that the composite bow was indeed a prerequisite for the adoption of the light spoke-wheeled chariot as a mobile archery platform. It also means that bow length unto itself was a significant advantage of composite construction above and beyond increase performance, at least with regard to chariot-based warfare. Conversely, should a bow of self construction be easily usable from a chariot cab the implication is that the adoption of the chariot as a mobile archery platform was an innovation that occurred independent of a particular method of bow construction. Furthermore, it would imply that the initial inception of chariot-based archery depended more on the development of the chariot itself, and the reduction of railing height and front wall height typically associated with the earlier Sumerian battle cart in particular rather than on a given method of bow construction or profile (Yadin, 1963, p. 37; Raulwing, 2000, p. 37; Gabriel, 2004, p. 54; Littauer and Crouwel, 1979, p. 32).

As the working hypothesis, as posited by Hamblin, is that a chariot requires a bow shorter than functionally possible using all-wood construction, the question becomes twofold. The first question is how short can a functional bow of self construction be made? The second question is how long of a weapon can be reasonably used within the confines of a chariot? If a degree of overlap exists between the minimum length of bow possible with self construction and the maximum length of bow usable in a chariot, the hypothesis of pre-requisition, or dependence must be rejected.

The first question does come with a number of caveats: bow design encompasses a number of factors, including but not limited draw weight, draw length, bow length, cost and suitability for a given environment. A bow of all wood or joined construction can be made quite short. The smallest of the self bows recovered from the tomb of Tutankhamen's tomb (item #596t) was a mere 67.5cm in length (Griffith Institute, 2004). As this particular artifact is undecorated, it seems unlikely that it was meant as a dedicatory item, but would have made a fine toy. Perhaps it was included in the tomb offerings as a memento of from childhood, for it certainly was not meant to be used in war (McLeod, 1981, p. 40). Along similar lines the Bushmen and Pygmy of southwestern Africa use short bows of which average between 90-95cm in length of self manufacture for hunting, but rely on poison, rather than arrow injury to bring down prey (Baker, 2000, pp. 57-58). As such, clearly bow length unto itself cannot be an accurate indicator without first imposing supplementary conditions.

The first condition then is that for the purposes of testing and evaluation of evidence a bow be capable of being drawn at 75cm or more representing full draw length to at least the archer's ear, the most common draw point found in both Egyptian and Assyrian artwork (Wilkinson, 1991, pp. 87-88). In truth, both Egyptian and Assyrian artwork at times depicts a draw point behind the archer's head in an act of "heroic overdraw" as discussed in Chapter Three, but this contradicts a tomb painting, depicting archery training and showing the anchor point at the archer’s ear during the New Kingdom Period from the tomb of Min at Sheikh Abd el-Gurhah (TT109) also containing the inscription reading "Draw your bows to your ears" (Yadin, 1963, p. 201; Wilson, 1951, p. 196). The second condition is that a bow be at least 18-23kg in draw weight, or the typical draw weight associated with bows from ancient Egypt (Blyth, 1980, p. 34; Spotted-Eagle, 1988, pp. 15-16; Hulit and Richardson, 2007, p. 57).

To clarify then, it is required that the minimum length which to which a bow of self construction can be made such that it can have a draw length of 75cm and a draw weight of 18 kg or more be known. Thankfully, experimentation on this particular point has already been done, with traditional archers in consensus that the answer for the majority of different types of wood, and assuming that the bow design does not incorporate a reflexed profile when the bow is unstrung, the answer is approximately 160cm (Baker, 1992, pp. 92-93). If a deflex is incorporated in the design, as seen in the double-convex self bows seen in ancient Egypt this could perhaps be shortened to 150cm, as limb deflex would partially reduce material stress in exchange for a lower arrow velocity, as discussed previously in Chapter Four.

The second question of what length of bow can be practically used within the confines of a moving chariot has received almost no attention up to this point. Other scholars, most notably Hulit and Richardson, have performed testing with regard to chariot archery in general and ballistics against replica armor in particular (Hulit and Richardson, 2007, p. 53). The testing therein utilized a bow of composite construction 145cm in length, but did not include any testing of longer bows. This length is somewhat longer than the longest composite bow recovered from the tomb of Tutankhamen (#48i, 139.5cm), but equal to Egyptian composite bows in the holdings of the Brooklyn Museum (145.2cm) and Oxford (145cm) (Griffith Institute, 2008; McLeod, 1962, p. 66; McLeod, 1958, p. 399; Balfour, 1897, pl. ix).

The measurement of 145cm can be cross-checked against ancient artwork. The earliest representation of chariot archery in Egypt comes from the pyramid temple of Ahmose I in Abydos (1514BCE) as seen in figure 5.1 (Spalinger, 2009, p. 22). A comparison of relative length between bow and figure height can provide a close estimate against which the length of physical artifacts can be compared. While overall figure height remains difficult to judge due to the presence of a headdress, measurement from the floor of the chariot to the neck can be used as a proportionate standard equal to 7/8 the total height of the figure (Fairbanks and Fairbanks, 2005, p. 35). This measure can be adjusted to an assumed life-size of 170cm. This process of presumed height estimation and relative bow length to figure height is discussed in greater detail later in the current chapter. In the case of the image found in the temple of Ahmose I, the relative measurements indicate a bow length of 157cm when measured along the arc (Maspero, 1904, p. 147; Forbes, 1998, p. 699). This measurement should be taken with some degree of caution however, as preliminary work in Chapter Three suggests that measurement along the arc in Egyptian art is exaggerated when depicting bows at full draw, a likely side effect of the unrealistic "heroic" draw length which also results in an overly long string that would be completely loose upon release if pictorially accurate. It should also be noted that composite bows *can* be made longer than the 145cm used by Hulit and Richardson, but physical testing done later in Chapter Six shows that at draw weights of between 18-23kg, to do so would be counter-productive with regard to bow performance and result in reduced arrow velocity.

In comparison, the image shown from the left exterior side of the chariot recovered from the tomb of Thutmose IV (1391 BCE) appears to be more realistic, having a tip to tip length of 128.6cm (136.7cm along the arc) as can be seen in figure 5.2. As the image depicts the bow at brace, rather than at full draw an accurate tip to tip estimation is possible, as can an estimation of brace height (16cm). The depiction of the bow at brace also avoids potential for artistic errors associated with "heroic overdraw."

This tendency to enlarge bow length when depicted at full draw compared to at brace can be cross-checked with other artwork, in this case by comparing the left exterior panel of the Thutmose IV chariot to the right exterior panel of the same chariot, which depicts Thutmose IV again, this time at full (again, heroic) draw as seen in figure 5.3. The resulting measurements indicate an along the arc length of 169.2cm, or almost exactly the height of the figure, and significantly longer in relative length in comparison to the bow depicted on the opposite chariot panel and notably longer than any composite artifacts from ancient Egypt found to date (Griffith Institute, 2004; McLeod, 1958, p. 399; Balfour, 1897, pl. ix). Finally, figure 5.4 shows a battle relief of Amunhotep II (1401 BCE) at Karnack. The bow is shown at brace, and in this case the relative measurements indicate a much shorter bow length measured tip to tip of 98.6cm. While substantially shorter than the longest composite artifacts described previously, it is comparable to the majority of the composite artifacts from Tutankhamen's tomb, which have a median length of 111cm (Griffith Institute, 2008).

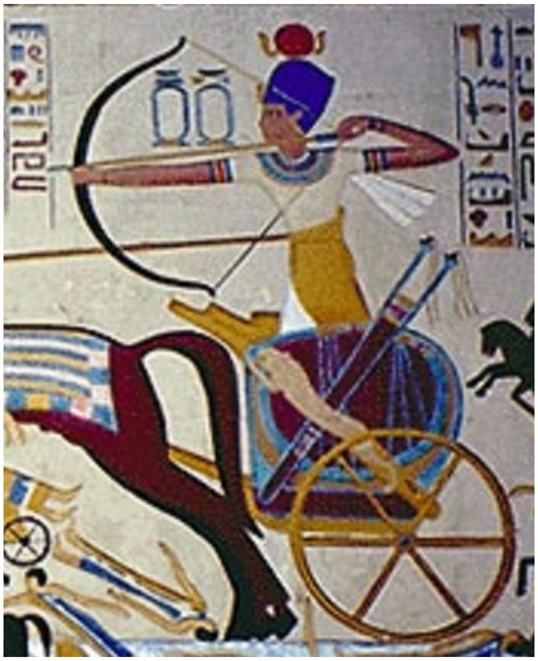

Figure 5.1 Painting from temple of Ahmose I (1514 BCE).

Figure 5.2 Detail of left (exterior) side of chariot of Thutmose IV (1391 BCE).

Taken together, while ancient Egyptian art does show at times depict bows used in chariots longer than 150cm, in such cases the depictions collectively show the bow at full draw, and are in direct conflict with both existing bow artifacts and bow lengths depicted with bows shown at brace. The comparative results between depictions of bows at brace, physical testing done later in Chapter Six and artifact evidence is consistent, and shows that known examples of bow use within the confines of a chariot in ancient Egypt all show a bow length of less than 150cm. While this figure is perhaps indicative, it does not provide sufficient evidence to determine the *maximum* usable bow length. As such, proper evaluation of the maximum practical bow length within a chariot requires physical testing.

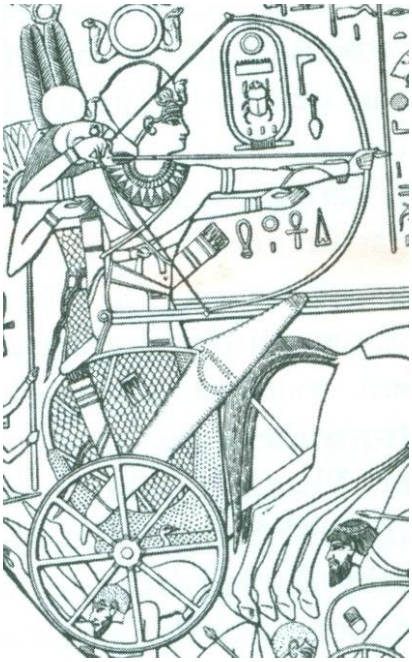

Figure 5.3 Detail of right (exterior) side of chariot of Thutmose IV (1391 BCE).

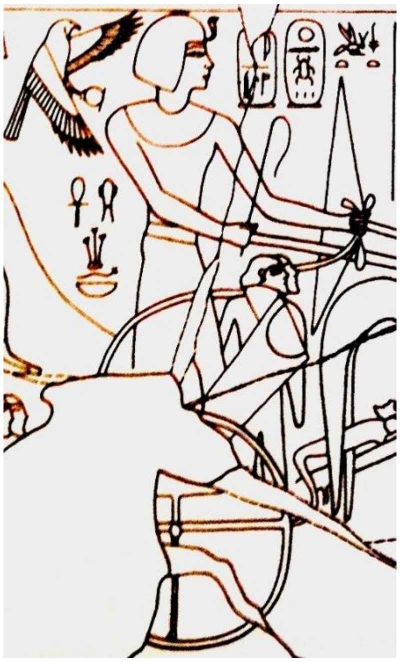

Figure 5.4 Battle relief of Amunhotep II, Karnack (1401 BCE.

CHARIOT TESTING

BOW CONSTRUCTION

Unfortunately, neither sets of bows of increasing length, nor chariots are commonly available for either rent or sale in the modern day. Ancient artifacts and careful iconographic evaluation show that relatively short bows of composite construction existed while evidence for longer composite weapons in excess of 150cm is either inconclusive or nonexistent in the ancient world. This merely provides a single data point however. Thorough testing on the other hand necessitated a set of bows in a range of lengths. As the primary purpose of testing was to evaluate how increasing bow length may have interfered with both reigns and railing, the purchase and/or creation of a set of bows made from materials used in the ancient world was not necessary, and functional replicas of modern materials would suffice. As such, identical construction materials for all of the bows was not strictly necessary, nor did the completed weapons need to perform well or achieve a particular arrow velocity. In the end, respite from the lack of commercial bows across a range of lengths came from a rather unlikely source: PVC pipe. While having fairly low compression strength and being significantly more massive than an equal volume of wood, PVC becomes quite flexible when heated. If bent into shape when hot, any curves will be retained so long as it is held in place until cool (Tomihama, 2011, p. 16). If the limbs are tapered in thickness, a heat-formed length of small diameter PVC pipe makes a poor-performing, functional bow, with a profile both at brace and at full draw matching that of a segment-shaped bow made of wood. An additional benefit is that heat-forming PVC pipe could be done quickly and with relatively few tools. While the use of PVC in no way can be expected to perform as well as traditional materials, as testing focuses on an examination of bow *length*, it provides an innovative means to easily produce a number of functional replicas in a short amount of time.

Trials creating bows with a flat profile and limbs of tapered thickness revealed that PVC pipe shrank slightly in length (but not in interior or exterior diameter) upon heating, and that this loss of length was permanent. A small canister of butane suitable for use in a portable burner or camp stove mated with a blowtorch attachment provided heat. A length of flat board with shims at one end slightly lower in height than the exterior diameter of the pipe undergoing testing provided a constant angle, allowing a smooth taper in limb thickness, while nocks were easily cut with a small rattail file. After the addition of a string of appropriate length, physical testing showed that for its draw weight PVC made bows which were high-mass and had a sluggish cast, yet were fully functional. The PVC was also surprisingly low in compression strength and readily took a set after use. Further testing revealed that despite the remarkable complex curves created by Tomihama in a number of his PVC bow creations, the precise matching of limb curvature was difficult for the author to achieve by hand (Tomihama, 2011, pp. 41, 53, 69). As such, a molding jig was made out of layers of plywood to ensure that limbs tapered evenly for both the top and bottom limb of each bow (figures 5.5-5.7).

Figure 5.5 Close-up of jig hinge.

Figure 5.6 Close-up of jig set screw.

Figure 5.7 PVC pipe ready to be heated.

Figure 5.8 Blunt "field point" arrow.

Figure 5.9 Medial stop disk for the safety tips pressed consisted of reused bottle caps into new service.

Figure 5.10 Assembled safety tips and completed arrow.

The resulting series of bows consisted of a set of eight matching weapons starting at 120cm in length and increasing in 10cm increments to a length of 190cm. All of the weapons were made with a straight profile from 20mm PVC pipe, and had an identical brace height of 18cm. As arrow velocity was not a consideration for this particular test, no efforts were made to record velocity, nor to normalize or even measure bow or string mass, but it was readily apparent during use that longer bows were under less material stress and imparted a correspondingly slower cast as a result.

With a complete set of bows of increasing length ready to use, attention next turned to choice of arrows. While actually hitting a target was unimportant to the question of bow length and the potential for interference of a bow with the railing, safety concerns remained with regard to using normal blunt, metal-tipped "field point" target arrows. The draw weights and arrow velocities of the PVC bows was sub-par compared to wood, but to minimize the potential for injury arrows were converted into safety tips consisting of two layers of foam with a thin metal disc between acting as a stop to prevent the narrow blunted tip from punching through (figures 5.8-10). These foam tips were then glued in place, making even intentional injury virtually impossible. The resultant pairing of bows and arrows remained functional throughout testing, and more importantly allowed accurate evaluation of railing interference with bows of differing lengths, thereby fulfilling their purpose with regard to testing the amount of interference that may occur when used within a chariot cab.

The second portion of the problem still remained; in order to answer the question of bow/chariot interference one needs not only a set of bows but also a chariot, or at the very least an approximation of an accurately sized chariot cab, or box. Again, as with the bows, neither a complete chariot nor a chariot box was readily available commercially for either sale or rent. The solution, like the set of bows, required that a chariot or chariot cab be built to order, the details of which are covered in the following section.

CHARIOT DESIGN

As the purpose of testing was to accurately assess bow/chariot interference, the use of a functional replica was deemed to be sufficient, thereby obviating the need to use traditional materials. That being said, as a major advantage of the adoption of the chariot as a mobile archery platform was its *mobility* the replica chariot would need to be similarly mobile. In addition, the replica also needed a suspension system comparable to ancient artifacts to gauge the impact of uneven terrain, a feature that had been noted as being of importance in earlier research (Hulit and Richardson, 2007, p. 62). As such, a simple mock-up of a riding box using wood or PVC pipe cut to size and joined with elbow joints was deemed to be insufficient. In short, testing required a full-sized working model, albeit one made of modern materials, to ensure accurate test results.

First and foremost, in order to fulfill the primary purpose of testing, the finished size of the chariot recreation would need to be an accurate reflection of ancient vehicles. This in turn required knowledge of the exact size and shape the chariot, and most importantly the chariot cab, should be (including railing height). This question was compounded by the fact that the chariot was not a static creation, but rather evolved over time, and depending on the time and place could vary not only in size but utilization (Gabriel, 2007, 86; De Backer, 2009. pp. 2-3).

As the question was to evaluate any potential for causation between the use of the chariot and the development of the composite bow, the style of chariot in question needed to be closely associated in time and place with that of the earliest complete composite bow artifacts. As such, the chariot of New Kingdom Egypt and Mitanni of the second millennium BCE was chosen as a point of reference. Thankfully, several complete and partial chariot artifacts have survived in precisely this period of Egyptian history, including the six examples from the tomb of Tutankhamen - the single largest cache of chariots found to date (Partridge, 1996, p. 122; Littauer and Crouwel, 1979, p. 97). In addition to the Tutankhamen artifacts, a single chariot has been recovered from the tomb of Thutmose IV, as well as a specimen from the tomb of Yuya and Thaya (1390 BCE) and the example currently in the Florence Museum (Griffith Institute, 2008; Spalinger, 2009, p. 14; Partridge, 1996, p. 117). All, save the Yuya-Thaya artifact, compare closely in relative size to artwork of the same period, and this particular artifact appears that it may have been intended for use either by a youth or perhaps was created solely for funerary purposes.

Table 5.1: Chariot Artifact Dimensions

Chariot	Cab Width	Cab Depth	Rail Height	Floor Plan	Date
Tut-#120	105cm	46cm	78cm	D-Shaped	1323 BCE
Tut-#121	100cm	48.8cm	75.2cm	D-Shaped	1323 BCE
Tut-#122	102cm	44cm	75cm	D-Shaped	1323 BCE
Tut-#161	107cm	50cm	71cm	D-Shaped	1323 BCE
Tut-#332	111cm	49cm	71cm	D-Shaped	1323 BCE
Tut-#333	96cm	38.5cm	-	D-Shaped	1323 BCE
Thutmose IV	103cm	52cm	86cm	D-Shaped	1388 BCE
Yuya-Thaya	90cm	48cm*	-	D-Shaped	1365 BCE
Florence	97cm	54cm	75cm	Curved Front	15th Century BCE

*** Depth of the Yuya-Thaya chariot was estimated based upon relative dimensions from figure 5.12**

As can be seen in table 5.1, not all cab measurements have been published for the above artifacts, but the above data is enough to note the fact that the chariot cab is universally wider than it is deep, a detail readily ascertainable from photos for the Yuya-Thaya chariot even if full details of its exact physical dimensions are unavailable. Additionally, while several of the chariots most likely were not meant for use in war, the consistency of cab dimensions across the entire group of artifacts provides support to the authenticity of the cab dimensions for the recreation undertaken herein. Further, it has been determined that the sloping nature of the railing of the

Florence chariot was the result of poorly understood reconstruction done during the 1800's, and that originally the railing was most likely of close to a uniform height as can be seen in other extant chariot artifacts (Littauer and Crouwel, 1985, p. 108).

Figure 5.11 18th Dynasty Egyptian Chariot, Florence Museum.

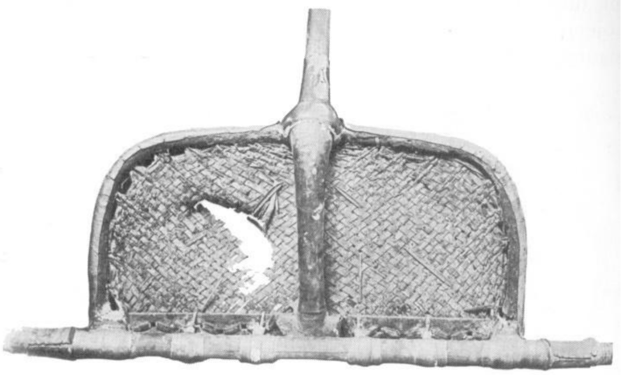

Figure 5.12 Yuya Thaya Chariot, top down view of cab.

CHARIOT CONSTRUCTION

With not one, but several examples of chariot artifacts providing measurements from which a recreation can be made, attention next turned to the process of building a full-sized model. Again, as accurate physical dimensions were deemed more important to the determination of potential bow/railing interference than the use of traditional materials, the chariot itself was constructed of a frame and yoke made from welded rebar. Similarly, the axle was constructed from steel pipe. Keeping in line with dimensions of the previously mentioned ancient artifacts, the riding box was 100cm wide by 50cm deep with an open bottom save for reinforcement struts to ensure sufficient structural stability. A floor reminiscent of the chariot artifacts from the tomb of Tutankhamen was then constructed by inter-weaving lengths of nylon webbing (rather than leather strips) such that if formed a taut panel.

As railing height from ancient artifacts (table 5.1) varied from 71cm to 86cm (with the railing of the Yuya-Thaya chariot unrecorded, but likely having a lower railing height still), building the railing of the reconstruction to a single "average" height was deemed to be insufficient given that railing interaction with bow length was of critical importance. Because of this, the railing was made using a two-part sleeved construction, with the uprights rising from the cab floor consisting of lengths of pipe into which the railing would fit as seen in figures 5.13-14. This unusual design decision allowed the railing to be raised and lowered from 90cm down to 50cm if desired, or set at any height in between these two extremes as needed. In this way testing could continue to progressively longer bow lengths beyond would otherwise be possible with a set railing height by the simple advent lowering the railing as needed.

A length of steel pipe 170cm long served as an axle and attached to the riding box by means of "U" clamps. The yoke, like the riding box, was constructed of a length of heat-bent rebar, which ended in a "T" bar reinforced with small diagonal braces to serve as a draught pole approximately 110cm high when the riding box was at a level position (figure 5.15).

The wheels were solid rather than spoked, and were of laminate construction consisting of four layers of 12mm thick plywood cut to shape and then held together with both glue and screws. Bearings sized to fit the metal axle were then packed into a center-cut hole in each of the wheels to minimize friction and wear allowing for smooth rotation even under load. The use of bearings also mitigated the higher rolling friction caused by the use of smaller diameter wheels of solid construction, a phenomenon functionally understood in the ancient world even if the exact reasons were not (Aristotle, *Mechanica*, 9.1-9.10).[27] To ensure that the wheels would endure testing without suffering from uneven wear, lengths of extruded aluminum were hammered flat into strips and nailed into place to serve as wheel rims (figure 5.16). The wheel and axle assembly, riding box and yoke were all designed such that they could be easily assembled and disassembled to facilitate transport and storage.

Figure 5.13 Chariot box base. Note the removable upright sleeves (two attached) allowing for an adjustable railing height.

Figure 5.14 Chariot box railing. The three vertical members slide into the sleeves shown in figure 5.14.

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[27] The assertion that Mechanica was written by Aristotle is disputed, and has also been attributed to Archytas of Tarentum (Winter, 2007, p. ii).

Figure 5.15 Assembled chariot. Note floor panel made of woven nylon webbing.

Figure 5.16 Aluminum wheel rim, partially affixed.

TESTING

A number of considerations went into the choice of propulsion. As the author currently lives in South Korea, horses or donkeys were not a viable option as they were both expensive to hire and would have required that the disassembled chariot be shipped cross-country for testing. Motorcycle or scooter power was also considered, but rejected primarily due to questions of both harnessing and control communication between the passengers in the chariot and the tow vehicle driver. Liability issues in the case of an emergency stop were also an issue. In the end, the author posted the chariot testing on a local events calendar asking for volunteers to help pull in two-man teams in exchange for the opportunity to ride in the chariot itself once testing was complete. While the resulting speed averaged the somewhat slow 15km per hour, it allowed for maximum safety, as people pulling the chariot could step away to the side quickly and safely if for some reason they needed to abandon pulling in an emergency. "Steering" was achieved by having the people pulling wear a harness on their torso with "reigns" leading back to the chariot thereby providing the driver with a sense of control. The inclusion of this rudimentary steering system allowed interference between bow and reigns to be measured.

At 189cm in height the author was too tall to act as a driver or archer during testing, as a taller than average individual could potentially influence test results focusing on interference between bow and railing. Estimates of average male height of course vary across both region and time. Hanson suggests that the average *hoplite* was 170cm tall (Hanson, 1999, p. 59). King Tutankhamen likely stood 167cm tall (Booth, 2007a, p. 140; Killen, 1994, p. 25). Similar estimates by Leek put the average Egyptian male at the same 167cm height, while Shahine places it at a shorter 159cm (Leek, 172, p. 16; Shahine, 2008). Given that the average charioteer (and the archer in particular) would not have belonged to the lower classes and as such would have better access to plentiful, nutritious food, Shahine's higher average height matching that of Tutankhamen will be used as a reasonable estimate. Taking this into consideration the two volunteers who rode in the chariot were 165cm and 168cm respectively, and chosen specifically for their height. Unlike in Egyptian warfare however neither the driver nor the archer was tied in to the chariot, allowing them to exit with a simple backward step should the need arise (Littauer and Crouwel, 1979, p. 63; Raulwing, 2000, p. 58). As the large foam safety tips of the arrows interfered with the use of a standard quiver, the author ran beside the chariot while in motion handing arrows to the archer one by one.

The testing site itself was a university sports pitch with a dirt field. Advertisement for volunteers resulted in a small amount of media interest, and as a result a writer and photographer from the Busan Ilbo newspaper were in attendance. The resulting story generated a degree of goodwill with the university while the newspaper itself was kind enough to allow use of their photographs (영미조, 2012).

Figure 5.17 Volunteers to draw chariot. Note the string harness and reigns allowing the driver to "steer."

Figure 5.18 Chariot archery test, Busan. Author (far left) hands arrows to the archer.

On the day of testing the field was somewhat muddy due to heavy rain the night before. The resulting runoff caused several ruts in the surface where the water had created channels, providing an opportunity to intentionally pass over an uneven surface. Initial use saw the charioteers resting on the front and back edges of the floor frame (as seen in figure 5.18). This originally made chariot use rather unstable, particularly when traversing ruts. Later use after the charioteers became more comfortable had their front foot on the floor proper, while the back foot remained on the back edge of the floor frame. The woven floor panel performed well, and both members in the riding box quickly adapted to the motion of the chariot on both smooth and uneven terrain, with the rear foot providing stability and the front foot resting on the woven panel providing shock absorption.

After becoming comfortable with the chariot while it was in motion, initial archery testing began at a standstill, allowing time for the archer to practice draw and release while standing in the riding box. Testing then progressed to firing with the chariot in motion, starting with a bow 120cm long and a railing height of 90cm. The 90cm railing height is higher than that recorded for existing chariot artifacts which ranged from between 71cm for one of the chariots recovered from the tomb of Tutankhamen to 86cm in height from the chariot found in the tomb of Thutmose IV (Griffith Institute, 2004; Partridge, 1996, p. 113). The added height had the dual purpose of providing a greater amount of initial support to both the driver and archer and also provided for an extra degree of conservatism in test results as the higher railing height would be more likely to interfere with archery in general.

TEST RESULTS

It must first be stated that in no way should testing considered to be a complete portrayal of chariot combat in the ancient world. Fully authentic field testing in many ways is unobtainable, as even if hundreds of accurate reproductions could be created from traditional materials, ethical concerns regarding the safety of both horses and people would be unavoidable in the modern day even without taking into consideration the lack of understanding large-scale chariot tactics. That being said, a number of points can be accurately gauged. First and foremost, with a railing height of 90cm (slightly higher than the highest rail height of any extant artifact), it was possible to easily use a bow of 170cm in length - a reasonable length for a bow of self construction. Such use was further possible without needing to adopt an asymmetric grip, such that the upper limb is longer than that of the lower limb. Further, a railing height of 80cm, a height still higher than all but one of the extant chariot artifacts, allowed the use of a bow of 180cm in length - a length 13cm longer than the archer was tall and fully long as several of the British longbow artifacts recovered from the wreck of the Mary Rose, all of which are at least twice the draw weight of that of the average bow in the ancient world (Hardy, 2001, p. 595; Blyth, 1980, p. 34; Spotted-Eagle, 1988, pp. 15-16; Hulit and Richardson, 2007, p. 57).

Lowering the railing to a height of 70cm allowed uninhibited use of a bow 190cm in length, the longest bow length tested. The results show that there is approximately 25cm of overlap between the minimum bow length possible such that it is of self construction, of a draw weight of at least 18kg, and to a draw length back to the archer’s ear (75cm or more) and the maximum reasonable bow length that can be used within the confines of a chariot that has a railing height of 80cm across both smooth and uneven terrain. Certainly a shorter bow length would be more convenient, but far from necessary. These findings expand upon, rather than conflict with archery testing done by Hulit and Richardson, who admittedly did not test any bows longer than 145cm (which was "easily handled within the confines of the chariot car") and did not test any bows of self construction (Hulit and Richardson, 2007, p. 62).

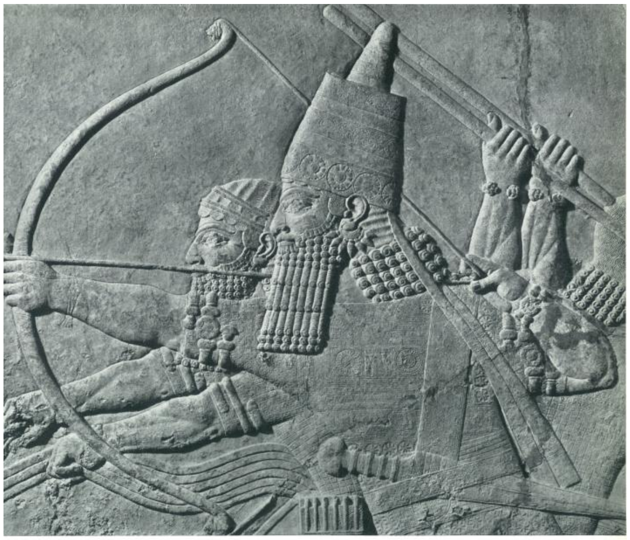

Figure 5.19 Close-up of Ashurbanipal I hunting lions. Note that the archers draw arm is depicted to the inside, next to the driver.

Figure 5.20 Ashurbanipal II, hunting lions. Note the consistent use of a right-hand draw, and positioning that maintains the king in the foreground.

Additionally, it was readily apparent that there was less interference between archer and driver when the archers draw arm was on the *inside*, rather than the outside, which resulted in some degree of bow/reign entanglement. As such, archers with a left hand draw should stand to the driver's right, while an archer with a right hand draw (more common, as it generally implies that the archer is right-handed) would stand to the driver's left. This discovery however cannot be definitively matched to ancient artwork due to artistic conventions in use at the time. While Assyrian art remains consistent with regard to the portrayal of a right-hand draw, it always depicts the archer in the foreground, possibly to imply the archer's greater importance. This means that if the archer is facing left, as shown in figures 5.19-20, the archer's draw hand would be on the inside, but when facing right, would be on the outside (Wilkinson, 1991, p. 87). This style of depiction holds true for Assyrian art even if the archer is facing backward. Artistic conventions for Egyptian art are conceptually similar. The convention of emphasizing the archer (typically the Pharaoh) remains the same but the execution takes this emphasis a step further, as the Pharaoh is typically shown *sans* chariot driver, even when engaging in battle (figures 5.21-22) and has a direct, or at times lowered point of aim, an unrealistic detail given the rate of fall for arrows over distance compared to Assyrian artwork which shows an elevated point of draw (Wilkinson, 1991, pp. 93-94; Spalinger, 2009, p. 18).

Further insights were gained with regard to the possible use of the Florence chariot. With the curved (rather than D-shaped) front of the cab, Littauer and Crouwel suggest that the Florence artifact was perhaps meant for a single person (Littauer and Crouwel, 1979, p. 76). While this certainly could be the case, it was apparent that two people could fit comfortably within the cab so long as both adopted a natural oblique stance, with the caveat that each person's inside leg was placed forward. This however is *opposite* the stance needed to minimize interference between archer and driver, or more appropriately, the archer and the reigns (the archer, with their inside arm being used to draw would mandate that their *outside* leg be placed forward), and therefore supports the suggestion that the Florence chariot was likely made for a single person, or at least two people not engaged in battle.

It was also readily apparent that the archer's firing arc, while expansive, did face some limitations. Shooting (with a slightly elevated point of aim to simulate aiming at a target some 50m or more distant) to the front, outside and rear was easy but firing across the reigns even with an elevated point of aim required caution. As such the firing arc was limited to approximately 250°. Shooting without a driver however resulted in an unrestricted 360° firing arc. The results on firing arc differ somewhat from the physical experimentation of Hulit and Richardson, who did not feel comfortable shooting directly forward over the heads of the horses, in large part because their replica chariot had a solid, rather than a woven floor, a point which the testing herein was careful to include as it more accurately replicated the shock absorbency of ancient chariot artifacts (Hulit and Richardson, 2007, p. 62).

Figure 5.21 Pharaoh depicted on chest lid (18th Dynasty).

Figure 5.22 Ramses II, shown driving chariot alone into battle. Note both the reigns tied around the Pharaoh's waist and the fact that the bowstring impossibly does not cut across the front of the Pharaoh.

Even Hulit and Richardson however found that their ability to fire forward was not *impeded* by the horses, but rather that shooting over the horses (with armor-piercing arrowheads) was deemed to be unwise due to their chariot's lack of shock absorption. Spalinger similarly agrees that shooting directly forward over the horses would not have been problematic, a point further reinforced by the experience of Simon Mulholland of Exeter UK, who has done archery using a saddle-chariot and longbow (approximately 170cm in length) with a team of ponies across meadow, field and rolling hills (Spalinger, 2009, p. 15; Mulholland, 2012). Finally, as it has been found that chariot archery is clearly *not* dependent upon the use of the composite bow, this discounts the possibility of using depictions of chariot archery as a substitute method of iconographic evaluation of bow construction.

CONCLUSION

Physical testing clearly shows a 25cm gap between the 150cm minimum length needed for a bow of self construction with a draw weight of 18kg and draw length of at least 75cm, and the 175cm maximum reasonable length with which a bow can be used within a chariot cab, indicating that the chariot was *not* the impetus for the development of the composite bow. This overturns one of Hamblin's major arguments against the early development of the composite bow construction (Hamblin, 2006, p. 94). While self bows of 190cm or longer would certainly have been impractical, historical evidence for bows within the 150-175cm length range are not uncommon, including eight of the self bows recovered from the tomb of Tutankhamen (Griffith Institute, 2004). That being said, given the enormous cost associated with the construction, use and maintenance of a chariot and the team of animals needed to draw it, the additional expense associated with equipping chariot archers with a bow of composite rather than a self construction would have been relatively minor in comparison (Hamblin, 2006, p. 146; Partridge, 1996, p. 81; Healy, 1992, p. 13). In this regard, the adoption of chariot warfare would likely have *encouraged* the use of the composite bow due to its potential for improved arrow velocity (and as a result, increased range) but it in no way *caused* (or was otherwise dependent upon) the development of composite construction.

As it has been found that chariot archery is not a viable substitute for bow profile as a means of iconographic evaluation of bow construction, attention must return to the remaining variables of materials, unstrung bow profile, and limb mass previously identified in Chapter Four. As such, the next chapter deals with physical testing and associated results. It is only after physical testing and quantification of the potential benefits of composite construction that have previously been identified in Chapter Four can iconographical evidence be re-examined in Chapter Seven, as the physical testing in Chapter Six forms an empirical basis upon which an improved method of evaluation for judging composite construction can be made.

CHAPTER SIX

PHYSICAL TESTING

With the factors of bow profile, limb mass, and materials influencing arrow velocity identified in Chapter Four, attention will now focus on the testing and evaluation of each of these variables. Starting with a brief outline of several directions of existing research, the chapter then progresses through each variable in turn. Discussion of each variable begins with a section dealing with test design, followed by testing and a separate summary of test results.

The first question is perhaps if it is possible to isolate and measure these variables through physical testing. The answer is yes, and in fact some of the relevant testing has already been done (Kooi, 1994, pp. 24-25; Kooi and Bergman, 1997, p. 129; Baker, 1992, p. 115). In addition to academic research outlined previously in Chapter Two, the author also attempted to contact a number of major archery companies. While most were both cordial and supportive of the current endeavor, they were understandably averse to releasing significant amounts of private research to what would essentially be public access, and as such an unknown amount of data remains inaccessible to both the public and scholars alike.

As a group, traditional bowyers are more forthcoming with their findings, but their research is typically limited to individual experience, at times may lack a systematic approach, and does not always correspond to the direct area of interest of this thesis. Additionally, unlike modern mass produced foam-core carbon fiber limbs, wood properties vary not only from species to species but also from tree to tree in a given species, with a given tree's growth environment creating slight differences in material strength (Hardcastle, 1992a, p. 26; Alrune, 2007, p. 17). Finally, given that the market for traditional archery is geared more toward hunters, relatively little data exists for higher draw weights (Baker, 1992, p. 115; Spotted-Eagle, 1988, pp. 15-16).

That being said, the authors of *The Traditional Bowyer's Bible* series of books have collated their data to provide a number of general rules of thumb for bow performance at the 22.7kg (50 pound) draw weight level, perhaps the most common draw weight for archery hunting equipment in use today. At 22.7kg draw weight, a 28.34g (one ounce) increase in mass placed mid-limb (on each limb) will decrease arrow velocity by 0.3m/s, or one foot per second (Hardcastle, 1992a, p. 40). A 1.296g (20 grain) increase in string mass similarly decreases arrow velocity by 0.3m/s, again at 22.7kg in draw weight (Baker, 1992, p. 73). The reduction of arrow velocity as arrow mass increases conveniently dovetails with Kooi's mathematical models with regard to string mass (Kooi, 1994, p. 7).

Similarly, *The Bowyer's Bible* series also provides data on how bow profile affects arrow speed, again for a 22.7kg draw weight. An average bow with "severe string follow" (approximately 10cm set) will yield an arrow velocity of 42.672 meters per second (140 feet per second), while a "severely recurved" bow (again having approximately 10cm in reflex) will have an average arrow velocity of 51.816mps (170fps) an increase of 21.4 percent (Baker, 1992, p. 115). As a broad body of evidence across many different bows the velocity data is quite useful, but a large sample size also has its drawbacks, at least with regard to the amount of information provided as it does not provide details as to bow construction (either self or composite) or bow mass. It also does not show how these variables vary with draw weight, an as yet unproven but potentially important consideration.

Finally, a very small group of scholars has taken a theoretical approach to bow performance. The resultant mathematical models have been used to better understand how bows work, and to provide draw weight estimates of bow artifacts that are too fragile to test physically. Existing models however have thus far tended to focus on bow efficiency rather than how differences in profile, mass or materials and their effect on arrow velocity vary with draw weight (Klopsteg, 1943, p. 177; Kooi and Bergman, 1997, p. 128; Karpowicz, 2007, p. 682). Such models also can also be rather difficult for those not specialized in scientific or mathematical disciplines to interpret, although careful reading of the text accompanying the equations and charts will reward readers with a broad understanding of conclusions even if the math cannot be easily followed.

As a whole then, physical test data to date remains either proprietary in the case of commercial manufacturers, incomplete in the case of data available from traditional bowyers, or theoretical in nature and difficult to understand for many classically trained historians and archaeologists. Simply put, a complete understanding of how and why a composite bow will typically show increased performance compared to a self bow requires further testing before firm conclusions can be made.

Such testing in itself is not difficult: draw-force curves for bows of different profiles, materials or draw weight can be made through the use of a hanging scale and a measuring stick (figure 6.1). Arrow velocity can similarly be checked by using either high-speed video or an arrow chronograph (figure 6.2).[28] By far the most difficult task is the purchase and/or creation of bows which are otherwise equal except in one parameter to ensure an accurate and valid comparison. Comparison of bow profile is particularly difficult in this regard, a topic discussed at greater length later within the current chapter.

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[28] While the use of high speed video is more versatile, it also is significantly more expensive. Examples of both can be seen in use in episodes of the TV show MythBusters (episode 119 for the arrow chronometer and numerous episodes with regard to high speed photography, the show's preferred method of speed calculation).

MATERIAL TESTING

TEST DESIGN

In many ways the easiest aspect of composite design to evaluate was the effectiveness of different materials through a series of functional object replication tests (Mathieu, 2002, p. 2). The factors affecting the force required to bend a beam were first postulated crudely by Galileo Galilee in 1638, and to a certain extent have already been discussed earlier in Chapter Four on bow mechanics (Galilie, 2000, p. 159). In particular, knowledge of the cross-sectional shape, width, thickness and length of a bow limb allow the calculation of force required to bend it a given amount for a given material (Wolfram Alpha, 2013a; Baker, 1992, p. 66). The initial calculation for a bow would be quite difficult if done mathematically, as bow limbs typically vary in cross-section throughout their length (Kooi, 1994, p. 15).

These initial calculations can however be easily replaced with the data provided by a draw-force curve as shown previously in Chapter Four, and as such the mathematical difficulties arising from a variable cross-section are of little import. Additionally, once initial measurements for a given bow have been made, uniform changes are easy to both model and predict. The implications of being able to predict the force required if the cross-section of a given bow is altered allows the evaluation of different materials as compared to the addition or subtraction of more of the same material (in the case of bow limbs, made of wood). Variations in the results from predictions can then be attributed to differences in materials performance. In this way, it is possible to determine if the use of different materials affects bow performance unto itself, or if the use of sinew and horn simply allows for a more highly stressed design. The entire premise of course requires the careful measurement of bow performance for a given bow, and then modifying, measuring and re-modifying the same bow as different materials are added and the measurements for the modified design checked against the predictive model.

For evaluation of energy storage, the bow was strung and then brought to full draw several times immediately prior to measurement to ensure that hysteresis was minimized (Baker, 1992, p. 72; Denny, 2007, p. 28). The bow was then strapped to a tillering stick with an attached meter stick measure. It was then flipped upside down, the bowstring hooked to a hanging scale and pulled downwards until it reached a full draw of 73cm, as seen in figure 6.1. Draw force was then recorded and the draw lessened by 5cm, where another force measurement was taken and the process repeated until the bow returned to brace height at 18cm. Measurements were intentionally taken starting from full draw, rather than at rest to ensure that force differentials between the draw and the release caused by hysteresis would be avoided. As such, the force numbers reported herein are those representing energy stored in the bow, rather than the slightly larger but potentially problematic numbers representing the amount of energy used to bring the bow to full draw.

Figure 6.1 Author measuring the draw weight of a heat-molded PVC bow.

Figure 6.2 Arrow Chronograph

As natural materials were used during materials testing, particular attention was paid to the moisture content of the bow immediately prior to testing. When needed, the bow was placed in environmentally controlled storage of 40% relative humidity to both prevent excess material stress and ensure consistent, comparable test results.

INITIAL BOW CONSTRUCTION

The starting point for materials testing was a wood bow of joined construction made by the author out of oak. As this particular bow was the author's first attempt at bow making, and was done several years prior to the research at hand, the fact that oak was a sub-par material choice compared to cherry which was equally available was only discovered after the fact. As the physical testing herein focuses on a comparison of sinew and horn as compared to a given wood however, the choice to use one wood over another does not materially affect the results.

Interestingly, while the purchase of high quality lumber of consistent and accurate dimensions has grown easier in the modern day, it has become significantly more difficult to purchase wood suitable for bow-making (Hardcastle, 1992a, p. 20). The reason for this is due to the requirement that the grain of the wood, particularly for a bow of self or joined construction, not violate growth rings across the back (outside) of the bow limbs (Alrune, 2007, p. 22; Hardcastle, 1992b, p. 138; Junkmanns, 2007, p. 49). This typically means choosing a given growth ring as the back of the bow, but a biased or edge-ringed layout is also possible (Alrune, 2007, p. 22; Baker, 1993a, p. 33). The production of commercial lumber however utilizes computerized machinery to maximize output for a given log. While this reduces waste, it pays no attention to how the grain of the wood lays within a given board. As a result, careful examination of wood grain is critical when selecting commercially produced lumber for bow-making as the grain almost always strays off parallel.

For initial construction a white oak board was selected with grain drift shallow enough that it could cover slightly more than half a bow length, allowing a bow to be made of joined construction. In this case two side-by-side half pieces were ripped lengthwise from the board, thereby creating two sister billets, or half-length staves cut from the same board or log. Each billet was next reduced through the use of drawknife and spokeshave so that it followed a single growth ring along the back. The billets were then joined with a Z-shaped splice. Sadly, the original design was too narrow and thick for the material used, resulting in the bow taking a set. After a period of use the bow further developed a crack along the back, and the bow was relegated to wall display until the time of the current research.

At this point, the bow was completely re-worked. First and most importantly, three growth rings of wood were removed from the back of the bow such that it was worked below the level to which the crack had developed. This also reduced the draw weight to a safer level, minimizing the possibility that a similar crack would develop. The bow now being exceptionally long for its draw weight, the ends of both limbs were trimmed. The resulting increase in draw weight caused by reducing the bow's length was mitigated by carefully removing material from the belly side of the limbs, which also changed the profile of the bow from having a set of several centimeters to a flat profile as the wood layers which had previously been damaged by excess compression were removed. With the additional bow-making experience gained over the intervening years, the resulting bow was of a draw weight better suited to its original design, drawing 4.2kg, having a mass of 400g and an overall length of 170cm. While this resulted in an exceptionally light draw weight, this did not affect the validity of testing and provided the additional benefit of certainty that the bow in its current design owed its survival of testing to the sinew backing, as initial limb thickness prior to being re-worked had resulted in near failure. This forms a key conclusion for material testing, and is discussed in greater detail later herein.

As shown in table A.1, the bow limbs were now uniform in thickness save for the transition points near the grip. To ensure proper limb curvature when at draw width tapers as distance increases from the grip giving a vaguely pyramidal front silhouette. This ensured the efficient distribution of limb mass, but also more importantly lends itself to mathematical modeling with regard to changes in limb thickness, as increases or decreases can be computed as an equal percentage increase throughout the length of the limb. Draw was then tested to plot a draw-force curve for the bow before undergoing further modification (figure 6.19).

SINEW BACKING

After gathering baseline information from the all wood bow, it was modified by adding a sinew backing. Common in composite designs, sinew backings can be found on artifacts ranging from ancient Egyptian angular bows to medieval European crossbows to North American bows used by Indians of the Great Plains (McLeod, 1970, p. 32; Payne-Gallwey, 2007, p. 62; Laubin and Laubin, 1980, p. 27). The application of a sinew backing is a time-consuming, multi-step process that ideally would be applied as a number of separate layers, a fact which no doubt contributes to the commonly repeated scholarly estimates that a composite bow would require anywhere between five and ten years to make (Drews, 1993, p. 110; Howard, 2011, p. 8; Rausing, 1967, p. 157).

The first step to a sinew backing is to procure a supply of sinew, typically recovered from either members of a domesticated herd when culled or from animals killed in the hunt. The leg and back tendons of members of the ungulate order are most commonly used due to their length although in theory even small game can provide lesser amounts of tendon albeit in miniscule amounts. In the United States, fresh leg tendon (either cow or during the autumn, deer) can often be gotten from butchers willing to process hunting kills at a nominal cost. Unfortunately, this option was not available to the author, who currently resides in South Korea. As such, locally procured cow tendon was used for initial processing. The resulting tendons, once removed from their casings and laid out to dry were of excellent quality, but as the foreleg cut is not considered to be a waste product within South Korea, it was deemed to be cost prohibitive (figures 6.3-5).

Figure 6.3 Block of frozen (cow) foreleg cuts prior to having tendons removed. The entire four kilogram block only contains eight tendons.

Figure 6.4 Tendons removed from foreleg cuts pictured at left set out to dry.

The now dried leg tendon underwent the second stage of processing, which involved pounding the tendons until the outer casing had broken and the resultant fibers began to break apart

(Hamm, 1992b, p. 217; Laubin and Laubin, 1980, p. 65; Spotted-Eagle, 1988, p. 37). During the pounding process, the tendons lost their translucent appearance and regained their original white coloration. Each tendon required extensive pounding, needing approximately 15 minutes of work before the separation process could begin (figure 6.6). Back sinew would have likely speeded the process, as it is purportedly much easier to separate (Spotted-Eagle, 1988, p. 36).

With the tendon just starting to break down the process of separating individual fibers could begin. While the previous pounding helped begin the separation process, each tendon remained an extremely durable unified mass. Reducing tendons to separate fibers required on average 45 minutes each. At first, the tendon was pulled into smaller strips using two pairs of pliers. Each strip in turn was further pulled apart by hand, with the resultant section "fluffing" somewhat as additional fibrous connections began to separate (figure 6.7). Individual fibers were then pulled apart, typically by using one's thumbnails to gain purchase. A fully separated tendon then makes up a small pile, resembling nothing so much as extremely tough meat-scented pillow fluff (figure 6.8). Given the overall difficulty in fiber separation and need to use pliers to process the sinew such that it could be separated by hand it is certain that a significant amount of further pounding would have been beneficial.

Further research eventually located a vendor selling leg tendon recovered from whitetail deer. Once delivered the most noticeable difference between the deer tendon and the cow tendon was size - the deer tendon was both thinner and slightly shorter than the locally acquired cow. This made for slightly faster processing, with an average time of between 45 and 50 minutes for both pounding and fiber separation each. With sufficient raw material to attempt a sinew backing, individual fibers were separated into piles sorted by length, and separated into bundles of approximately pencil thickness.

With sinew fibers sorted, bundled and ready the next step was to prepare a batch of hide glue, an adhesive used in prehistory and still in use for specialty purposes in the modern day (Pantel, 2007, p. 179; Bearing Specialists Association, 1991, p. 1; Zammit and Guilaine, 2005, pp. 107-8). Coming in the form of either small pearls, or a flake-like powder, hide glue must first be mixed with water, stirred and allowed to set for several hours (Schellmann, 2007, p. 55). After setting, the container must then be gently heated, preferably in a double boiler system, so that it reaches between 55° and 65° centigrade (Hamm, 1992b, p. 222; Pantel, 2007, p. 185). If the ratio of water to glue is correct, the entire solution will, with a great deal of stirring, be reduced to a uniform consistency. The glue is then taken off of the heat and allowed to set again, whereupon it will be ready for use upon re-heating. After some experimentation, a ratio of six parts water to one part glue powder was determined to be of both thin enough consistency but of more than adequate strength.

Figure 6.5 Dried (cow) leg tendon ready to be pounded. Approximately 25cm in length.

Figure 6.6 Same dried leg tendon as shown in figure 3.5 after approximately 15 minutes of pounding. Note the separation of fibers at right.

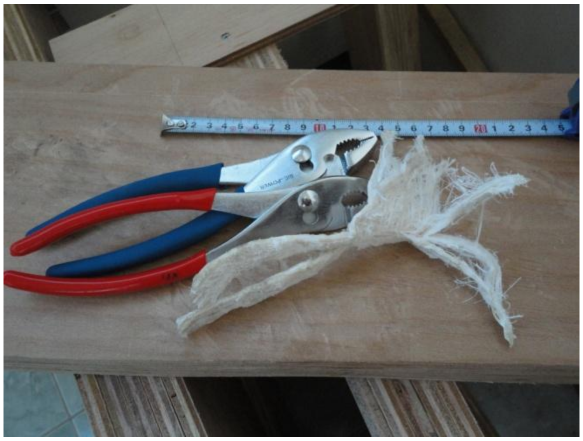

Figure 6.7 Pulling the pounded tendon apart with two pairs of pliers.

Figure 6.8 Fully separated tendon.

Figure 6.9 Inverted iron, placed in a corning ware pot and stabilized with dish towels.

Figure 6.10 Complete double boiler assembly. Note the cloth under the jar of glue preventing it from coming in direct contact with the bottom of the pot.

Figure 6.11 Close-up of partially laid sinew backing.

Figure 6.12 Finished, partially dried sinew backing.

A small amount of the finished hide glue was then removed and further thinned with five parts additional water. This thinner glue was then applied to the back of the wood bow as a sizing agent and allowed to dry, thereby partially sealing the porous nature of the wood and preventing excessive absorption of glue during the backing process. After the bow dried, the remaining glue was heated and a separate bowl of warm water prepared to re-hydrate the individual bundles of sinew.

After each bundle of sinew was soaked in warm water for a minute, it was dipped in the hot hide glue, excess glue removed, and the bundle laid out lengthwise in a brickwork pattern on the back of the bow starting from the middle (figure 6.11) (Hamm, 1992b, p. 225; Spotted-Eagle, 1988, p. 39; Klopsteg, 1992, p. 35). Working toward the ends, successive bundles were then laid out until the entire back of the bow was covered forming a layer some two millimeters thick and the bow carefully set aside to dry. The freshly laid backing strongly resembled a layer of white muscle (figure 6.12).

The color of the sinew backing shifted back to translucent beige as it dried, and roughly halved in thickness. After three days, the color shift was complete and the backing felt as hard as unprocessed dried tendon to the touch. The entire process was then repeated, adding a second layer, which when dry formed a backing approximately two millimeters thick and increasing total bow mass to 526 grams. Careful sanding eliminated inconsistencies in the thickness of the backing, which brought back the now familiar white appearance to the surface. The overall dimensions of the wood/sinew composite bow are outlined below in table A.2. Draw-force curve data was gathered (figure 6.19) and the process of preparing a horn belly begun.

To the author's surprise, the sinew backing, while appearing completely dry, apparently still retained some amount of excess moisture which continued to evaporate, as over the next two weeks the bow was pulled into a three centimeter reflex, prompting another round of data collection (figure 6.19). The cross-sectional measurements however remained identical.

CONTROL TESTING: WOOD BELLY SLATS

To cross-check that the mathematical model used in later analysis did in fact provide accurate results, a control step was added consisting of adding a wood belly slat to both bow limbs. Slats were made from pieces of the same board from which the original bow was constructed to ensure that the control test had the highest level of validity, essentially adding thickness consisting of exactly the same material as the bow itself. In a perfect test, the bow would have started out thicker and then thinned, but in this case the control step could only be done *after* the addition of the sinew backing, as the original unmodified bow showed that the additional thickness could potentially result in limb breakage, particularly with the now shortened limbs. Indeed, one reason to apply a backing in the first place, and a sinew backing in particular, is to enable the use of wood which is either sup-par or to allow a bow design which would normally be too thick or too short to be used safely (Hamm, 1992b, p. 227; Spotted-Eagle, 1988, p. 33; Laubin and Laubin, 1980, p. 54).

After cutting a pair of rectangular slats exactly two millimeters thick from a larger piece of wood of the same board from which the bow was originally made, each slat was trimmed to a pyramidal shape matching the shape of each limb and sized with a thinned mix of hide glue. Once dry, un-thinned hide glue was again used as an adhesive, the pieces held in place with wood clamps and the bow set aside to dry for two weeks (figure 6.13).

Draw-force curve data was again collected (figure 6.20). Upon de-stringing the bow however had again changed profile, resuming its flat profile due to compression damage in the added wood slats. After testing the wood slats were removed through the use of a spokeshave and cabinet scraper, and cross-sectional measurements double-checked to ensure that no excess material had been taken off (figure 6.14). As when the belly was originally thinned, the deflex in bow profile disappeared with the removal of the compression-stressed slat material. The bow however did not return to its previously reflexed profile and instead maintained a flat profile identical to when the sinew backing had not completely dried, prompting yet another round of data collection (figure 6.20).

HORN BELLY

Composite bows which include a high compression strength material in the pre-modern world typically incorporated horn into their design, although antler, bone or even baleen was also used at times depending on local availability (Elmy, 1968, p. 20; Credland, 1993, p. 47). As a final stage of materials evaluation, a horn belly was added to the wood-sinew composite bow to investigate the benefit of materials with high compressive strength. Unlike sinew, various types of horn can be found fairly easily online. Unfortunately, not all horns (and even more so, antlers) are appropriate for use as an archery material. First and foremost, the horn or portion of horn to be used should not have an inherent twist.[29] This immediately removed many types of sheep and goat from consideration. For convenience sake, the author also decided that a horn long enough to cover an entire limb lengthwise would be greatly preferable, as it would eliminate or minimize the need for splicing. With bow limbs 75cm long, this further removed the majority of horned animals from the pool of possible candidates, leaving only several types of cow, water buffalo and antelope. Ordering whole horn online from almost all of the remaining choices was also risky unless the seller had a clear understanding of exactly what was needed for use as a bow component, and was willing to sort through their stock to accommodate the needs of no twisting, sufficient length and thickness and minimal need to remove curves through the advent of steam bending. In the end, a single gemsbok horn was ordered as it had sufficient length, no twisting, and minimal to no curvature thereby bypassing the need for extensive sorting by the supplier, and the fact that a single horn was sufficient to cover both limbs. Gemsbok horn was also historically available at least in Egypt, where it was used in a number of bows of joined construction which also made it historically accurate (Rausing, 1967, p. 70).[30]

While straight, gemsbok horns have a number of horizontal growth rings forming ridges along the length of the horn (figure 6.15). Removal of these ridges with file and rasp was the first order of business, followed by sawing the horn lengthwise in half. The inside of the horn was smooth, but hollow for much of its length (figure 6.16). This made the lengthwise cut in half much easier, but also presented a problem as this meant the inside of the horn was naturally curved across its width, and too strong to reasonably press flat for easy gluing (figure 6.17). Initial attempts at steam bending this radial curve were unsuccessful, probably due to the author's inexperience. As a compromise solution, the two halves where each cut lengthwise into quarters, leaving eight lengthwise strips with a small enough radial curvature that each strip could be worked flat. The strips were then given a rectangular cross section through the use of a file and a spokeshave.

With the horn reduced to a number of relatively narrow strips that could fit flush to the belly of the bow, the bow itself was re-sized with hide glue. The lengths of horn, while square, were narrow enough to require that three separate lengthwise strips butting against each other side by side to cover the bulk of each limb (figure 6.18). Initial attempts to clamp a horn strip to the belly resulted in extensive joint slippage, to the point that standard clamps were deemed unstable. As an alternative means of clamping, surgical tubing was used, providing a much tighter glue line. Horn shims cut to size and glued in place covered any remaining gaps along the edges of the belly of both limbs, ensuring full coverage. The entire belly was then carefully scraped down with a cabinet scraper so that both limbs had a uniform thickness of 12.2mm, upon which final data collection of draw-force curve measurements were taken (figure 6.22).

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[29] Twisting can be removed to some degree by steam bending, but as this was the author's first attempt at making a composite weapon, keeping the process as simple as possible was also of importance.

[30] An analysis of ancient Egyptian composite bows has yet to be done to determine which exact species may have been used.

Figure 6.13 Close-up side view of composite bow. Note the glue line between the main body of the bow and the added wood slat on the belly.

Figure 6.14 Close-up of belly of composite bow after the wood belly slats were removed. Note the faint traces of glue remaining.

Figure 6.15 Uncut gemsbok horn.

Figure 6.16 Uncut gemsbok horn, interior view.

TEST RESULTS

The entire basis of testing rests on the fact that increasing a bow's thickness will increase the force required to bend it (its draw weight) by a predictable amount. As draw-force curves measure energy stored, rather than energy released, differences in bow mass may be completely discounted from this portion of the analysis. Normally, computing a force-bend model for tapered limbs would be quite complex. Thankfully, these initial computations were not needed, as initial draw-force data provided a baseline against which all further computation could be measured. Limb taper would have complicated matters if a baseline were not available but, as both bow limbs maintained a constant thickness throughout their working length at each stage as the bow was re-worked this allowed width to be treated as a constant, thereby leaving a direct comparison of thickness as the only variable. A mentioned in Chapter Four, the moment of inertia for a rectangle is {(Width x Height^3)/12} (Wolfram Alpha, 2013a; Baker, 1992, p. 66).

Looking at the cross-sectional measurements of both the initial baseline of the wood bow and comparing it to the wood/sinew bow, it can be seen that width remains constant (tables A.1-2), and as such can be eliminated, as can the divisor of 12. This leaves the measure by which force needs to increase with changes in limb thickness. A simple doubling of thickness then would be $(2^*\text{Height})^3$ or an eightfold increase in draw weight. For comparing the wood and wood sinew bows, the computations are $\{9.5\text{mm (the new thickness) / 7.5mm (the old thickness)}\}^3$, which reduces to 1.26666^3 for a final result of 2.032296, meaning that starting from a baseline of 7.5mm of thickness, a 2mm increase in limb thickness *should* roughly double the final draw weight at all points along the draw-force curve.

Looking at the draw-force curves shown in figure 6.19, this was clearly not the case. The addition of sinew certainly increased draw weight, but markedly less than what the beam model predicted. True, once the sinew dried completely, the results closely approximate the predictive model, but this difference could also in part be explained by the accompanying change in bow profile. As profile will be evaluated separately later within the current chapter the change in bow profile needs to be backed out before an accurate comparison of materials can be made. The resulting differences from the predictive model, presuming that it is accurate, are a measure of how beneficial the addition of sinew is compared to an equal volume of wood. Given that sinew is stronger in tension than wood, one would normally expect the results to show a better than expected performance from the addition of sinew, and yet physical testing shows the exact opposite.

Figure 6.17 Gemsbok horn halves split lengthwise. Note radial arc.

Figure 6.18 Gluing horn lath to belly of bow limb, two thirds complete. Note surgical tubing used as clamping.

This of course brings the veracity of the model itself into question. Fortunately, the addition of the wood belly slats provided a control against which the model, which assumes a uniform construction consisting of a single material, could be measured. Since 2mm slats were added to the belly of each limb, the result according to the predictive model would be a draw weight increase of 100%. As mentioned previously, this was not done as it likely would have compromised the integrity of the weapon as a whole. Because of this, the additional factor of the sinew backing must be taken into account. This can be easily accomplished, for while the predictive model for a given thickness is proportional to the cube of the increase in limb height, the resulting draw weights are *additive*. This means that by adding the actual increase in draw weight caused by the addition of the sinew backing (and change in profile) to the predicted draw weight increase caused by adding 2mm of thickness to the original baseline bow, the total represents a prediction of the total draw weight for the composite weapon as a whole. The data and associated computations can be found in table A.6. Upon first glance, the accompanying results as seen in figure 6.20 tend to indicate that the predictive model based upon the cube of percentage of increase in limb thickness is indeed flawed. The results in figure 6.20 and accompanying table however fail to account for the change in un-braced bow profile from a reflex back to a flat profile after being worked in. As such the comparison is not entirely an accurate one, and was in need of further investigation.

For the revised data, the draw-force curve measurements for the wood baseline bow are still subtracted only this time from the data gathered from the wood/sinew bow *after* the slats have been removed. The residual measurements, which accurately represent the extra force provided by the sinew from the flat profile bow, are then added to the predicted forces for the wood/slat bow which remains unchanged. The total then represents a slightly lower set of data points which removes the extra variable caused by the shift in bow profile. As seen in figure 6.21, the predicted results match the actual results almost exactly. Clearly then, the predictive model of draw force being proportional to the cube of the percentage increase in limb thickness is accurate. This however still does not explain why the material performance for sinew, with approximately four times the tension strength of the same volume of wood, performs significantly *less* well when compared to its materially weaker counterpart, wood (Kelekna, 2009, pp. 76-77; Landels, 2000, p. 106). The point is of considerable importance and will be given a full explanation after investigating the relative performance of horn.

With the predictive model validated and a means of separating increases in draw strength due to sinew from the sinew/wood reconstruction of the test bow accomplished, the exact same process was applied to the addition of horn slats to the belly. The overall figures differ somewhat from that of the addition of the belly slats as the horn strips were left thicker than the two millimeter increases used thus far. In this case, the horn strips were scraped to a consistent layer 2.7mm in thickness. With the original thickness of the bow limbs remaining unchanged at 7.5mm, the calculations then are: $(10.2/7.5)^3$, resulting in a multiplier of 2.515465. This figure is then multiplied by the force of the original baseline bow, and then added to the residual force representing the sinew layer in a flat profile.

Figure 6.19 Draw-Force Curves: Wood Baseline, Wood/Sinew (Actual) and Wood/Sinew (Predicted) Comparison

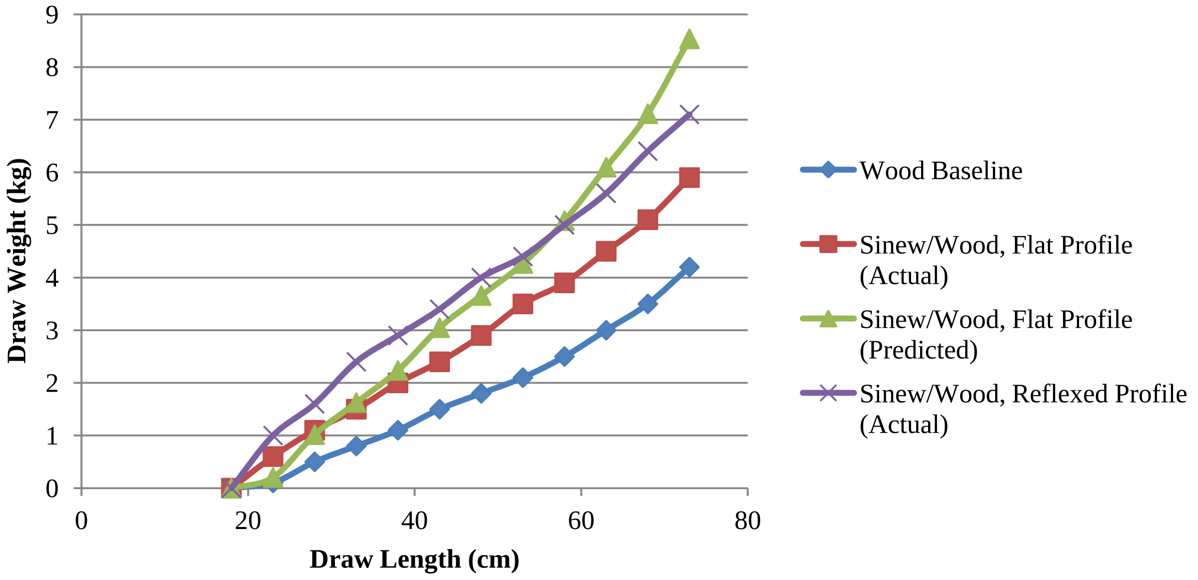
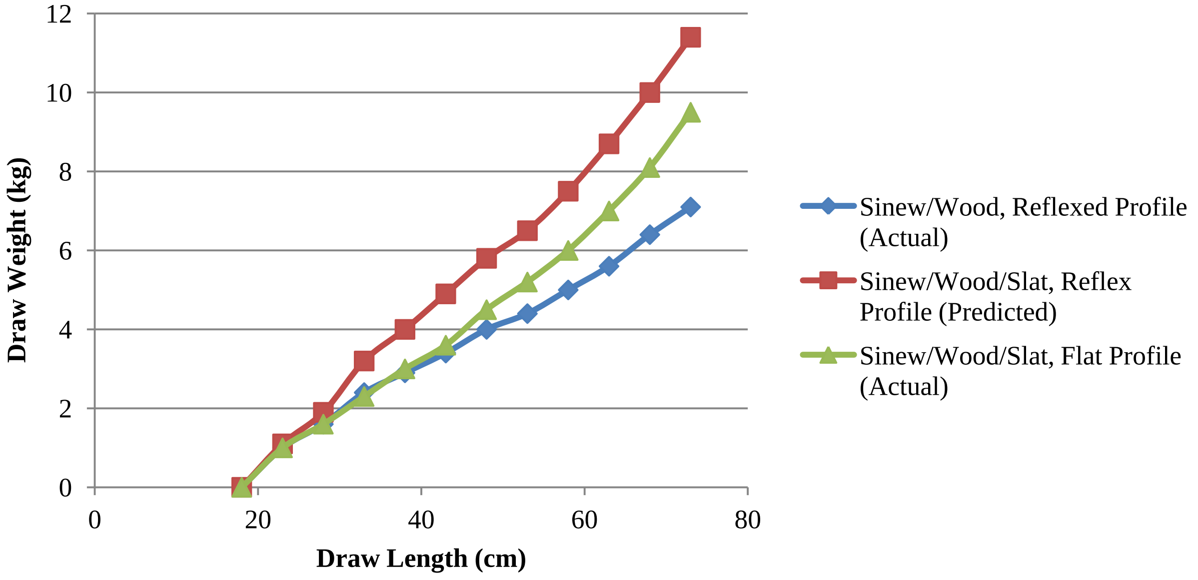


Figure 6.20 Draw-Force Curves: Sinew/Wood, Sinew/Wood/Slat (Predicted) and Sinew/Wood/Slat (Actual) Comparison



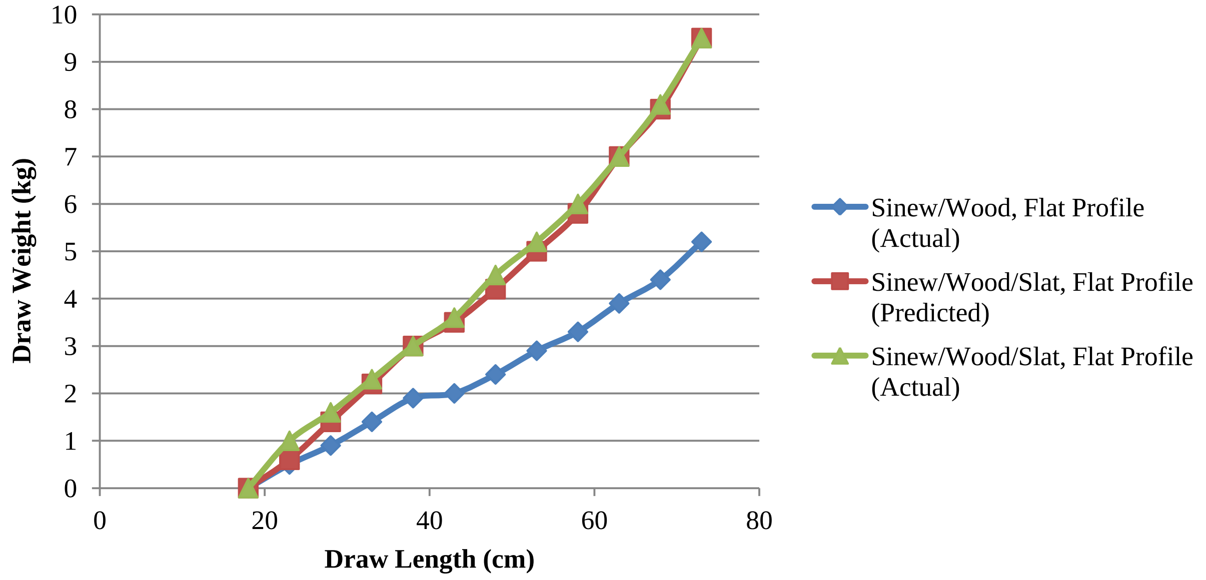


Figure 6.21 Draw-Force Curves: Sinew/Wood, Sinew/Wood/Slat (Predicted) and Sinew/Wood/Slat (Actual) Comparison - Revised

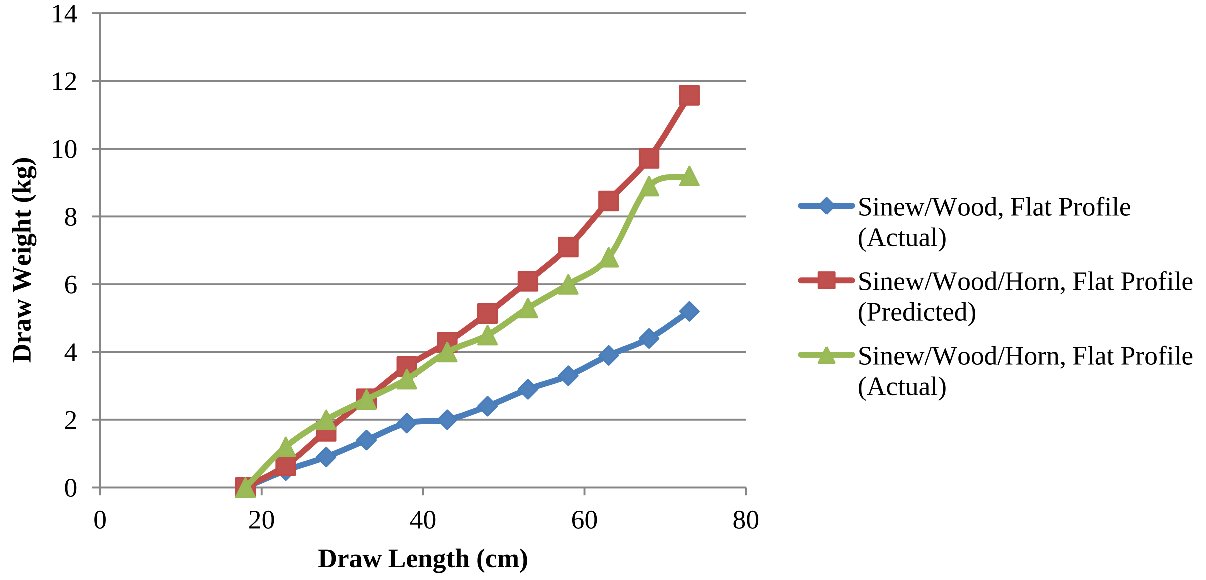


Figure 6.22 Draw-Force Curves: Sinew/Wood, Sinew/Wood/Horn (Predicted) and Sinew/Wood/Horn (Actual) Comparison

Again however, the results were not as expected as can be seen in figure 6.22. Indeed, the addition of a horn belly underperformed not only compared to the predicted results, but also the actual results of the wood slats which were 0.7mm thinner. The difference, while unexpected, is consistent with that of the sinew backing despite the superior strength of both materials compared to wood with regard to tension (sinew) or compression (horn). The question then remains as to why, and the implications of the results may have with regard to the current research.

MATERIALS TESTING: CONCLUSION

The underperformance in both sinew and horn has been noted before (Baugh, 1994, p. 119; Kooi, 1994, p. 18). Key to understanding why is that while horn and sinew are *stronger* than wood in compression and tension respectively, they have a *smaller* modulus of elasticity or in other words, less stiffness (Baugh, 1994, p. 119).[31] Simply put, both sinew and horn are more durable, enabling them to take a higher degree of stress than wood before suffering material failure but both are also *easier to bend*, having a modulus of elasticity of 0.09kgf/cm^{2}x10^5 for sinew and 0.22kgf/cm^{2}x10^5 for horn compared to between 1.0-1.2kgf/cm^{2}x10^5 for different varieties of wood, a quality which explains why both horn and sinew underperform the predictive model for draw force found during physical testing (Gordon, 1987, p. 321; Kooi, 1991, p. 28). This distinction between ultimate tensile (for sinew) and compressive (for horn) strength and bending strength, or stiffness, is key. The testing of a more highly stressed design with highly reflexed limbs would yield greater improvement, but the comparison would provide false results, as it would combine the effects of both a change in materials *and* a change in profile. Properly evaluated performance, as seen in figure 6.22, shows that the predictive model for material performance is accurate. As such, any performance differences that differ from the predictive model can be confidently attributed to differences in the stiffness of the materials themselves - in this case sinew and horn.

This underperformance would become even more noticeable when evaluated by means of arrow velocity and range due to the relatively greater density of sinew and horn compared to wood, thereby resulting in a comparative increase in limb mass. Because of this, both horn and sinew are *only* useful in cases where the stress of a given bow design would result in material failure if wood was used by itself (Kooi, 1994, p. 18). In all other cases, superior performance will be gained by simply using more wood to increase limb thickness.

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[31] Technically speaking, bending stiffness is the modulus of elasticity of a material multiplied by its moment of inertia. As the moment of inertia for all of the physical tests herein remains constant however, the relative performance of both sinew and horn can be attributed solely to differences in Young's Modulus.

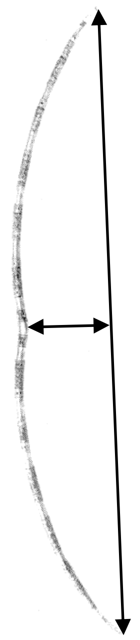

Figure 6.23 Angular composite bow from the tomb of Tutankhamen, reflex depth/length ratio: 12.7%.

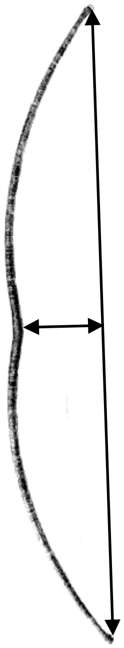

Figure 6.24 Angular composite bow from the tomb of Tutankhamen, reflex depth/length ratio: 12.7%.

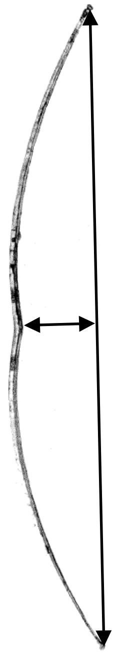

Figure 6.25 Angular composite bow from the tomb of Tutankhamen, reflex depth/length ratio: 11.6%.

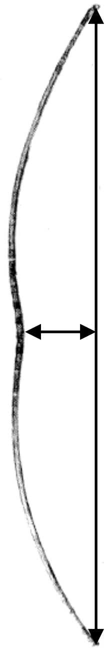

Figure 6.26 Angular composite bow from the tomb of Tutankhamen, reflex depth/length ratio: 10.6%.

The implications are important, and cannot be overstressed with regard to the focus of the research at hand. It essentially means that sinew and horn (or baleen, bone or antler as the case may be), is useful in some situations, but in themselves do not ensure superior performance.[32] Indeed, those cases where composite construction would yield superior performance can in essence be condensed into a single reason: a more highly stressed bow design than can be achieved with wood alone. In contrast this also means that the addition of horn or sinew in a design which does *not* exceed the material strength of wood will result in sub-par performance.

This singular reason requires a bit of explanation. The self bow artifacts recovered from the wreck of the Mary Rose clearly show that all wood bows can and have been made with draw weights at the upper end of the human physical limits (Hardy et al., 2011, p. 627; Hardy, 2005, p. 17). Further increases in draw weight can be imparted by incrementally decreasing limb length. If this process continues, eventually the bow will either take a set as a result of partial compression failure or break outright as a result of failure under tension. It is at this point, *and only at this point*, is where the addition of different materials would become advantageous. The addition of horn, with its greater compressive strength and used in sufficient quantity, will prevent a bow from taking a set. The use of a sinew backing will likewise prevent the breaking of a limb under tension.

While the case of a highly reflexed design appears to be different, the same principle (increased stress) still applies. While it is understood that wood generally grows straight, curved sections of wood can be chosen intentionally for use in a highly reflexed design. More likely however curvature would be imparted by steam bending or the bending of green wood and curing or seasoning over a form to impart a curve (Schleining, 2002, p. 14; Baker, 1992, p. 95). Another possibility, but more technologically advanced, would be the process of pre-stressing a limb by bending different laminations into shape prior to gluing, a process which may be done with either different layers of wood, or the application of a sinew backing (Klopsteg, 1992, p. 33; Schleining, 2002, p. 95; Insulander, 2002, pp. 51-52).

This process of pre-stressing a limb by pulling it into reflex was in use by the rise of the Ottoman Empire in the fourteenth century CE and was likely used by the Scythians given the short length and high degree of recurvature shown in Greek artwork, but it is not known exactly when or where the practice first began (Klopsteg, 1992, p. 33; Drews, 2004, p. 101). As shown in physical testing, the addition of a sinew backing naturally pulls bow limbs into reflex to a certain extent, and this practice could be increased to a lesser extent without pre-stressing the limbs by allowing each layer of sinew to fully dry prior to the application of the next layer. Composite bows from the tomb of Tutankhamen vary in length and depth of recurvature, but by comparing bow length measured nock to nock and comparing it to the recurve depth as measured from the imaginary nock to nock line of the un-braced bow to the outside of the handle, a figure of

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[32] The individual performance of these alternate materials will of course vary depending on both their material strength and stiffness.

between 10-13% depth to length ratio can be computed (figures 6.23-6.26).[33] Given the amount of limb recurvature expressed during physical testing which showed a reflex depth to length of less than 2%, this indicates that the process of pre-stressing bow limbs (whether by steam bending or pulling material layers into a reflex) was used in ancient Egypt as well.

Regardless of how the reflex is imparted, the result is higher stress on limb materials. Given sufficient limb length, any degree of reflex can (theoretically) be imparted safely to an all-wood bow, but in practice the required length would quickly exceed physical limitations for practical use. The answer then would be again to move to a shorter bow with a sinew backing and/or a horn belly.

As important to understanding when composite construction is advantageous is the fact that *composite construction does not inherently alter braced bow profile*. Throughout the reconstruction process, the bow in question maintained a segment profile when braced, even when the un-braced profile had been pulled into reflex by the application of the sinew backing. By extension, this means that the stereotypical double-concave profile with a set-back grip needs to be intentionally built into the bow, thereby disproving the commonly held belief that composite bows must always have the stereotypical "Cupid" shape. This in turn reinforces Rausing's claim that composite bows can take any profile and stresses the need to find a secondary measure, such as bow length or degree of unstrung reflex to supplement iconographical evaluation (Rausing, 1967, p. 20; Collon, 1983, p. 53). With a clear understanding of how materials and their strength and stiffness affect draw weight, and that the use of horn and sinew do not inherently increase performance save as a byproduct of bow design, analysis can move to the testing and analysis of unstrung bow profile.

PROFILE TESTING

TEST DESIGN

As mentioned previously, the main problem with profile testing is that it is fairly difficult to change a bow's profile except through the use of steam-bending, and even then the profile can typically only be changed once, thereby limiting the amount of data that can be collected. Additionally, the few wood varieties that can be readily steam bent such as white oak are generally not considered to be top choices for bow making (Schleining, 2002, p. 146; Alrune,

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[33] In actuality, the degree of reflex is significantly higher, as the limbs of angular bows would be deflexed without the sinew but the measurement of reflex made herein only takes into account the amount of reflex based upon a flat limb profile. This additional reflex does not however translate into a higher arrow velocity beyond the measured 10-13%, as it is mitigated by the inherent deflex formed by the angular grip - a design which combines the benefit of a somewhat higher arrow velocity while maintaining a high degree of stability while in use.

2007, p. 17; Vögele, 2007, pp. 97-8). In theory, a matched set of identical bows could be made, from which individual bows could *then* be steam bent into differing profiles. Such bows would most likely be made of white oak to ensure that the maximum range of profile adjustments is attained. The creation of a number of matched sets of bows covering both a range of profiles *and* a range of draw weights would however be both extraordinarily time consuming and beyond the author's current level of skill as a bowyer. All of these solutions however would result in a series of bows with *different* final draw weights. Accurate testing however requires the comparison of bows with the same draw weight but different profile, a much more difficult task with regards to bow creation. Additionally, testing should be done with matched pairs of bows at several data points across a range of draw weights. Ideally, the bows would be made of identical construction as far as material, length and un-braced profile, and would cover a range in draw weights from approximately 11kg in draw weight up through 45kg or higher.

To accommodate the need for bows with differing profiles but identical draw weights, two separate manufacturers were chosen to each supply a single model of bow which could be made to order in draw weights between 11kg and 57kg. One model of bow consisted of a longbow design of self construction made of hickory and having a D-shaped cross section and segment profile. The other was a Hungarian style double-concave static recurve bow consisting of wooden grip and ears, but with a working (bending) portion made of fiberglass. Four bows for each style were purchased at 25, 50, 75 and 100 pounds of draw weight (11.34, 22.73, 34.09 and 45.45kg, respectively). The comparison of matching pairs of bows from the two sets thereby allowed a direct comparison of differences in stored energy based upon differences in profile, isolating profile differential as a performance factor.

DRAW-FORCE CURVES

As the longbows were made of natural materials, the vendor could only guarantee an approximation of the desired draw weights. Such variations are to be expected to a certain extent, as draw weight will vary with the relative humidity of the environment as well as from one piece of wood to the next (Karpowicz, 2007, p 680; Klopsteg, 1992, p. 24). As such, the final draw weights at a draw length of 73cm varied somewhat from what was ordered, as can be seen in table A.16 (figure 6.27). In particular, the longbow with the heaviest draw weight was seven kilograms lighter than desired. The draw weights of the double-concave recurve bows also differed somewhat (table A.17, figure 6.28), but the variations were smaller than the longbows as was expected when using modern materials such as fiberglass. The author was however happy to note that the longbows had all been varnished and waxed thereby slowing the intake and loss of humidity from the local environment considerably. Additionally, minor variations in brace height occurred between bows. To correct for this, bowstring length was adjusted by progressively twisting the bowstring to shorten it slightly as needed. The final brace height used in testing for all bows across all of the testing done throughout the research process was 18cm as measured between the string and the belly side (inside) of the bow at the grip.

A draw length of 73cm was used throughout testing, as this happened to be the draw length which allowed the author's knuckle on the thumb of the (left) hand drawing the bowstring to touch the corner of the author's mouth while using a thumb ring method of draw (Elmy, 1990, p. 41). This provided the greatest amount of consistency in draw length, thereby minimizing variation in test data. The final draw length also helped determine the choice of brace height, as a brace height of 18cm allowed draw-force curve measurements to be taken at convenient 5cm intervals during both material and profile testing discussed later in the chapter allowing a total travel, or distance between full draw and brace height, of 55cm.

Bows from each set had identical un-worked profiles, the segment bows a 2.5cm deflex and the double-concave bows a 21cm reflex. By comparing the draw-force curves from each set of matching draw weights, the effect of bow profile could be noted, and checked to see if it varied with draw weight. For the testing herein, the range included bows appropriate for youths (11.36kg), to those of a useful weight for hunting (22.72kg), up through the lower end of documented draw weights appropriate for war in the Middle Ages (45.45kg).

It became immediately apparent, at least with regard to the segment profile self bows made of wood, that while the entire set had identical profiles upon arrival, profile did *not* remain identical after use. While typical in bows of all-wood construction this variance complicated matters in two ways. First, profile within the set was no longer constant. The second problem was somewhat more problematic, as each bow did not have a single unstrung profile, but three: one profile measured before initial use (initial profile), a second profile immediately after use (worked-in profile), and a third after the bows had been given a chance to recover after use (recovered profile), as seen in table A.18. Further testing showed that both the worked in and recovered profiles remained stable after further use. The question of which profile should be used when comparing different bows was now a concern. As both draw-force measurements and velocity data were always gathered only after a bow had been brought to full draw several times immediately prior to measurement the worked-in profile, recorded immediately after a bow was unstrung after use, was deemed to be the most accurate. The double-concave bows, with the working portion of the bow limbs consisting entirely of fiberglass, retained their initial 21cm reflex even after use.

As expected, neither set of bows matched the desired draw weights exactly, with the segment longbows varying to a greater extent than the double-concave bows due to the increased difficulty of matching desired draw weights when using wood as compared to machine molded fiberglass. Also as expected, the two sets of bows differed in mass, with the double-concave bows showing surprisingly little variation in mass within the set, and being significantly heavier than the wood bows overall (table A.18). Most importantly however the final draw weights of supposedly matching bows between each of the sets was different, as can be seen in figures 6.29-32 and tables A.19-20.

Ideally, the draw weights for each bow within a given set would match the draw weight of its counterpart in the other set, but variations between the two sets for all practical purposes are unavoidable. The differences make a meaningful comparison between the two sets of bows impossible until the draw-force curves of can be adjusted so that they have an equal final draw weight. Such adjustments were made by increasing or decreasing all of the points of a given draw-force curve by a set *percentage* such that it matched the final draw weight of the matching bow from the other set. By adjusting a draw-force curve by a percentage, rather than by simple addition or subtraction, the overall shape of the curve remained intact, allowing minor adjustments so that two bows of slightly unequal draw weight to be accurately compared.

In this case, the segment bows of self construction were adjusted to match that of their counterpart of double-concave profile, resulting in a 17.33% decrease in draw weight for the 25 pound longbow, but increases of 14.76%, 16.13%, and 24.35% for the 50, 75 and 100 pound segment bows, respectively. The resulting draw-force curves are shown in figures 6.33-36.

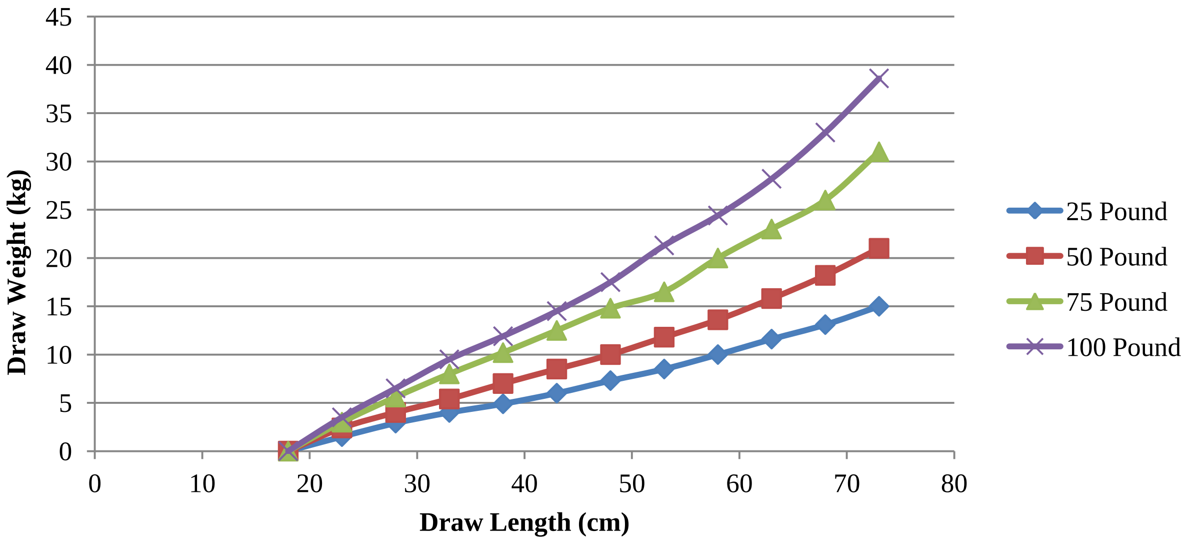


Figure 6.27 Force-Draw Curves - Segment Longbows

Figure 6.28 Force-Draw Curves - Double-Concave Bows

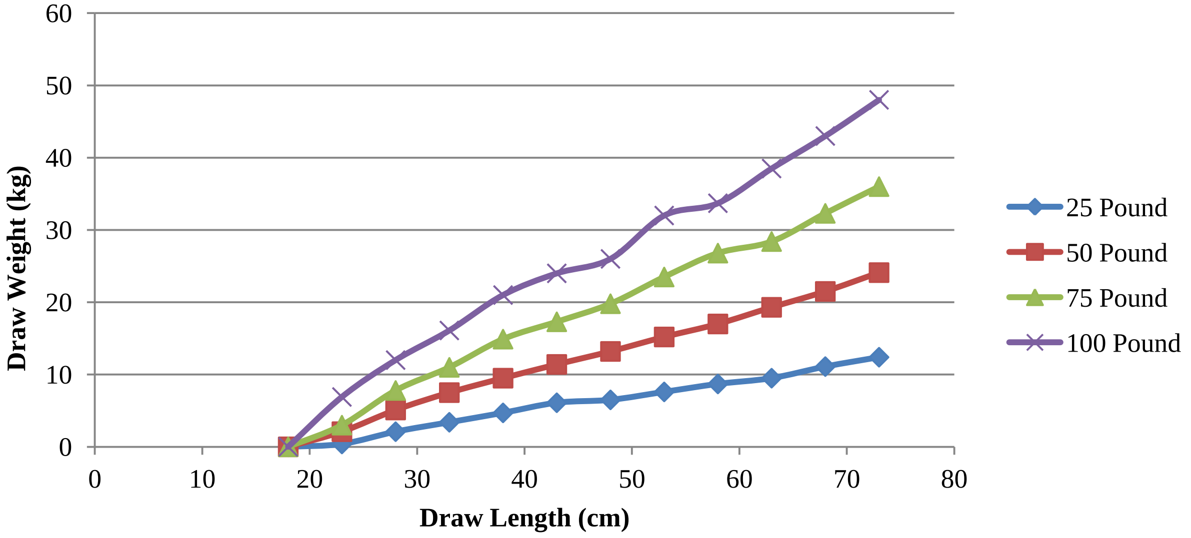


Figure 6.29 Draw-Force Curve Comparison - 25 Pound Segment and Double-Concave Bows

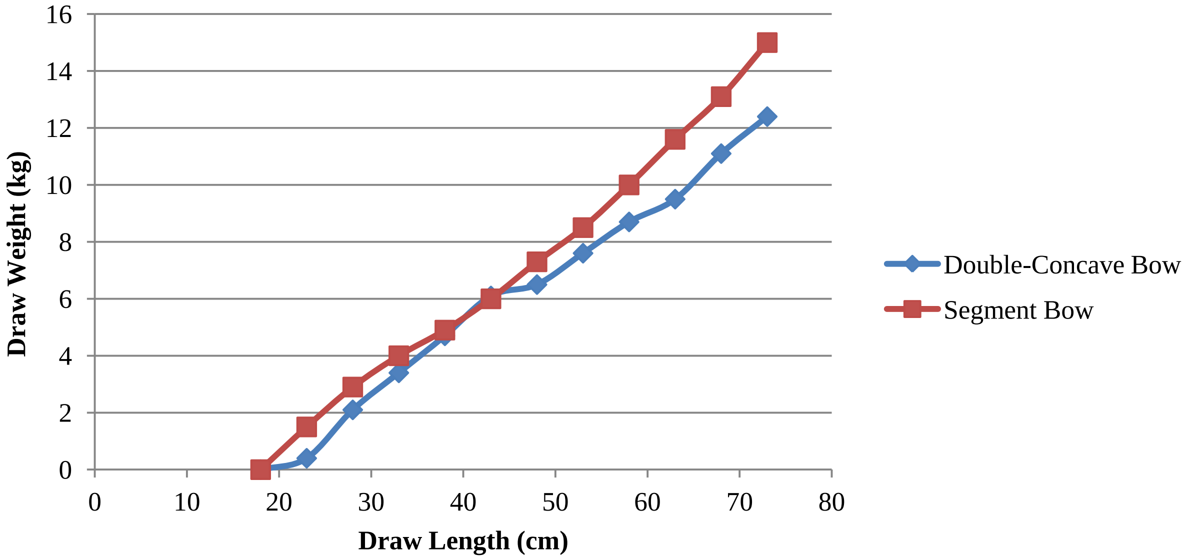


Figure 6.30 Draw-Force Curve Comparison - 50 Pound Segment and Double-Concave Bows

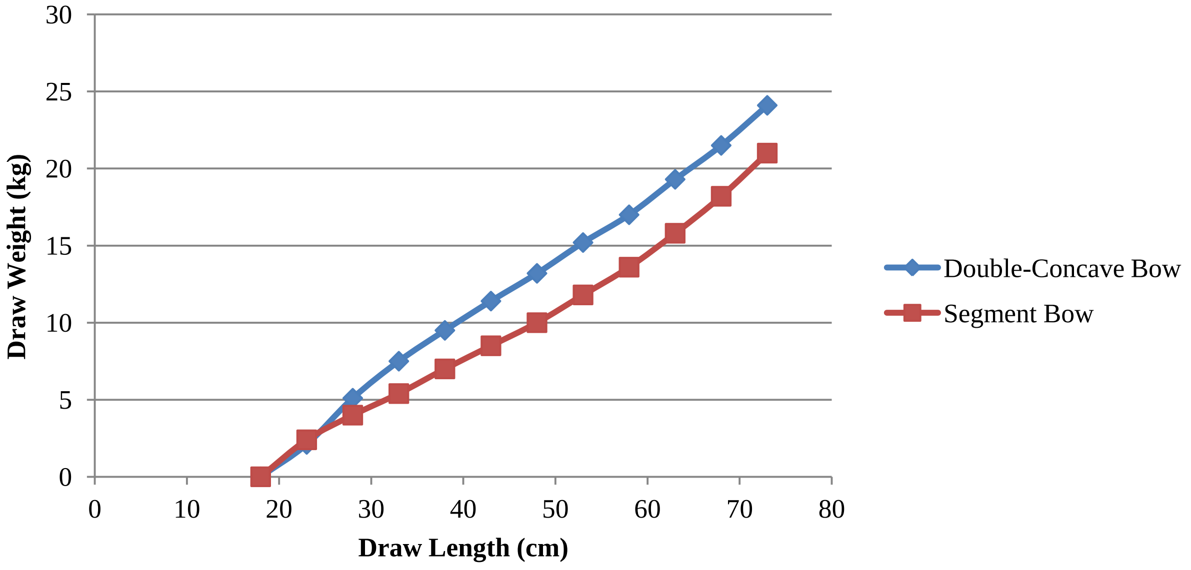


Figure 6.31 Draw-Force Curve Comparison - 75 Pound Segment and Double-Concave Bows

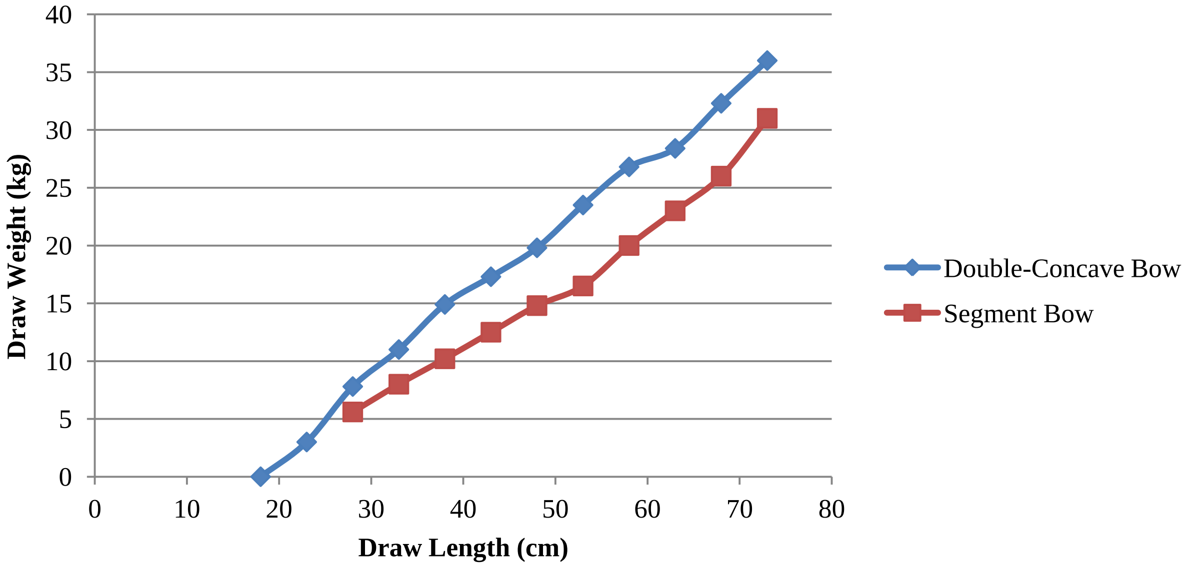


Figure 6.32 Draw-Force Curve Comparison - 100 Pound Segment and Double-Concave Bows

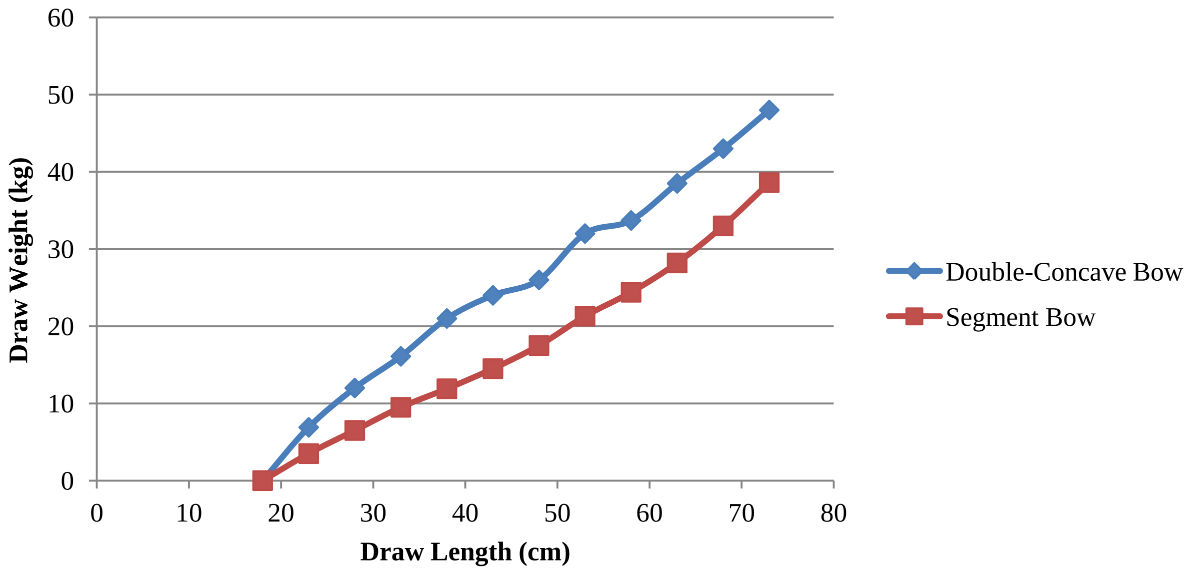
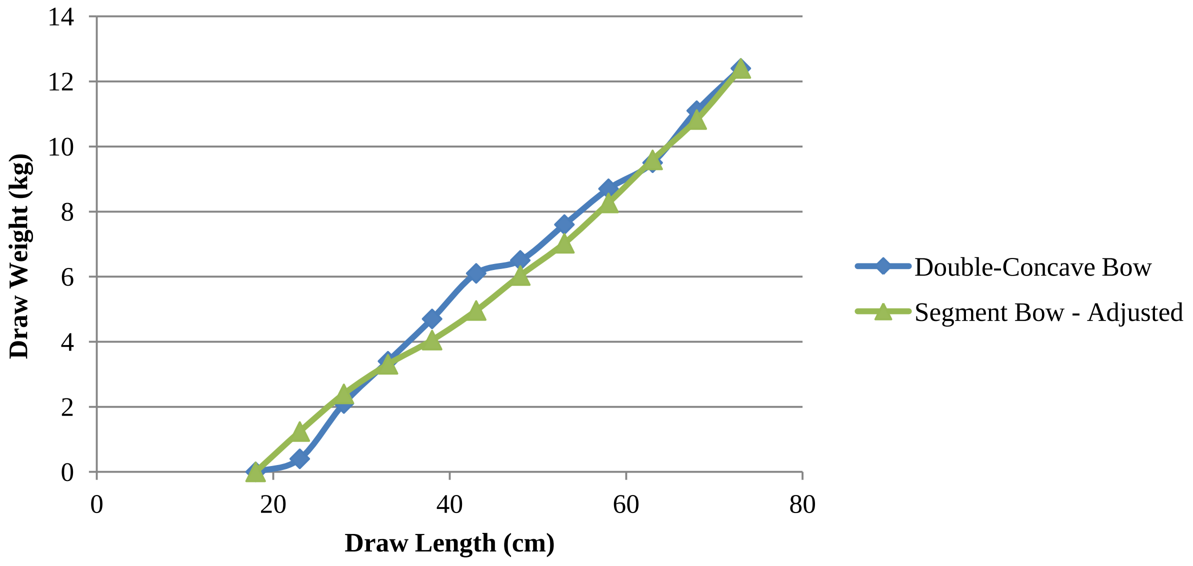


Figure 6.33 Adjusted Draw-Force Curve Comparison - 25 Pound Segment and Double-Concave Bows



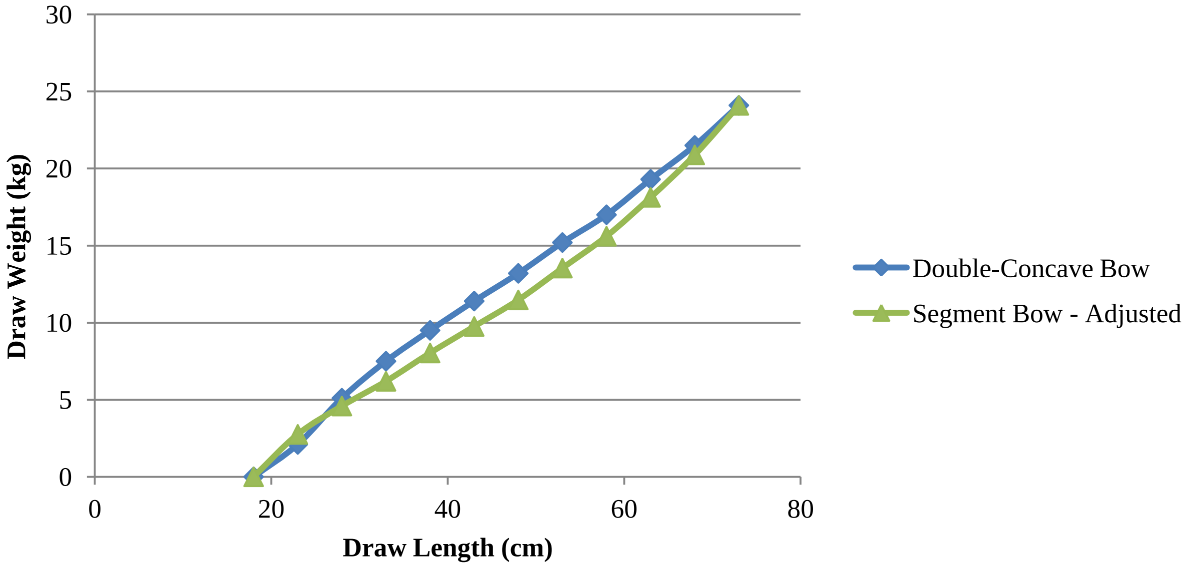


Figure 6.34 Adjusted Draw-Force Curve Comparison - 50 Pound Segment and Double-Concave Bows

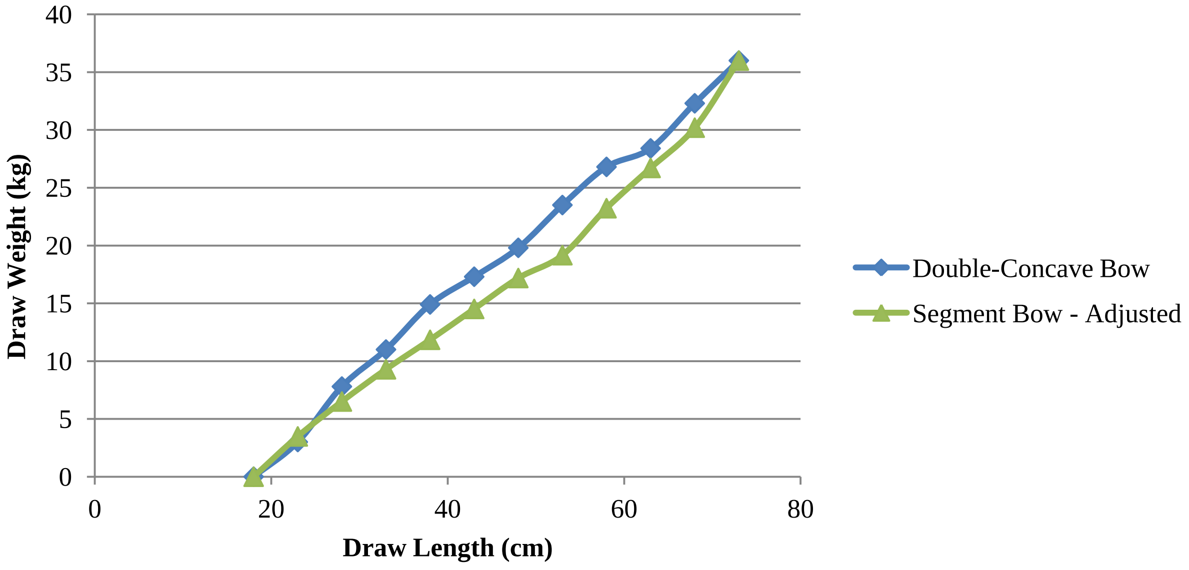


Figure 6.35 Adjusted Draw-Force Curve Comparison - 75 Pound Segment and Double-Concave Bows

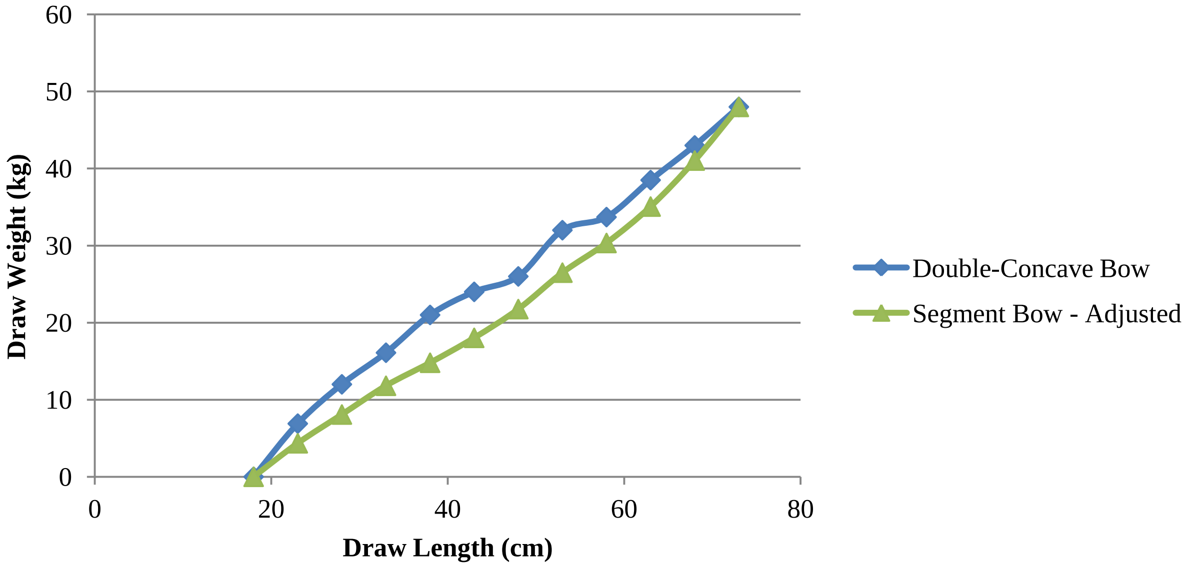


Figure 6.36 Adjusted Draw-Force Curve Comparison - 100 Pound Segment and Double-Concave Bows

The now-comparable draw-force curves can now be compared solely upon the basis of profile, as matching the final draw weight of the two bows sidesteps the issues of bow construction method, materials, and mass completely. As predicted by Hooke's law and the bow mechanics discussion covered in Chapter Four, the draw-force curves for the double-concave bows are indeed less concave than those of the segment longbows, with the difference representing an increase of stored energy.

In order to determine exact amount of difference in stored energy, the area beneath a given pair of curves must be compared. The exact measurement of the area beneath a curve across a specific range, or definite integral, requires the formula representing each curve to be evaluated. A close approximation is however possible by dividing a curve into equal segments along the x-axis. The area of the resulting individual columns can then be determined and added together, a process commonly known at the "Trapezoid Rule" (Ryan, 2003, p. 231).

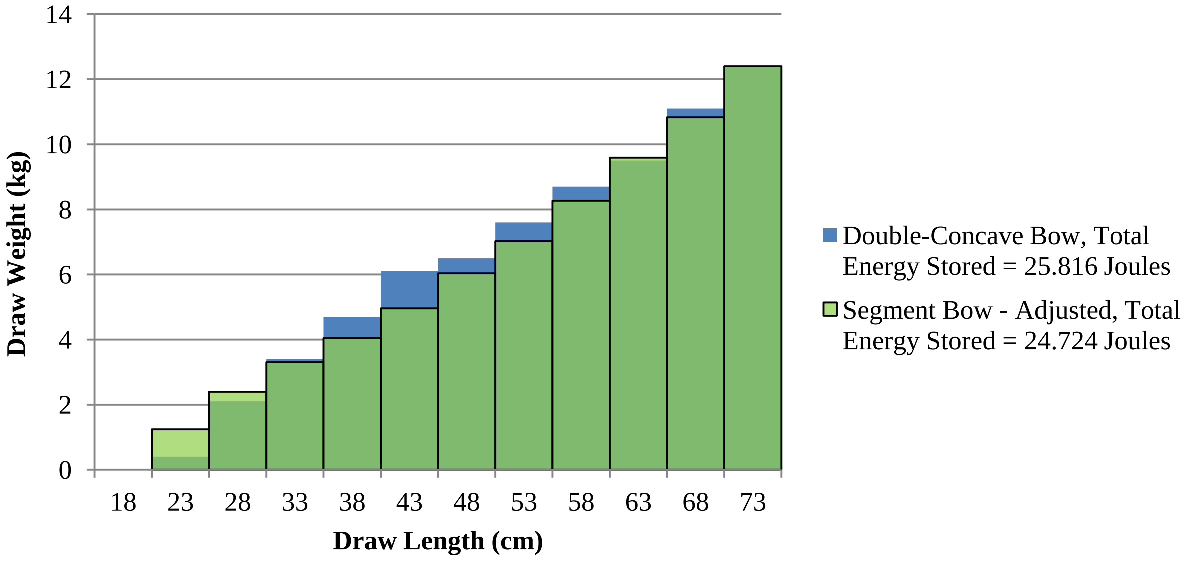


Figure 6.37 Draw-Force Curve Areas - 25 Pound Segment and Double-Concave Bows

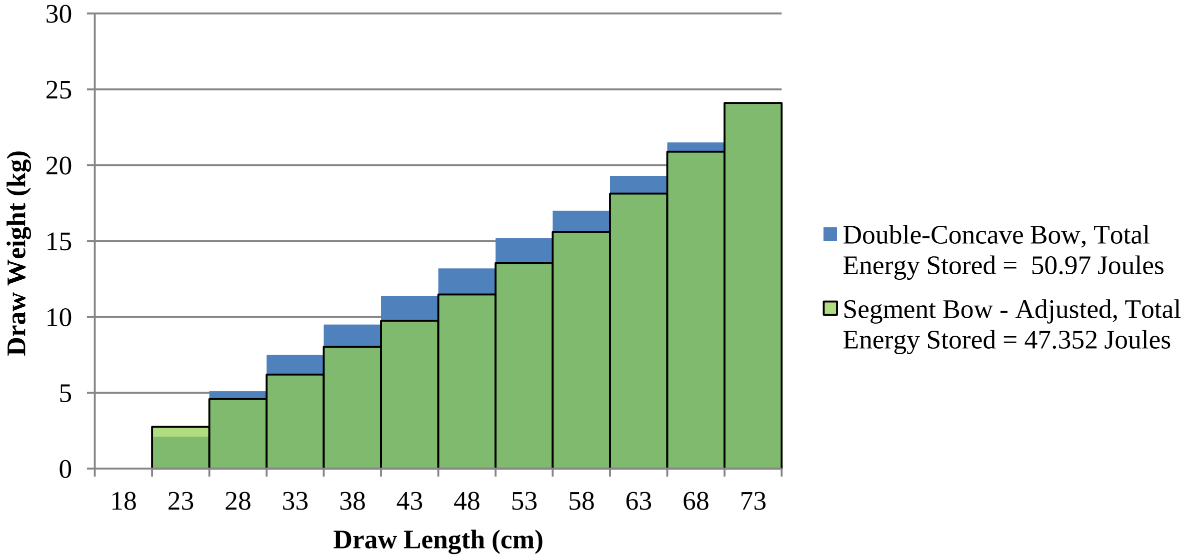


Figure 6.38 Draw-Force Curve Areas - 50 Pound Segment and Double-Concave Bows

Figure 6.39 Draw-Force Curve Areas - 75 Pound Segment and Double-Concave Bows

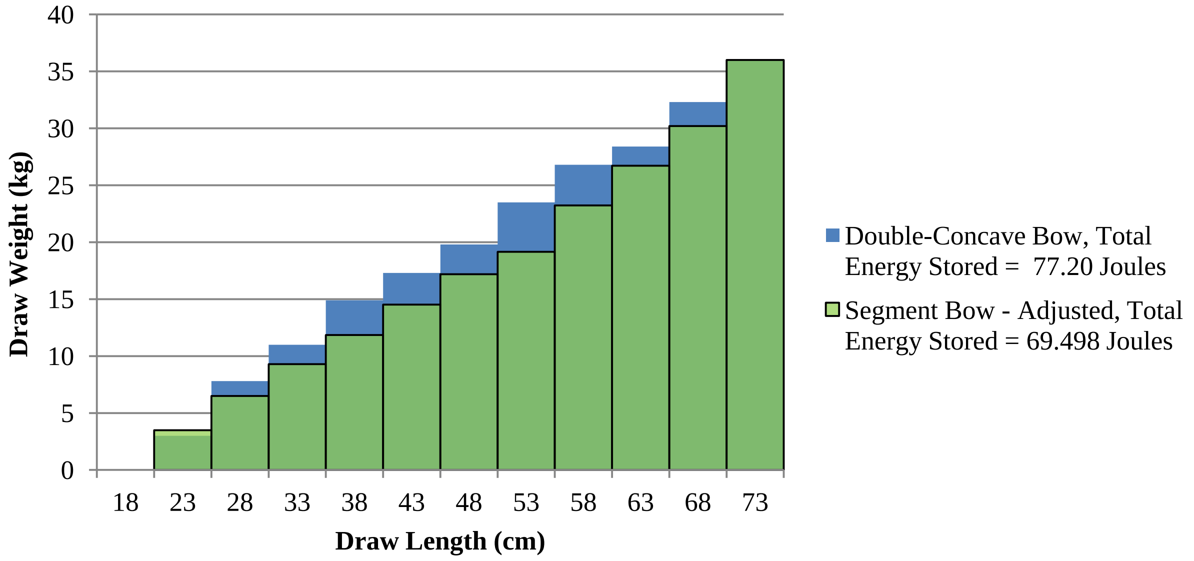
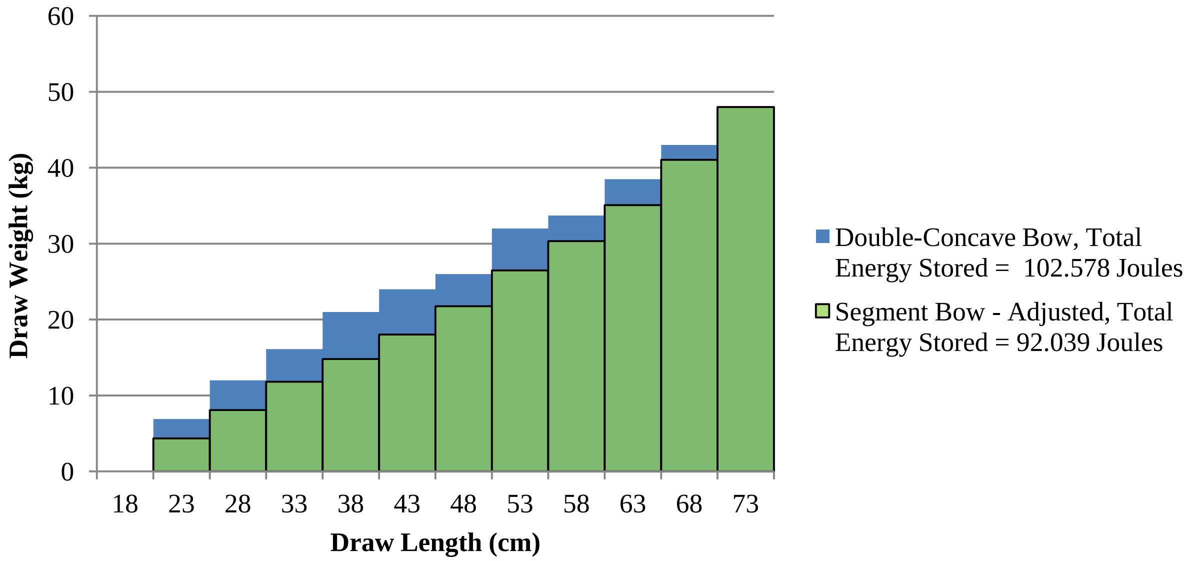


Figure 6.40 Draw-Force Curve Areas - 100 Pound Segment and Double-Concave Bows



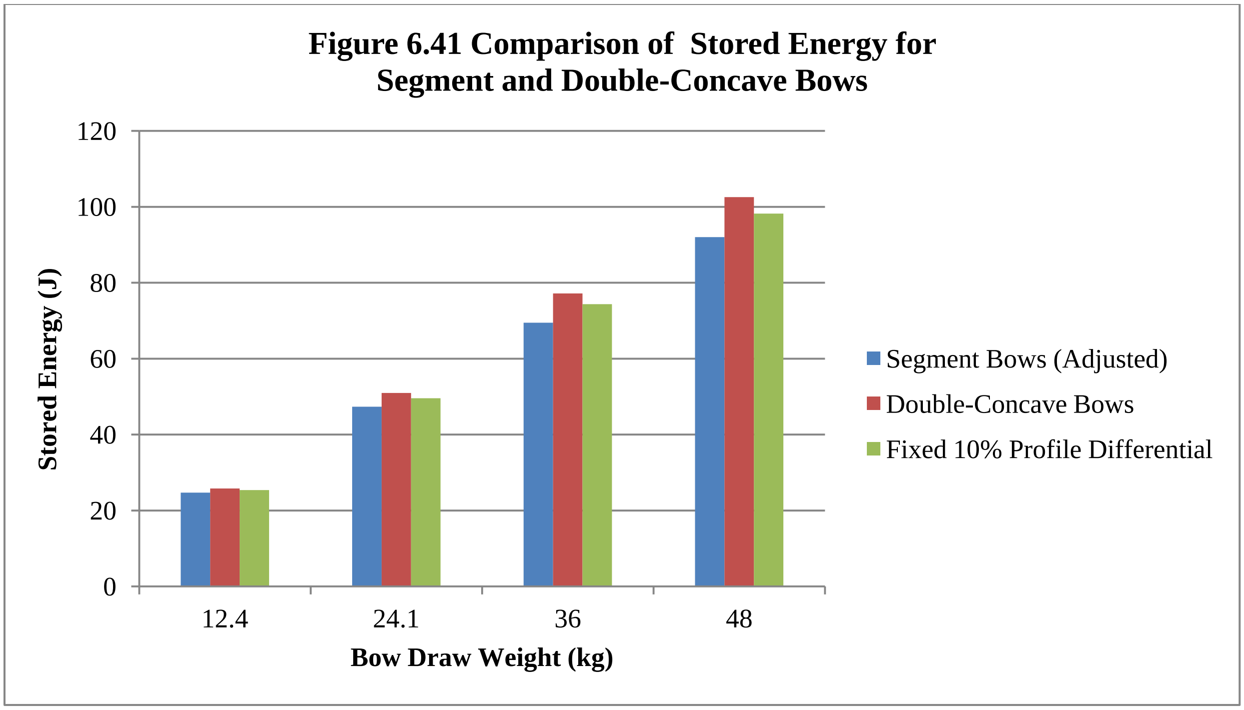


Figure 6.41 Comparison of Stored Energy for Segment and Double-Concave Bows

As draw weight was measured in 5cm increments, these data points naturally formed segments along which individual columns could be formed, the areas computed and then summed, thereby reaching a very close approximation of total energy stored for a given bow at a given draw length. Figure 6.37 depicts this representation of the trapezoid rule graphically for both 25 pound bows, with each column representing the amount of energy stored for that particular 5cm segment of draw length. Summing the total area of these columns for the 25 pound segment bow yields 24.724J (overlaid, in green) of stored energy at full draw, and 25.816J for the 25 pound double-concave bow (under-laid, in blue), an increase of 4.42%.

The 50, 75, and 100 pound bows show similar results as seen in figures 6.38-40. The 50 pound double-concave bow stored 50.97J, while the segment bow stored 47.352J, an increase of 7.64%. The 75 pound bows stored 77.2J for the double-concave bow and 69.498J for the segment bow, an increase of 11.1%. Finally, the 100 pound double-concave bow stored 102.578J, and the segment bow 92.039J, an increase of 11.4%.

PROFILE TESTING: CONCLUSION

Clearly, increased unbraced bow reflex results in energy storage even when final draw weight remains constant (Baker, 1992, p. 48; Wolfram Alpha, 2013b). Initial examination of how much extra energy is stored on a percentage basis shows that the final number is fairly small compared to expectations, topping out at slightly less than 12% (figure 6.41). This finding is however biased, as it fails to take into account the fact that the worked-in profile of the segment longbows was not identical, as outlined in tables A.21-22. Once these variations have been normalized and expressed as a fixed profile shift of 10%, it can be seen that the amount of extra stored energy, expressed on a percentage basis, is even less than first believed, reaching a high of 7% (figure 6.41 and table A.24).

Of key importance is that comparison of the amount of reflex (or deflex) reported as a unit of *length* is insufficient, as changes in the amount of additional energy stored for a given shift in profile is in turn dependent upon bow length as a variable. Simply put, the amount of extra energy stored from 10cm of reflex will be significantly greater in a shorter bow, as the underlying material is put under a comparatively greater amount of strain than that of a longer bow (Karpowicz, 2007, p. 677; Middleton, 2007, p. 44). To be valid then, a comparison of bow profile would also require bows of identical length. As bow artifacts are rarely made exactly the same length however, this would preclude the possibility of easy means of comparison. Bow length can however can be removed as a variable if degree of reflex or deflex is expressed as a *percentage* of bow length rather than as a unit of length unto itself. With the earlier determination that worked-in reflex is the most applicable, a direct comparison of reflex/deflex, expressed as a percentage of bow length for a fixed 10% differential can be seen in figure 6.41.

Finally, it should be noted that the performance difference did *not* remain constant, and instead varied between 2.78% for the pair of 12.4kg bows, up to 7.02% for the 36kg bows. While the degree of performance does tend to increase with draw weight, the fact that this amount decreases between the 36kg and the 48kg bows and that this trend does not continue upward throughout the tested range indicates that the variation instead is caused by variances in construction causing the individual draw-force curve for a given bow to stray from a typical linear progression (Science Buddies, 2015). Such being the case, the variance should be understood as variation around a mean. Taking the four figures and averaging them together then yields an increase of 5.305%, or almost exactly one half the amount of change in limb profile when expressed as a percentage. In condensed form then, differences in bow profile do affect energy storage, as described below.

- Differences in bow profile should be expressed as a percentage of bow length, with the amount of reflex or deflex initially measured as the length of the arc the nock point must travel to reach the neutral plane (passing longitudinally through the grip), and then divided by the total along the arc length of the bow.

- The difference in the amount of total stored energy (expressed as a percentage) when comparing two bows of equal draw length and equal draw weight is equal to *half* the amount of their profile differential. This same amount also represents the resulting range differential (ignoring the effects of drag).

While the difference is real, the additional energy stored is far from that needed to achieve the 200-300% difference in range commonly cited (Drews, 1993, p. 110; Hamblin, 2006, p. 95; Anglim et al., 2002, p. 10; Archer, 2010, p. 61). This being the case, testing must then progress to an evaluation of bow limb mass.

MASS TESTING

TEST DESIGN

While the negative effects of increasing limb mass on arrow velocity are well established, there is no published data on how this phenomenon may change with draw weight (Baker, 1992, p. 45; Kooi and Bergman, 1997, p. 129; Kooi, 1994, p. 21). Since bow limb mass acts as an impediment to the transfer of energy from bow to arrow, it cannot be accurately shown with a force draw curve. That being said, the effects of added mass can be shown by graphically plotting mass increases against arrow velocity. It also can be expressed as a percentage representing the efficiency of energy transfer from the bow to the arrow.

As the last remaining variable that could potentially contribute to comparative performance, it was hoped that differences in bow mass resulting from differing forms of bow construction could not only account for the remaining range differential, but also vary with draw weight. To address this issue, the two sets of bows used during limb mass testing were again pressed into service.

Physical testing to better understand the phenomenon of bow limb mass was fairly straightforward: weights in the form of strips of lead were attached to both limbs of a bow in increasing amounts (figures 6.43-44), and the resulting arrow velocity measured. The exact form this extra mass takes from both a physics and engineering standpoint makes no difference so long as it does not impede the return of the bow limb from full draw to brace upon release. As such, strips of lead in many ways were ideal, as they could be folded into a compact size thereby preventing any interference in bow function (limb stiffness). To ensure that mass placement remained consistent across all phases of testing, the sections of lead were attached at a point two thirds of the way up the bow limb between the nock and grip, a point which matched the mass distribution which would occur with an overall more massive bow limb. A total of six data points were chosen to represent a range of added masses: 0g added mass (representing the baseline, unaltered bow mass), 50g, 100g, 200g, 400g and 600g, providing a wide range of limb mass greater than would normally be seen in mass differences between ancient self and composite weapons.

As the accurate measurement of arrow velocity was of prime importance, consideration next turned to the question of a convenient means by which this could be accomplished. Historically this was done by comparing arrow range, but as this would have required the use of a stretch of open land several hundred meters in length, this was not considered a viable alternative. Additionally, the use of velocity instead of range has the benefit of not being subject to variations in angle of release or local wind conditions.

A radar gun used by law enforcement would have been the most convenient option, and is capable of measuring the velocity of objects significantly smaller than a car or motorcycle; such equipment is currently employed by major league baseball teams to record the speed of a pitch (Repanich, 2010; Roland, 2011). Unfortunately, the cross-section of an arrow is too small to pick up with a radar gun, making it unsuitable for the task at hand. While either a high-speed video camera or an arrow chronograph would have served, high-speed video would have also required both a laptop computer with a large amount of hard drive space to record the results, and a variegated background to shoot against (Citizens in Space, 2012). As such, an arrow chronograph was chosen as the most expedient option. Consisting of a light interrupt system, a projectile is fired over the unit such that it passes above a pair of light sensors. When the first sensor detects a drop in visible light it starts an electronic timer which is then stopped when the projectile passes over the second sensor. The velocity is then computed based upon the time it took for an arrow to travel between the two sensors, and the results displayed on screen at the front of the machine.

Figure 6.42 Lead Strips 5g, 10g, 20g, 30g and 40g in mass.

Figure 6.43 Bow with broken string and added mass. Note the folded strip of lead taped to both front and back.

The site selected for testing consisted of a cul de sac, with the back side of a tall building on one side and a rock slope on the other, ensuring that no random foot traffic would occur in front of the firing line. After passing over the chronograph the arrows would clear the end of the chronograph before impacting a safety backdrop. Additionally, the firing line was set some five meters away from the chronograph itself, allowing sufficient time for arrows to finish accelerating after leaving the bow (Denny, 2011, pp. 17-18; Competition Electronics, 2011). Netting was chosen for the backdrop material as it provided a combination of durability and flexibility, as it would not suffer from degradation as the arrows impacted or became entangled in the successive layers. Netting also minimized potential problems with wind speed, as it was much less subject to the effects wind compared to a solid sheet of material. All of the arrow speed tests used throughout this investigation used identical arrows weighing 26g each.

Throughout all phases of physical testing strings of identical mass of 17g were used. In cases where string mass varied, mass was normalized by adding additional levels of serving until a mass of 17g was reached, a process that further allowed for identically thick nock points, thereby rendering both string mass and nock friction constant.

TESTING

With bows, arrow chronograph, and site ready and arrow mass, string mass, and nock friction standardized, testing could now proceed. Immediately there were a number of issues both major and minor with the arrow chronograph. Upon occasion it would display obviously false readings that were grossly out of line compared to the other velocities recorded for a given data set. Thankfully, these erroneous readings were blatantly obvious, typically registering as either 20 feet per second (6.1m/s), the minimum speed the chronograph could measure, or absurdly high readings, occasionally reaching over one thousand feet per second (304.8m/s). Finally, while the frontal display screen was eminently convenient, it also proved to be vulnerable to the depredations of poor aim. As a result of variances in aim and false readings, approximately twice the number of shots was made compared to the number of shots recorded. As an extra precaution, each data set of ten recorded velocities consisted of fifteen recorded data points. The fifty percent increase in set size allowed not only blatant errors, but also less severe but obvious variations in draw length and release to be identified and discounted as outliers.

Testing itself was straightforward except as outlined above with several notable exceptions; the 75 and 100 pound draw weight bows were too powerful to be drawn by the author by hand and as such were shot whilst strapped to the author's feet. While the resulting shots were surprisingly accurate, the process required some additional setup. First, as both feet were strapped to the bow firing had to be done from a seated position. This in turn required that the arrow chronograph be placed on the ground. The author's legs were kept at a set elevation by resting them atop a support, thereby improving accuracy. Shooting with one's feet also precluded the use of the author's preferred method of draw and release, which utilizes a thumb ring.

Figure 6.44 Close-up of double-concave recurve bow. Note the attached foot straps on either side of the grip.

Figure 6.45 Author firing a longbow using feet. Note the use of plastic crate as a footrest and release aid on left wrist (author is left-handed).

Figure 6.46 Quick release aid.

Figure 6.47 Release loop attached to bowstring.

As the draw weights were quite high, a quick release aid was used instead, thereby preventing a number of possible hand injuries and preventing premature firing. Worn on the wrist, a release aid both relieves pressure on the fingers and allows for a clean, fast release of the arrow. Such aids can also however damage the string of a bow, and as such necessitated the addition of a release loop. This loop provided a separate point for the release aid to fasten, and ensured a consistent nock point on the string as the arrow is placed on the string between the attachment points of the loop. The additional mass of the nock loop was taken into account prior to the start of testing when adjustments to nock serving were made, thereby keeping string mass uniform at 17g. Finally, an unexpected consequence of firing from a seated position with a bow strapped to one's feet was that it was impossible to accurately judge draw length. With consistency of draw length of prime importance, the arrows were marked at the proper draw length and the aid of an assistant was employed to tell when this mark reached the outside edge of the bow. The assistant also aided in arrow recovery.

TEST RESULTS

It was immediately clear that the data sets had some degree of variation. As mentioned during the discussion of the relative merits and problems associated with using an arrow chronograph, some of this variation was machine error while the remainder was due to discrepancies in the draw and release of the bows themselves, more properly described as user-variation. Data sets for a particular bow and added mass ranged from extraordinarily tight to exceptionally wide, these latter sets were however tightened to the point of statistical validity once obvious recording errors and outliers were omitted. As expected, the data clearly indicated that increasing limb mass did indeed result in the expected decrease in arrow velocity as seen in figures 6.48-49 (Baker, 1992, p. 45; Kooi and Bergman, 1997, p. 129; Hardy, 2005, p. 411). Also as expected, the degree of impact on increasing limb mass was less than would be expected compared to an equal amount of increase in arrow mass.

With the physics confirmed, attention must then turn to an examination of energy transfer efficiency. The computation of arrow velocity with 100% efficiency can be expressed by the equation $v = \sqrt{2 * \frac{KE}{m}}$, with v equal to arrow velocity (in meters per second), KE equal to the total amount of stored energy (in joules), and m equal to the mass of the arrow (in kilograms). These ideal results can then be compared to the amount of energy actually transferred to the arrow to achieve the observed velocities to determine the energy transfer efficiency of a particular bow.[34] The results (shown in table A.36) clearly show that, as expected, the actual amount of energy transferred to the arrow was less than the amount of energy stored in the bow. Results also clearly show that while the double-concave bows of fiberglass construction maintained a high level of energy transfer efficiency at approximately 75%, the segment bows of self construction showed a rapid decrease in transfer efficiency as draw weight increased.

The difference between amounts of stored and transferred energy however merely proves that inefficiencies exist. This is not surprising, as a number of potential inefficiencies were outlined as a part of the theoretical framework previously discussed in Chapter Four. It cannot however prove to what extent this decrease in efficiency is specifically due to limb mass. The mathematical isolation of how much energy it takes to return a given bow's limbs from full draw to brace is certainly possible, but requires knowledge of several variables, including the exact mass of each bow limb, the amount of distance each limb must travel when released, and the time it takes for the limbs to return from full draw to brace.

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[34] Energy transfer efficiency also shifts with arrow mass. Testing however held arrow mass constant at 26g, thereby negating this as a source of variation.

Figure 6.48 Added Mass/Velocity Curves: Longbow Comparison

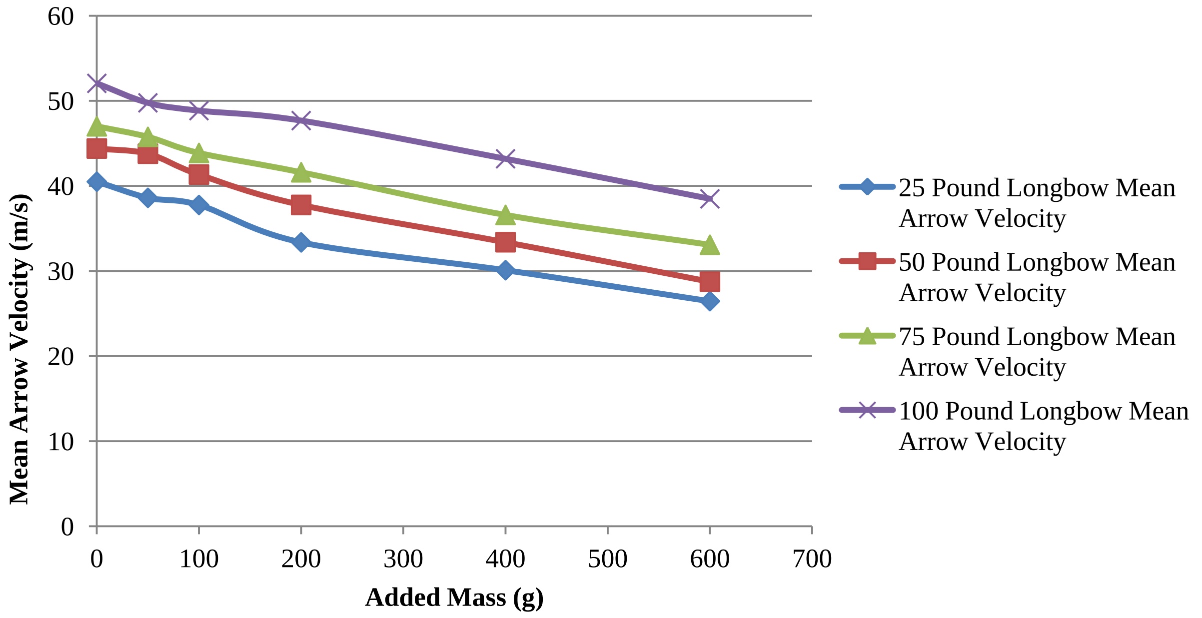
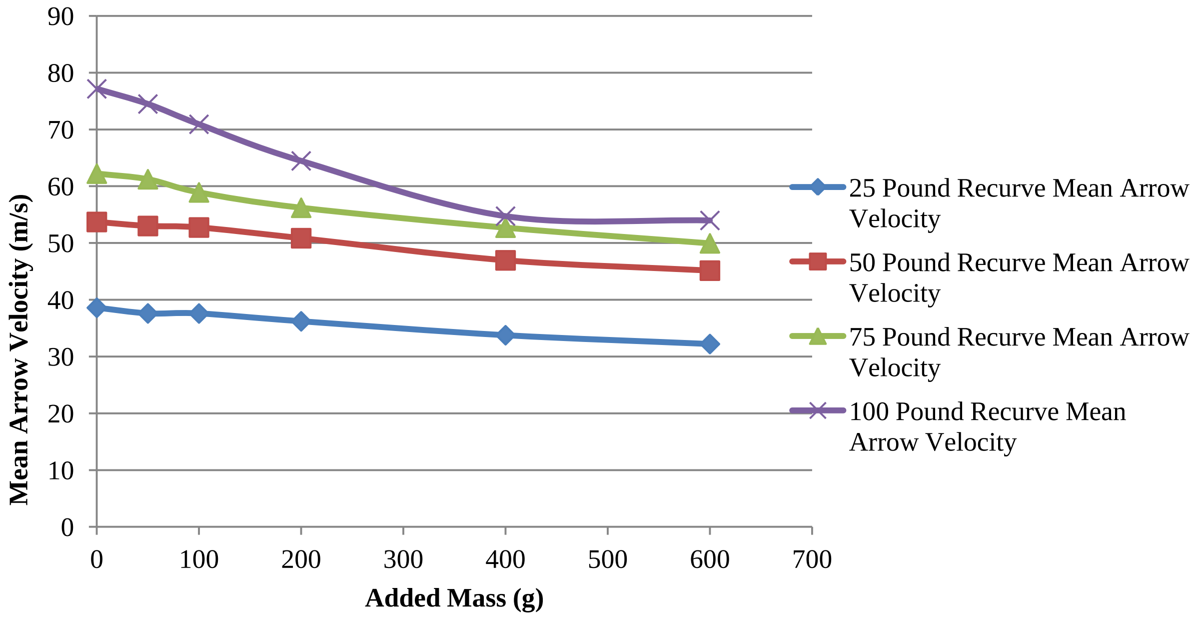


Figure 6.49 Added Mass/Velocity Curves: Recurve Comparison



As this process attempts to determine energy expenditure, it is essentially the same process as determining energy storage, or the area under a force-draw curve, in this case depicting the amount of energy expended by the bow limbs as they returned from draw to brace. As such, we are faced with the same problem as previously dealt with in the section on bow profile – only now an accurate representation of this energy expenditure represents the sum of the mass and distance traveled for each and every point along the bow limbs (rather than every point along draw length). A close approximation of this definite integral can however be computed using the same system as that used for the draw-force curve, namely the division of each bow limb into separate sections, computing the amount of energy required to move each section, and totaling the results.

Unlike the draw-force curve however, the individual components of mass can only be approximated. Total mass for each bow was easily measured. An estimation of the mass of each section of each bow limb however required a certain amount of creativity. The exact mass of each section of bow can be determined by a variety of methods, the most direct of which would involve cutting the bows physically. As this would result in the destruction of the bows, a less extreme method was used whereby each bow was sectioned and marked with ink such that each limb was divided into 10 parts (not including the grip). Each bow was then progressively lowered section by section into a dip tank and the amount of displaced water recorded to determine the volume of each section. The volume of each section was then multiplied by the material density to arrive at a mass estimate for each section. As the segment bows were made entirely out of hickory, with a density of 870kg/m^3, this was a relatively simple matter. The double concave bows however were somewhat more difficult as the bow limbs consisted of alder wood ears with a density of 400kg/m^{3}attached to a fiberglass/epoxy bar stock with a density of 1910kg/m^3.

The distance each limb section must travel was also needed, and was determined by mounting each bow to a tillering stick and laying it onto a large sheet of paper so that its outline could be traced. Each bow was then brought to partial draw and then full draw such that the different outlines overlapped each other at the stationary grip, thereby allowing easy measurement of limb travel for each section as shown in figure 6.50.

The time required for the bow limbs to return to brace remains constant for each section, but exact measurement was again problematic. Using observed arrow velocity would result in a dramatic overestimation of the amount of energy required, as measurements were taken *after* the arrow had already finished accelerating. As the bow limbs start with a velocity of zero, previously observed arrow velocities would then underestimate the time required for limb travel.

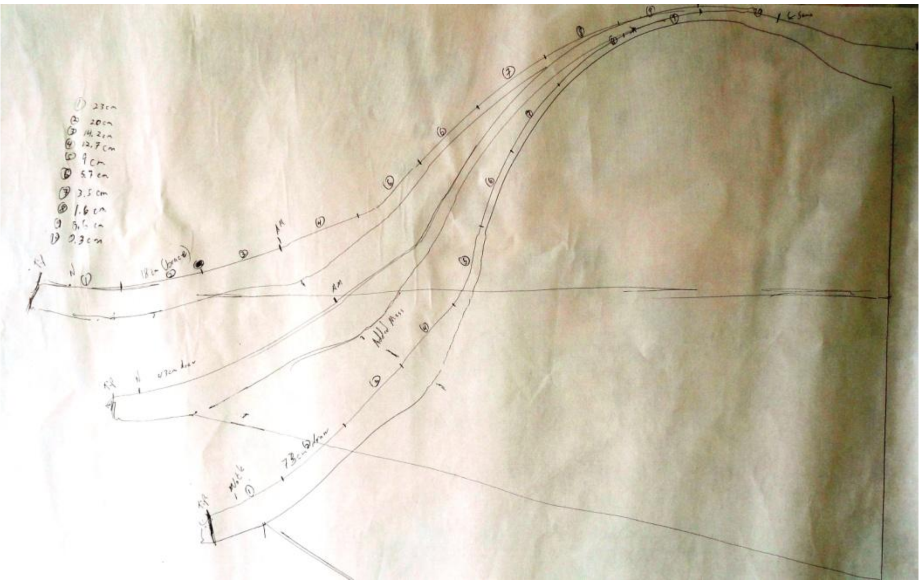


Figure 6.50 Overlaid profiles of single double-concave bow limb at brace (top), half draw (middle) and full draw (bottom).

To solve this problem, new velocity measurements were taken, this time with the arrow chronometer positioned directly in front of the bow such that the arrow would trip the second light relay just as the bow returned to brace. If the distance between the light relays on the bow chronograph were exactly 55cm apart (the string travel distance from full draw to brace), the resulting velocity would be quite accurate. Unfortunately, the distance between the chronograph was less than 55cm, meaning that the resulting velocity measurement would again result in an overestimation in required energy (underestimation of time), but still be a much closer result than if the arrow had finished acceleration. It also represents the most accurate measurement possible with the available equipment. High speed video would have been advantageous at this point, but an extensive search revealed that none was available for hire within South Korea. Velocity testing was redone, and then working backwards from velocity the amount of time was then computed for the arrow to move the 55cm representing the travel between full draw (73cm) and brace (18cm). Results of this revised testing designed to measure limb return velocity can be seen in tables A.37 and A.38.

With mass, travel (distance), and time for each segment available the total amount of work (energy) needed to move a given bow limb segment can be computed as $J = kg*m^2/s^2$ (Middleton, 2007, 2; Physics Classroom, 2013). The energy results for the segments are then added together, representing an estimate of energy needed for limb return, which is then multiplied by two to reach the total amount of energy needed for a bow to return *both* bow limbs from draw to brace. The results for each of the bows are shown in tables A.39-A.46.

As expected, higher draw weight bows required increasing amounts of energy to return their more massive limbs to brace in shorter amounts of time (thereby resulting in higher arrow velocity). The amount of energy computed for limb return can now be subtracted from the total energy stored for a given bow, and compared to the amount of energy actually transferred to the arrow. Given the fact that the computation method for limb return underestimates the time required for limb return the resulting figure for energy required for limb return is overestimated by a small amount.

The results show that limb return represents the vast majority of energy loss, as the resulting predicted velocity measurements were consistently *lower* than observed mean arrow velocities, as seen in figures 6.51-8. Use of high-speed video would likely have yielded more accurate results, but the base premise – that bow limb mass (and mass placement) is the primary cause of energy transfer inefficiency – has indeed been proven.

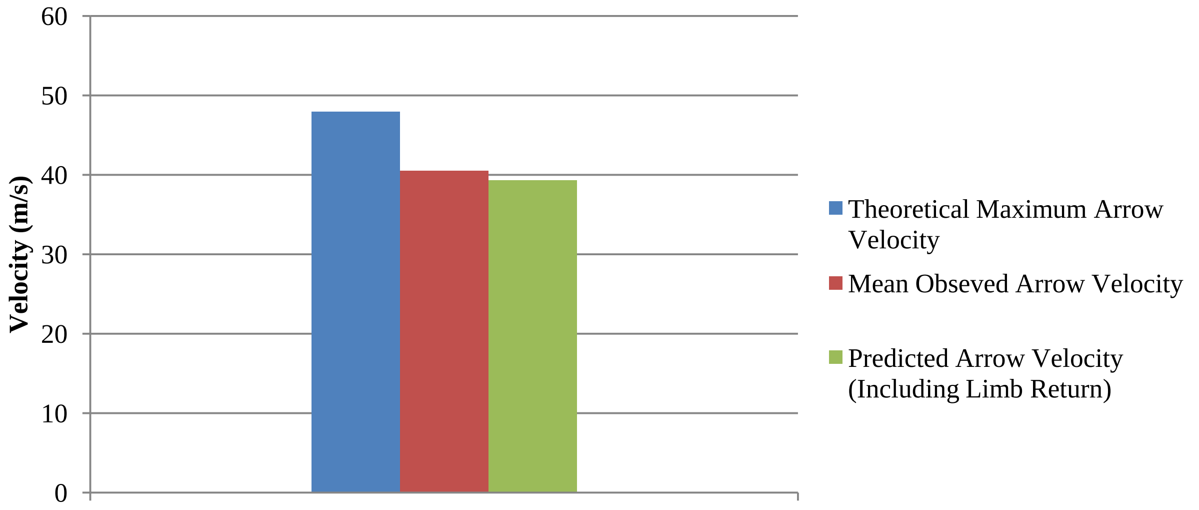


Figure 6.51 Ideal, Observed, and Predicted ArrowVelocities - 25# Segment Bow

Figure 6.52 Theorectical, Observed, and Predicted ArrowVelocities - 50# Segment Bow

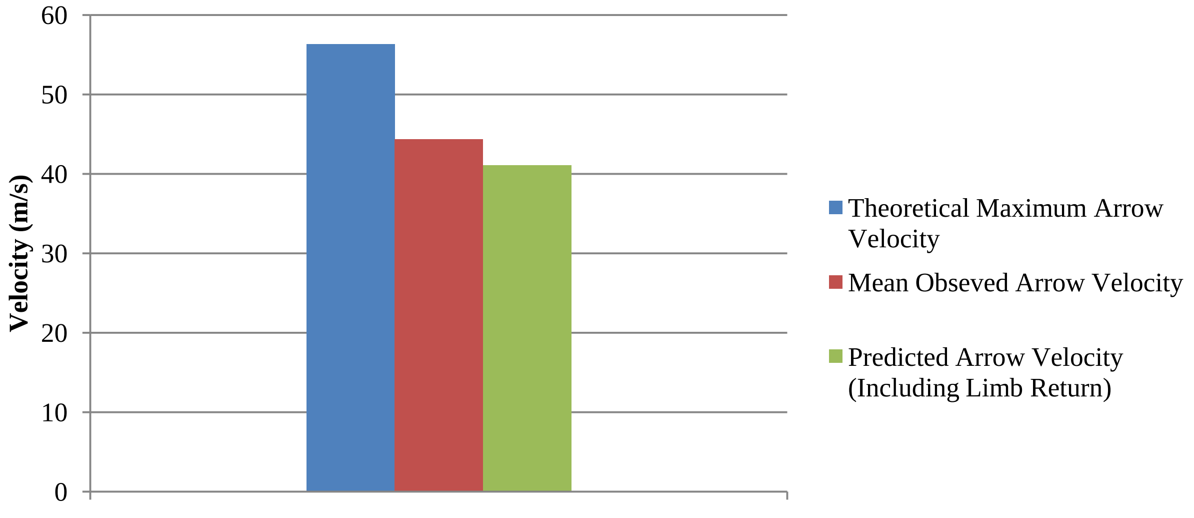
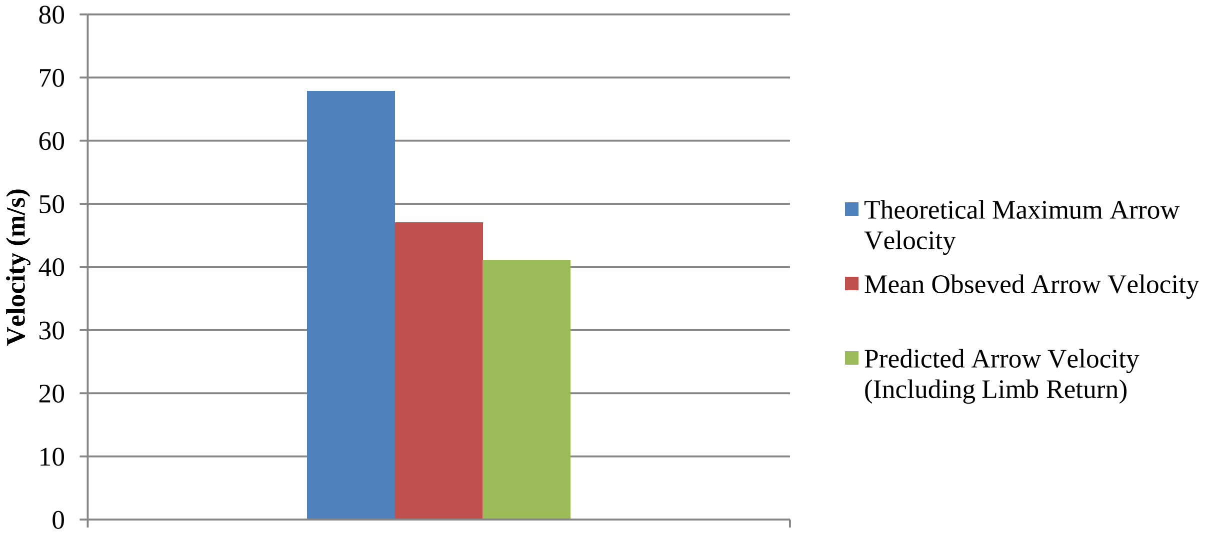


Figure 6.53 Theorectical, Observed, and Predicted ArrowVelocities - 75# Segment Bow



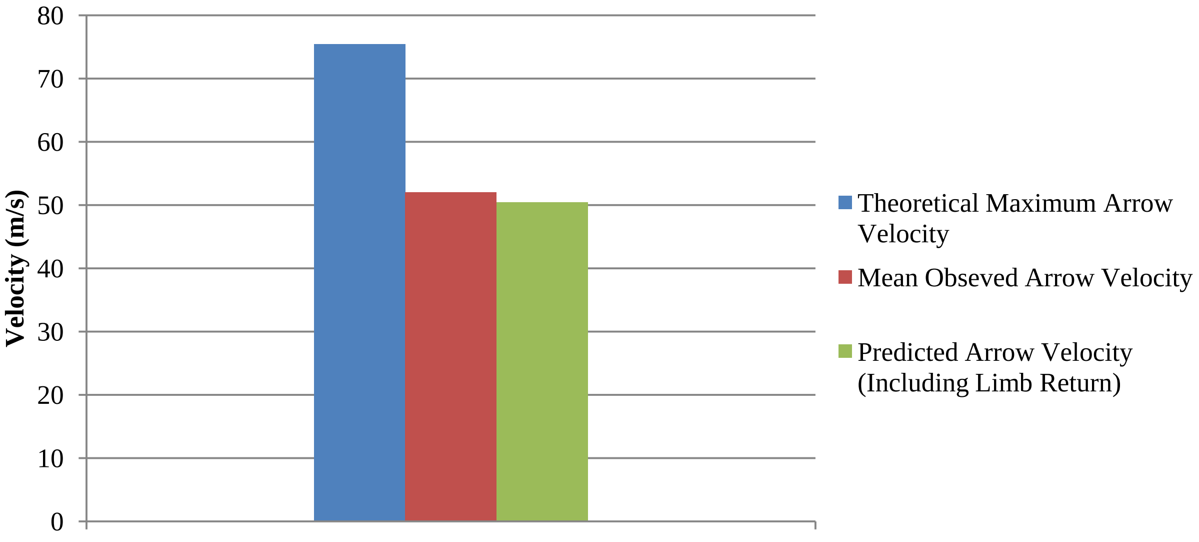


Figure 6.54 Theorectical, Observed, and Predicted ArrowVelocities - 100# Segment Bow

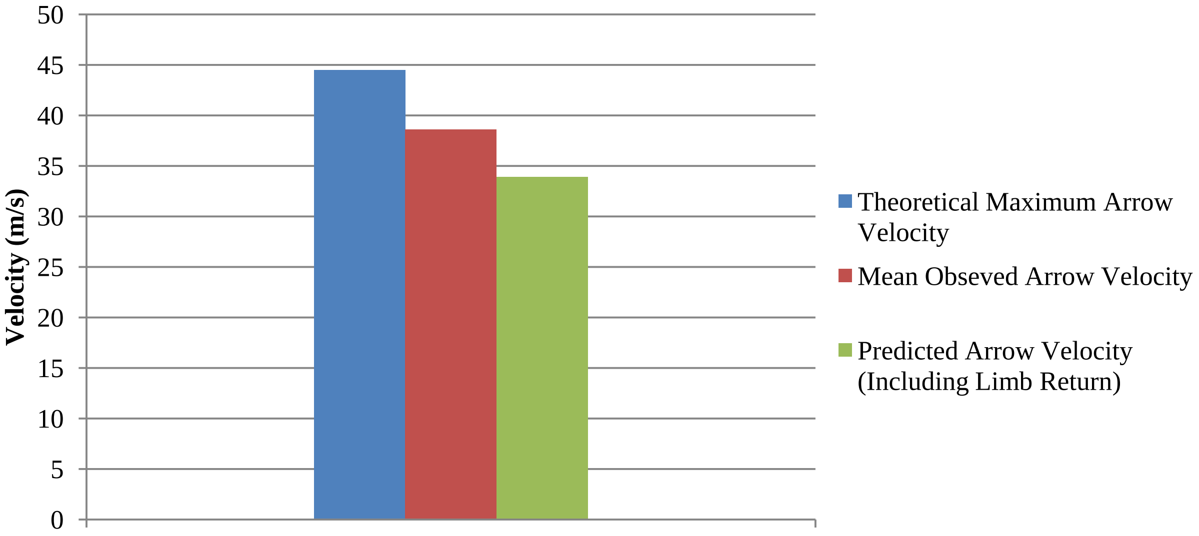


Figure 6.55 Theorectical, Observed, and Predicted ArrowVelocities - 25# Double-Concave Bow

Figure 6.56 Theorectical, Observed, and Predicted ArrowVelocities - 50# Double-Concave Bow

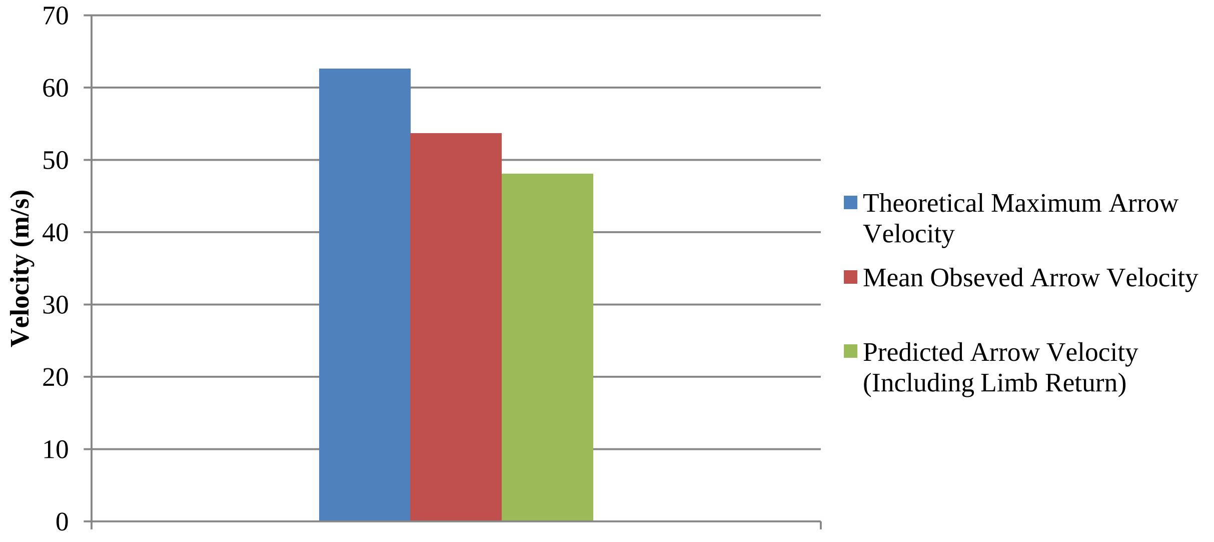
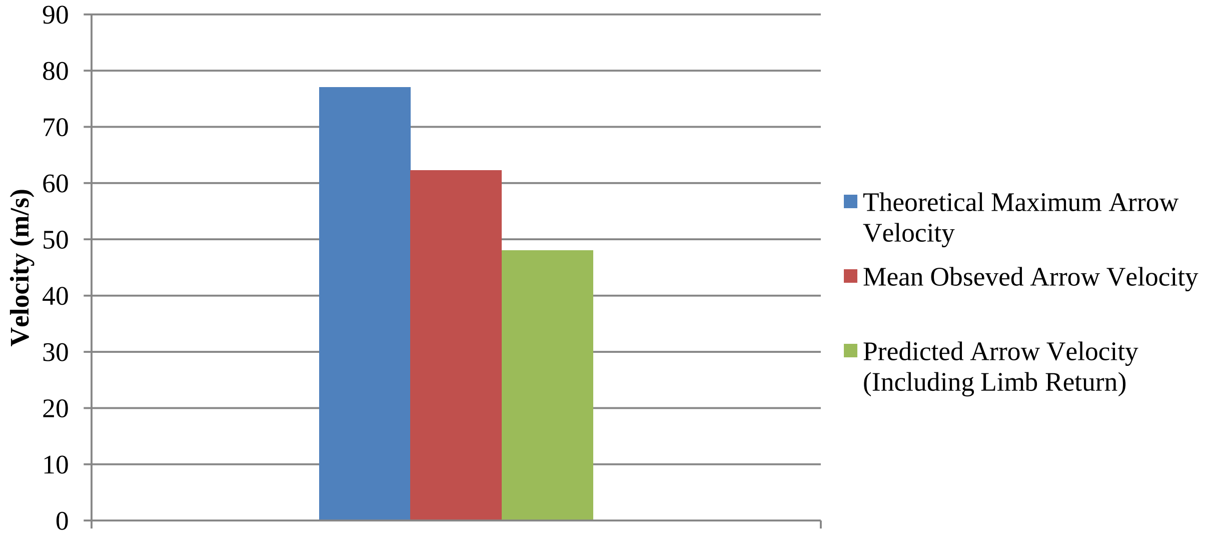
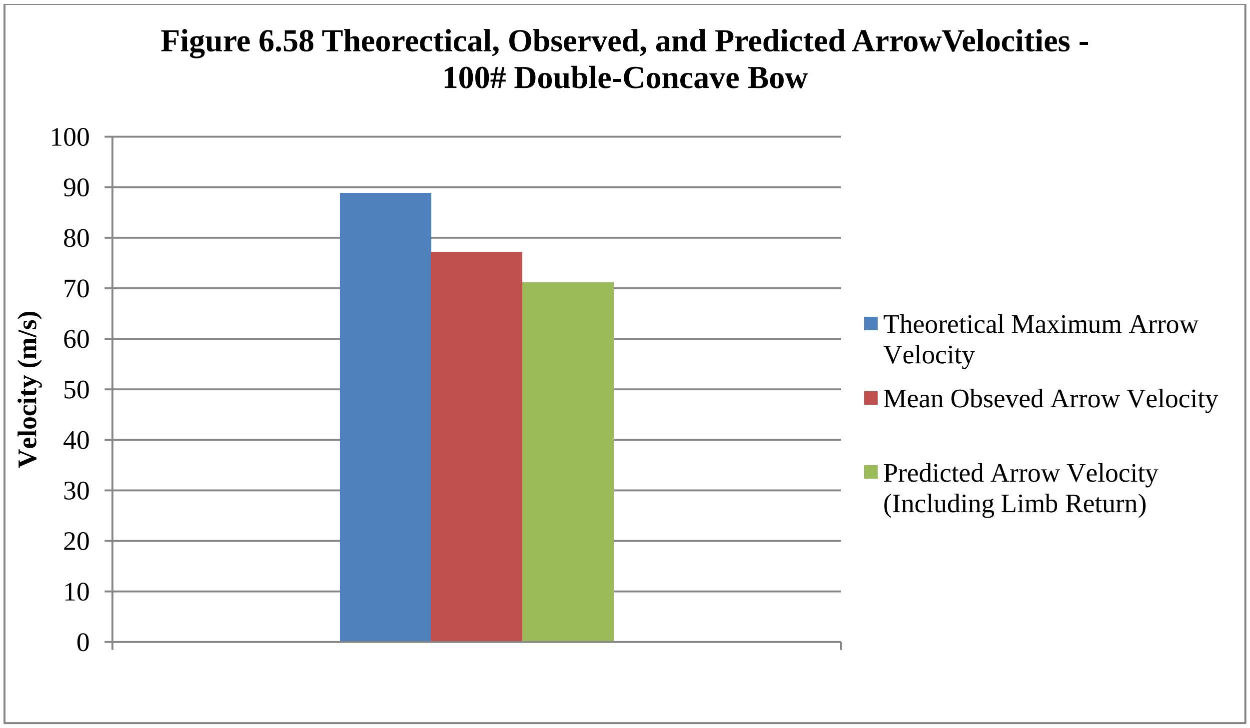


Figure 6.57 Theorectical, Observed, and Predicted ArrowVelocities - 75# Double-Concave Bow





MASS TESTING: CONCLUSION

Limb mass indeed has a negative effect on arrow velocity and indeed is the primary source of energy transfer inefficiency. Additionally, it is clear that the energy required for bow limbs returning to brace upon release increases with draw weight. This is to be expected, as increased draw weight results in increased arrow velocity; in order for this to happen, the bow limbs must return from draw to rest in a shorter amount of time (they are traveling faster), hence requiring more energy (Verma and Keller, 1984, p. 569).

More importantly however, is that limb mass by itself is not nearly as important as limb length and mass placement along a limb. The segment bows as a group all have a limb mass smaller than that of their double-concave counterparts (tables A.39-46). Despite this, the segment bows are less efficient (Table A.36), meaning that they use a greater amount of energy to return their limbs to brace. The difference in efficiency is small at the 11kg draw weight, but becomes increasingly large as draw weight increases. The reason for this is that the segment bows must be of increasing length to accommodate the higher levels of limb stress, mandating that the product of mass and distance a segment bow's limbs must travel is larger than that for the shorter double-concave bows. In particular, this energy expenditure increase is proportionate with changes in limb mass, but proportionately to the *square* of changes in limb travel distance. In short, size matters - in this case with shorter limbs being more efficient at energy transfer at a given draw weight.

The final question then is how representative these energy efficiency results are of bows from the ancient world. The segment longbows design and materials choice (wood), make them excellent proxies for bows with limbs that are either round or D-shaped in cross section – a conclusion confirmed by the fact that the material and physical dimensions for the 15kg and 21kg draw weight bows are nearly identical to those of self bow artifacts from the tomb of Tutankhamen (McLeod, 1981, pp. 39-40). Similarly, the two higher draw weight bows, with draw weights of 31kg and 38.6kg) have a mass comparable to the lower draw weight bows recovered from the wreck of the Mary Rose (Hardy et al., 2011, p. 626). As a general trend then, while bows of self construction generally start with energy transfer efficiencies of 71% their energy transfer efficiency declines as draw weight increases falling to less than 50% at a draw weight of 31kg (table A.36).

One would expect to see slightly higher energy transfer efficiency (and arrow velocity) for bows with limbs having a flat cross-section, rather than the stereotypical "D" shape associated with the English longbow in bows of self construction (Kooi, 1994, p. 17; Soar, 2005, p. x). While an evaluation of flatbows lies beyond the scope of this thesis, a very rough proxy can be found in world record arrow distances. Although the records do not include sufficient information to ensure a fully accurate comparison, record distances for the flatbow design indeed do fall between the traditional English longbow design with a "D" shaped cross section and those of a double-concave design for *all* weight classes, strongly suggesting that it is indicative of a design more efficient that a "D" shaped cross section segment bow, but less efficient than comparable bow with short, double-concave profile and as a design fits within modeling presented herein (World Archery Federation, 2012, Kooi and Bergman, 1997, p. 132).

Finally, the double-concave bows tested herein were able to maintain a 75% level of efficiency across the entire range of draw weights tested, but as the bows are made of fiberglass rather than of horn, wood, and sinew, the applicability of the results can rightfully be called into question. While the author was unable to test composite bows of traditional manufacture, a complete listing of mass, draw weight and physical dimension information from a number of composite bows from the Topkapi Palace Museum in Instambul are available (Karpowicz, 2008, p. 41). Bows from the palace collection ranged from 18kg in draw weight up through 109kg. Bow mass on the other hand ranged from 220g (at a draw weight of 18kg) up to 625g (for an unusually massive example with a draw weight of 59kg). On average however, draw weight and mass were 57kg (draw weight) and 389g (bow mass). Put in perspective, the average bow mass from Topkapi palace (389g) has a mass slightly less than the *lightest* segment bow tested herein (398g), despite representing a draw weight more than *three times as heavy* (59kg as opposed to 18kg).

Even without velocity information, the draw weight and mass information makes it clear that bows of composite manufacture utilizing horn wood and sinew are able to maintain a lower mass and overall length (averaging 108cm from nock to nock for the Topkapi artifacts), which would in turn result in higher energy transfer efficiency compared to bows of self manufacture, and indeed higher than the solid fiberglass bows tested herein, averaging 80% or higher up through draw weights of up to 56kg (Karpowicz, 2005). Simply put, composite bows are able to maintain a much higher level of energy storage per unit of mass – if properly designed such that they take advantage of horn and sinew's higher ultimate breaking strength (i.e. a short, highly reflexed design).

This efficiency is however highly dependent upon both limb length, with a shorter bow requiring less limb travel and limb mass (hence needing less energy to return bow limbs to brace). Additionally, at low draw weights of approximately 12kg, the differences in bow efficiency will be minimal for bows of almost any design so long as they are well made, as can be seen with the high efficiency rating of the 18kg segment bow. Above this draw weight however, segment bows with a round, elliptic, or "D" shaped cross sections typically found in medieval English warbows will begin to show decreased energy efficiency of energy transfer, with similar results for bows with the above mentioned cross-sections in a double-convex profile typical of Egyptian self bow artifacts (Soar, 2005, p. x; McLeod, 1981, p. 37). Starting at a draw weight of approximately 20-25kg, all-wood bows with a flat-limb design will likely begin to lag in efficiency, as at this point they too must increase in length to accommodate the additional material stress (Karpowicz, 2008, p. 33). Beyond this draw weight composite construction has the ability to maintain a high level of efficiency, as the use of sinew and horn, antler or bone can benefit from their higher overall material strengths while self construction efficiency will continue to decrease.

CONCLUSION

A number of sources of potential error remain despite the best efforts of the author. First and foremost, future testing would benefit from the use of high-speed video, particularly with regard to determination of limb return speed. Additionally the various bows could be attached to a stock with a pulley system to aid draw, resulting in a more consistent draw length and release. Use of an indoor test site would also add an additional layer of control over variations in lighting and wind, but as noted in *Designing Experimental Research in Archaeology*, such a venue is often difficult to secure even within an academic setting (Whittaker, 2010, p. 211). The current testing however allows a number of clear conclusions to be made. First and perhaps most importantly is the fact that while some of the historical anecdotes with regard to comparative bow ranges may be questionable, current distance records for archery are not, meaning that with modern materials at draw weights of approximately 90kg, composite bows using the latest in modern materials *do* have the potential to have a significantly greater range than a comparable self bow of roughly 300%.

This difference in performance however is *not tenable at lower draw weights*, and in fact at draw weights of the most common draw weights seen in the ancient world (18-23kg), the range differential between bows of self and composite construction would be approximately 45%, with approximately 10% of the range increase attributable to differences in bow profile (an average estimated by comparing profiles of self and composite bows from the tomb of Tutankhamen; the angular bows averaging a 10-13% reflex and the double-convex bows a 5-7% deflex), and the remaining 35% due to increases in efficiency caused by decreased bow mass and limb travel. This differential would continue to widen as draw weight increased, and by 45kg, would result in a range differential of 85%, again with 10% directly attributable to profile (and assuming an identical 20% profile differential as used for the lower draw weight example), and the remaining 75% due to continued decrease in self bow energy transfer efficiency.

Certainly bows of heroic proportions have existed throughout history and can be found in many cultures. From Odysseus and Heracles in Greece, to Rama in India, there have always been extraordinarily strong individuals who were able to use correspondingly high draw weight bows (Apollodorus, *Library*, 2.5.10; Valmiki, *Ramayana*, 1.67.17). During certain periods and places in history such as medieval England the number of such people may have been relatively more common due to systematic training (Hardy, 2006, 133; Selby, 2006, p. 196; Skulsky, 1975, p. 18). These high draw weight weapons when looked at through the larger lens of history are however the exception as the vast majority of bows both historically and in the modern day average between 18-23kg in draw weight (Baker, 1992, p. 79; Blyth, 1980, p. 34; Spotted-Eagle, 1988, pp. 15-16).

The implications of the test results are difficult to understate. To wit: the commonly cited improvement of the composite bow of double or triple the range of comparable self bow has the power to influence the view of scholars insofar that it has the potential to bias their expectations when viewing historical evidence. The advent of such a vastly improved range would potentially result in the sudden, widespread adoption of its use as can be seen in such technologies as the axe and the chariot (Hamblin, 2006, p. 94). In fact, the immediate adoption of new ideas or technologies is not always the case due to a host of reasons, including but not limited to such factors as sunk costs in earlier technologies (use of gas versus electric lighting), and cultural norms (the acceptance of insects as cuisine) (Basalla, 1999, p. 47; Ramos-Elorduy, 1998, p. 3; Belloc and Bowles, 2013, p. 93). The composite bow similarly faced a number of potential problems to its adoption, including increased costs in time, materials and labor, and unsuitability for use in a climate that is frequently wet or highly humid (Stehli, 2007, p. 136). Most importantly though, while composite technology, if utilized in a design that exceeds the mechanical properties of wood alone, does result in increased performance, the degree of improvement was typically less than commonly claimed in the majority of sources, and as such requires an adjustment of expectation with regard to the overall impact on the introduction of composite manufacture to a culture or region.

While a 45% increase in range for bows of equal draw weight is quite impressive it was not, unto itself, enough to cause a significant shift in military strategy although it likely did contribute to the adoption of changes in armor and shield design in New Kingdom Egypt. Comparative performance of composite technology does however increase with draw weight. The performance increase will eventually reach the point where the claimed double and triple the comparable range are possible, but only with a bow pulling more than the 45kg tested herein, a draw weight which was not seen until Late Antiquity. In short, the majority of scholars have been looking for the proverbial mountain with regard to composite bow performance (and corresponding changes in sport, military and warfare strategies) when the reality is that at the draw weights seen in the ancient world the range increase was a significant but more modest improvement of 45%.

Nor does this performance increase come without cost, as a composite bow represents a significant increase in the amount of time and materials needed compared to a bow of self construction, composite weapons would also be correspondingly more expensive. That being said, the amount of time needed to complete a composite bow is overstated by many today. While a number of sources mention that a composite bow takes "5-10 years to make," this estimate most likely starts from the time a tree is felled rather than when the actual construction process begins, combined with batch work that progressed on a seasonal basis, thereby significantly skewing the results outward by a period of years (Drews, 1993, p. 110; Klopsteg, 1992, p. 39; Rausing, 1967, p. 157).[35] The author's own experience shows that assuming appropriate materials are on hand (including seasoned wood), a composite bow can be completed from start to finish in a space of two to three months depending on the number of layers of sinew applied to the back, with most of that time devoted to allowing the sinew to cure.

As to exactly why and to what extent a composite bow has the potential to out-distance a self bow, the test results are clear, and outlined below:

- The use of composite materials and construction unto *itself* does not increase bow performance, but does contribute indirectly in that it allows for a more highly reflexed profile, and shorter, less massive bow limbs – both of which directly contribute to performance.

- Increased energy storage caused by differences in bow profile (regardless of method of construction), will equal *half* the amount of profile differential when expressed as a percentage of bow length.

- Decreased limb mass and limb travel caused by shorter bow limbs accounts for the majority of difference in comparative performance between bows of self and composite construction. Presuming a comparison of bows with identical profiles, draw length and draw weight, this differential is significant 35% (80% or higher efficiency for composite

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[35] Wood generally takes one year per inch (2.54cm) of radius to season assuming proper storage and if not subject to kiln drying. Reducing a green log to rough staves or billets greatly speeds the drying process, but it remains unclear if this technique was known or used prior to the Middle Ages.

construction compared to roughly 60% efficiency for self construction with limbs having a round or D-shaped cross section) at draw weights seen throughout the majority of history (between 18-23kg). Furthermore, this differential increases with draw weight due to decreases in energy transfer efficiency associated with self manufacture, reaching a 75% range differential at a draw weight of 45kg (80% efficiency for composite construction compared to 45% efficiency for self construction with limbs having a round or D-shaped cross section).

- The benefits obtained from both profile (differences in energy storage) and changes in limb mass and limb travel (differences in energy transfer efficiency) are *additive* when expressed as a percentage, and represent both the comparative difference in arrow energy and arrow range. For a draw weight of between 19-23kg then this would be a range increase of 45%, which gradually increases to 85% at 45kg.

The confirmation of the variables previously identified in theoretical modeling performed in Chapter Four, and the calculation of to what extent how both profile and bow mass contribute to increased performance accomplishes the first and second goals of the thesis. The identification and as important, quantification of the affect of both bow profile and limb mass and travel allow comparative bow performance to be both understood and easily calculated across a range of draw weights. This in turn allows previously differing research results to be placed within a larger unified framework, permitting future scholars to easily make accurate comparisons and performance predictions regardless of their primary research focus. The results not only provide a clear unifying framework for bow performance but were also an immensely satisfying accomplishment for the author, in no small part because the proposal committee initially questioned if the goals were even possible.[36]

It also provides a basis for understanding and refining a new methodology of iconographic evaluation of bow construction – namely the comparison of bow length relative to figure height. Composite construction only results in increased performance when used in a design that has significantly higher materials stress. It is this point that forms the basis of relative length, rather than profile, as an improved method of evaluation supported by both extant artifacts and physical testing. As such, the following chapter will expand upon this improved system that was first posited by Rausing, and then apply it to iconographic evidence from Mesopotamia and Elam for the third and fourth millennia BCE (Rausing 1967, pp. 20, 26).

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[36] The committee relented once it was made clear that the author was not only both an archer and bowyer, but also had already done similar experimental work at the Master’s level.

CHAPTER SEVEN

ICONOGRAPHIC ANALYSIS

Chapter Seven will analyze iconographic evidence from Mesopotamia and Elam from the third and fourth millennia BCE. Results of this analysis show that composite construction was introduced sometime prior to 3000 BCE, and that this period is marked by depictions of bows of both self and composite manufacture. This supports the possibility that the use of composite construction was accompanied by a transitional period, during which the new construction method became integrated into the iconography of the time.

To accomplish this, a new method of iconographic evaluation based primarily upon the comparison of relative bow length to figure height will be used. The need for the new methodology was proven previously in Chapter Two, which showed that the current method of iconographic evaluation based solely upon bow profile was insufficient. In contrast, the new evaluation system is based on results gathered from physical testing performed in Chapter Six, and backed by the collective experience of modern bowyers working in traditional materials (Baker, 2002, pp. 92-3). Additionally, the new methodology matches all existing composite bow artifacts from the ancient world (McLeod, 1970, p. 2; McLeod, 1962, pp. 15-6; McLeod, 1958, p. 397; Michael, 1958, p. 12; Eckhardt, 1991, p. 144; Čugunov et al., 2003, p. 135). The methodology further matches composite bow artifacts from medieval China, Korea, and the Ottoman Empire, as well as early North America (Karpowitcz, 2008, p. 41; Schmidt, 2000, p. 99; Gray, 2002, pp. 53, 59; Mason, 2007, pl. lxii; Grayson, et al., 2007, p. 19).

Prior to the analysis itself, the discussion will first focus on the new methodology, outlining its basis, proper method of implementation, and limitations. This will be followed by a review of Mesopotamian and Elamite iconography of the third and fourth millennia BCE. Within this section major artistic conventions are outlined and their potential impact on the following analysis detailed. As Hamblin has raised several points of contention with regard to the use of Mesopotamian and Elamite art as it specifically applies to the evaluation of bow construction, these concerns will be addressed as a part of this process (Hamblin, 2006, pp. 92-94). It should be noted that as this review of artistic conventions uses a number of images to demonstrate the different aspects being discussed, some images will be repeated in the analysis section which follows. The accompanying discussion within each of these sections however differs.

The iconographic analysis itself consists of three parts, tracing the development of differences in both bow profile and artistic conventions. The first section traces the use of bows with an angular profile in Mesopotamia and Elam dating to between 2300-1850 BCE. The second section covers the appearance of bows with a double-concave profile from the same region, and date between 2400-1900 BCE. The third section covers bows with a double-concave profile, but have a significantly different styling which occurs prior to 2400 BCE. Each of these sections focuses on a particular bow profile with the accompanying discussion arranged by reverse chronological order, an organization that allows different trends to be tracked with regard to bow design. Using a variety of source material ranging from monumental cliff-side rock reliefs to cylinder seals and *bullae*, the analysis not only identifies an approximate point of appearance of composite construction and period of integration into the iconographic record for the fourth millennium BCE in Mesopotamia and Elam, but also acts as a proof of concept for the improved methodology.

METHODOLOGY FOR THE ICONOGRAPHIC IDENTIFICATION OF COMPOSITE CONSTRUCTION

While composite construction can potentially be identified from either textual or ideally, artifact evidence, it is often the case that these sources of evidence are either inconclusive (in the case of textual evidence) or non-existent (in the case of artifact evidence). As such there exists a need to be able to reliably identify composite manufacture solely from iconographic sources. In this regard, imagery is perhaps the most useful source of data to the historian or archaeologist, because it occurs in relatively large numbers and from a wide range of contexts.

The evaluation of pictorial evidence is however significantly more difficult than the comparable evaluation of artifacts, particularly since it has already been determined in Chapter Two, and empirically proven in Chapter Six that bow construction need not follow a particular profile, and that an all wood bow of self construction can take a double-concave profile if it is of sufficient length (Hamm, 2000, p. 117; Rausing, 1967, p. 20).

The results found in Chapters Four and Six offer insights as to a more suitable methodology. Improved performance was found to be the result of a combination of unstrung bow reflex and reduced bow mass. Alas, the vast majority of both ancient and modern iconography depicts bows either at brace or at full or partial draw rather than unstrung. Additionally, testing found that with the exception of a bow's ears (if any), bow profile at brace is *not* a predictor of unstrung profile, leaving bow mass as the sole remaining means of iconographic evaluation to determine method of construction. Bow mass is also problematic, as such information cannot be gathered from imagery. That being said *ceteris paribus* a short bow will have less mass and hence require less energy to accelerate and return bow limbs than a longer bow. While such a comparison can potentially yield information with regard to performance, bow mass does not directly impact the question of method of construction.

The concept of using bow length and more particularly proportional length *unto itself* (unrelated to bow mass), as opposed to profile was first suggested by Rausing, but was also used by Collon in the analysis of an early potsherd (Rausing, 1967, p. 55; Collon, 1983, p. 53). The idea was briefly touched upon earlier in Chapters Four and Six, as decreased length naturally places increased stress upon bow limbs until such a point that it exceeds the material strength of wood alone. Such a bow would then by definition be required to use composite construction, which takes advantage of the higher material strengths of components such as sinew and/or horn (Landels, 2000, p. 106; Kelekna, 2009, pp. 76-77; Klopsteg, 1943, p. 182). The undifferentiated call to evaluate bow length however would be nearly as flawed as the existing methodology of profile evaluation for several reasons. The first problem is that bow length, like bow profile, does not exist solely in a small number of measurements but rather across a continuum. As such, bows as a category of artifacts can be found anywhere in length from less than a meter to over two meters in length (McLeod, 1970, p. 22; Bartlett et al., 2011, p. 595). Nor can a hard line be drawn at any one point delineating bows of composite versus self construction without first imposing a number of supplementary conditions, as shown by the use of short bows of self construction used during Middle Kingdom Egypt outlined previously in Chapter Three. Finally, a number of issues pertaining to artistic accuracy and convention can also present problems. While several of these issues were reviewed in Chapter Three, further discussion relating specifically to the artwork of the third and fourth millennia BCE in Mesopotamia and Elam will follow later herein. It is perhaps in part because of these combined issues that a revised methodology has not been produced earlier; while Rausing advocated the idea of proportional length, the concept was never fully developed so that it could be reliably applied.

Despite these problems, the concept of increasing stress as bow length decreases remains sound, and can indeed yield reliable results if several supplemental conditions are applied. Iconographic representations of bow length are easy to measure, but also have limitations. First and foremost, bow length in pictorial representations must be measured relative *to* something, preferably a human figure but also possibly an object of known size. In short, the evaluation of bow length cannot be usefully applied to a depiction of a bow by itself. That being said, while absolute length is unusable, *relative* length compared to a figure, while not completely error-free, can provide an estimate of bow length. If the resulting estimate shows that a bow is atypically short, this could be taken as a possible indication of composite design. The resulting estimation of relative length relies upon two facts. First is the fact that the vast majority of bows used throughout history tend to range between 18-23kg in draw weight (Baker, 1992, p. 79; Spotted-Eagle, 1988, pp. 15-16; Pope, 1947, p. 15). The second is that traditional bowyers have a clear estimation as to how much stress wood can take before breaking for a particular bow style. For a segment profile bow of self construction of rectangular cross-section and rounded corners (a more efficient design than an round, elliptical or D-shaped cross-section) with a draw weight of 22.7kg and a draw length of 73cm or more, this limit is approximately 160cm in length depending on the type of wood, below which a bow will begin to suffer reduced performance due to partial compressive failure (Baker, 1992, pp. 92-93; Kooi, 1994, p. 17).

Wide, flat limbs would safely allow for slightly shorter limbs, but wide limbs means using thicker wood and larger diameter trees, no small task even when using modern hand tools (Hardcastle, 1992a, p. 32). It also results in a greater amount of material wastage and is therefore rather inefficient from a materials efficiency standpoint. For both of these reasons, wide, flat limbs were not widespread through much of the ancient world, or indeed the world in general.[37] It is for this reason that unless evidence suggests otherwise, it is assumed that sources describe or otherwise show bows with relatively narrow limbs. In such a case, assuming a draw weight typical for hunting of approximately 18kg and a draw length of 73cm or more, a bow to figure ratio which would result in a bow having length of less than 150cm will be considered to be of composite construction. This is a slight underestimation of required bow length, but errs on the side of conservatism.

Setting a break-point of 150cm in length as an indicator of composite construction is only half of the problem however, as neither the bows nor the figures depicted in artwork are likely to be exactly life size. As such, the average height for a man in ancient Egypt and/or Mesopotamia is also needed; a question dealt with previously in Chapter Five and for the iconographic analysis presumed to be 170cm. This is slightly higher than the similar estimate posited by Hamblin, who presupposes a figure height of 160cm (Hamblin, 2006, p. 439). While not every example of artwork will depict a king, god or similarly heroic figure any increase in relative figure height that may inadvertently occur will only result in a small variation in final computations and will additionally yield a more conservative figure, adding a layer of safety to the resulting estimations.

Taking the figure of 150cm, representing the break-point for composite construction, and dividing by the estimated average figure height of 170cm yields a ratio of bow length to figure height of 0.882. The evaluation of iconographic representations in ancient artwork can then be reduced to a matter of simple division. This in many ways results in an almost mechanistic evaluation process – intentionally so, as to be useable the methodology should be both simple to understand and easy to apply. So long as the supplementary conditions of both draw weight and draw length have been applied and iconography of the period and culture under investigation has a high degree of proportional accuracy, the results will be clear, concise and more accurate than an evaluation of bow profile.

In cases where either part of the figure or part of the bow is damaged, some additional estimates are needed. If the representation of a figure is damaged, the measurement of the remaining undamaged portion of the figure can be referenced against average anatomical proportions to determine total height (Fairbanks and Fairbanks, 2005, p. 36). In cases where a portion of the representation of a bow is damaged, the measurement of a single limb can in most cases be taken as equal (or almost equal) to half the total bow length. This latter estimation however cannot be

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[37] Exceptions do of course exists, the two best known being the Mere Heath artifact and a number of bows used by Native American tribes of the Eastern Woodlands region.

used in cases where the use of an asymmetric bow design is known to exist within a given culture. As the vast majority of bows used across cultures have been symmetric, hand position represents the sole remaining source of error, resulting in range of potential error of perhaps 5cm (Baker, 1992, p. 92; Alrune, 2007, p. 26).

This methodology of utilizing relative proportion can be a powerful analytical tool, but it is not without its limitations (Panofsky, 1955, p. 61). First and foremost, it presupposes that either the image in question depicts, or comes from a culture or larger body of works which draw the bow to either the corner of the mouth or ear or equivalent length. Additionally, it assumes that draw weight be *at least* 18kg. The system will also work with higher draw weights, but use for comparison in a culture with lower draw weights is problematic. While these two caveats include the vast majority of bows created throughout history, some cultures such as the Pygmies in Africa utilize very short bows of self construction with short draw lengths, at times in conjunction with low draw weight which rely on poison rather than physical injury (Baker, 2000, pp. 57-58; Gray, 2002, p. 73; Grayson et al., 2007, p. 139). Nevertheless the process of utilizing bow length as a means of determining composite construction is viable and when properly applied is more accurate than bow profile while remaining easy to use, thereby fulfilling the third goal of the thesis.

ICONOGRAPHIC CONVENTIONS IN EARLY MESOPOTAMIA AND ELAM

While the previous discussion clearly outlines the mechanical limits of the new methodology, it has yet to address what is perhaps the most important and potentially contentious issue – artistic accuracy. More specifically, proportional length as a method of iconographic evaluation is inherently limited by degree of proportional accuracy of the image being analyzed.

It should be noted that of primary concern for the forthcoming analysis is *proportional accuracy*. In contrast, the concept of *realism* is of lesser concern for two reasons. First is the fact that a high level of naturalistic realism was not a priority for either Mesopotamian or Egyptian art in the ancient world, although when compared side by side, Mesopotamian art is generally considered to be more naturalistic of the two (Westendorf, 1968, p. 12; Bleiberg, 2005, p. 266; Kantor, 1966, p. 146). Second, even in such cases where sufficient detail exists, fine features above and beyond the depiction of a bow string, such as unique and accurate facial expression or clothing texture are of little benefit to the current endeavor, which focuses on proportionate length.

First and foremost then is the question of whether Mesopotamian and Elamite art utilized an artistic canon similar to previously established in Chapter Three for ancient Egyptian art. The answer is yes – Mesopotamian art does utilize a set system of proportion, and like Egyptian art, the standard measure is that of a human figure. Some evidence even supports the possibility that the Egyptian proportional canon may have been partially adopted *from* the Mesopotamian standard (Tomabechi, 1983, p. 125; James, 1985, p. 13; Benzel et al., 1998, p. 43; Carter and Steinberg, 2010, p. 103). Unlike the fairly stable proportional system of used in Egypt however, the artistic canon in Mesopotamia underwent several shifts over time, sometimes occurring within a given medium, such as cylinder seals, as can be seen in the stretched appearance of figures during a portion of the Akkadian period depicted in figure 7.1 (2300-2159 BCE) (Collon, 2005, p. 34). In contrast, art of the fourth millennium and first half of the third millennium BCE typically depicts figures with arms and legs having a "joined on," puppet-like appearance, large eyes and prominent, almost beaked noses as seen in figure 7.2 (2650 BCE) (Strommenger, 1964, p. 22). The result then is not a single system of proportion, but several, each with its own minor variations existing within a consistent, larger whole (Mosteller, 1990, p. 389; Tomabechi, 1983, pp. 125-6).

Figure 7.1 Akkadian Seal Impression, 2300-2159 BCE.

Figure 7.2 Stele Fragment (cropped) 2650 BCE.

Mesopotamian and Elamite art also depicts figures with torsos in a three quarter view, but with faces depicted in full profile, and typically shows a lack of perspective (Benzel et al., 1998, p. 43). As this portrayal is already familiar from Egyptian art, it does not present any significant problems. Additionally, the portrayal of figures in this manner naturally mimics a typical archery stance, meaning that depictions of archery are more likely to depict a realistic body positioning than images showing craft activities or seated figures, which continue to follow the same artistic convention of profile depiction despite its lack of realism, as shown in the depiction of the seated figure in the seal shown in figure 7.3. Finally, while the vast majority of art from ancient

Mesopotamia and Elam does not make any pretense at depicting perspective, this means that details such as bow limb width are typically concealed. In several examples however, depictions show what appears to be an attempt at an oblique perspective. With the foundation of knowledge provided earlier in Chapters Four and Six, these attempts can be clearly identified as showing bow limb *width*, as the creation of such a bow as variations in limb thickness would result in an unusable weapon that would break the first time it was drawn (figure 7.4).

Figure 7.3 Seal Impression, 2254-2218 BCE.

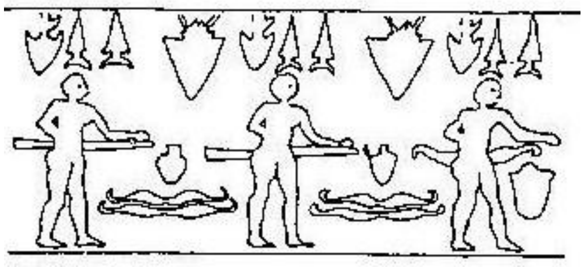


Figure 7.4 Sketch of Seal Impression, 3500-3000 BCE.

Again, in a fashion similar to Egyptian art, Mesopotamian and Elamite art is typically portrayed in a register system. The depiction of figures within this system at times utilizes proportional hierarchy for the depiction of kings and gods, a practice that is most commonly utilized in steles and monumental rock art as seen in figure 7.5 (Kantor, 1966, p. 147; Tomabechi, 1983, pp. 124-125). In such cases figure heights should not be compared to each other, as it would result in gross inaccuracies. Figure size on an absolute scale is of course limited by the size of the register – and it should be noted that registers within the same work of art are not always equal in height. For the majority of art depicted in Mesopotamian art, figures take up the entire register height, even more so than that typically seen in Egyptian art (Kantor, 1966, p. 174). This particular nuance of figure sizing is most commonly seen in cylinder seals, but also occurs occasionally elsewhere, as shown in the Rimush stele (figure 7.6). This preference in figure sizing is not absolute however, as can be seen in the Naram-Sin stele (figure 7.7), and reduced proportional figure sizing that allows the depiction of a landscape scene occurs in several instances in cylinder seals as can be seen in figure 7.8 (Kantor, 1966, pp. 148-9).

The confined space in registers, particularly when the figure takes up the entire height, is potentially problematic when depicting a bow in use, as it could result in some degree of foreshortening. This problem was observed in Egyptian art in Chapters Three and Five, where bow length as measured along the arc typically overestimates bow length when shown at full draw, but remains accurate when bow are depicted at brace. Egyptian art of course benefits from having actual bow artifacts against which iconographic measurements can be made, while Mesopotamian and Elamite art do not. As it is widely accepted that the composite bow came to Egypt from lands to the East as a part of the Hyksos invasion, and the analysis herein picks up less than a century prior to this event, the overall size of composite bows from New Kingdom Egypt make a reasonable, but inexact proxy from which length comparisons can be made (Spalinger, 2009, p. 15; Cotterell, 2005, p. 57; Credland, 1994, p. 30; Drews, 2004, p. 49).

Figure 7.5. Rock relief showing proportional hierarchy (note reduced size of captive foe at right), 2200 BCE.

Figure 7.6 Figures taking the entire register height, Rimush Stele, 2244-2236 BCE.

The use of Egyptian artifacts as a proxy length against which Mesopotamian and Elamite imagery is to be measured is however only viable if it can be determined that Mesopotamian art is as least as accurate as Egyptian art which uses similar conventions. Both the use of register and relative sizing of figures within a register for both of these regions are quite similar. As previously mentioned however, Mesopotamian and Elamite art generally benefit from a slightly higher level of naturalistic realism in its depictions. While realism does not always correspond to accuracy, such is the case here, as can be seen summarized in tables 7.1-3. All of the tables show a high level of correspondence of bow length as measured along the arc when both at brace and at full draw, particularly compared to Egyptian artwork. While this higher standard of realism is at times broken, as can be seen in the extremely high brace height (distance between the bow string and the interior edge of the bow at the grip) shown in figure 7.5, it can be said that a comparison of bow length, as measured along the arc between bows depicted both at brace and bows shown at draw shows that Mesopotamian and Elamite art quite consistently show a high level of accuracy.

Figure 7.7 Naram-Sin stele, 2254-2218 BCE.

Figure 7.8 Cylinder seal impression 2334-2193 BCE.

Indeed, if a significant amount of foreshortening was to occur, then one could expect to see proportionately longer weapon lengths in works of art where figures did not take up the entire register height as shown in figures 7.7-8. Such is not the case however, and instead proportional bow length remains remarkably consistent throughout the second half of the third millennium BCE regardless of register usage, a point which tends to support both the accuracy and reliability of proportional length for Mesopotamian and Elamite art during the period at hand.

Error can still however be found in a comparison of bow string length compared to bow length measured along the arc length when at draw. In this regard, Mesopotamian and Egyptian art show a similar flaw – namely that both conventions generally overstate bow string length when at draw (figures 7.9-10). Egyptian art compensates by depicting an overly long depiction of bows (as seen in Chapter Five), while Mesopotamian art tends to under-represent the bending of bow limbs, at times portraying a bow at half or even full draw with either very slight or even no limb curvature. This results in some level of inaccuracy with regard to the depiction of the profile of bows depicted at full draw (which does not factor into the analysis herein), but increases the degree of accuracy with regard to measurement of bow *length*.

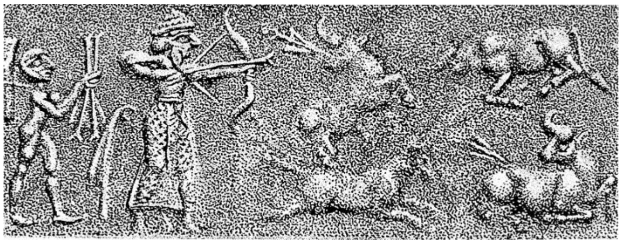
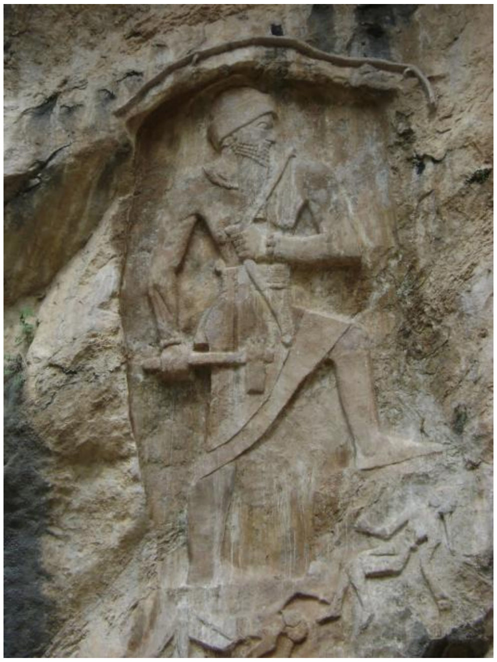


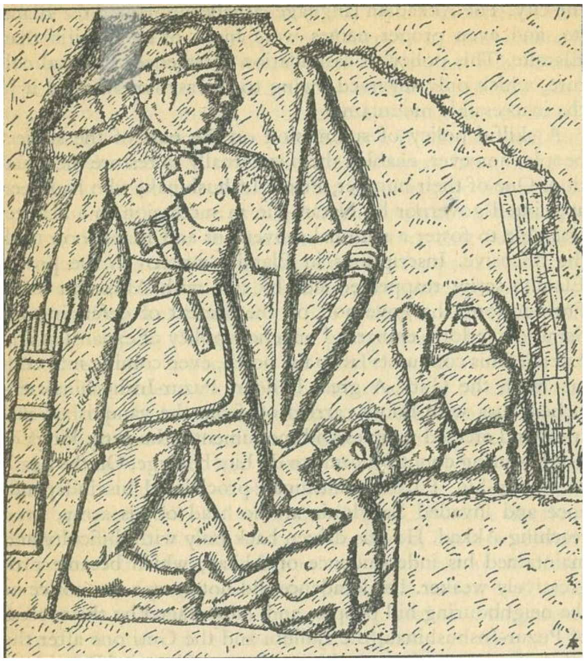
Figure 7.9 Seal impression, Uruk, 3300-3000 BCE.

Figure 7.10 Incised plaque, Mari, 2500-2250 BCE

The end result however is that the bow artifacts of New Kingdom Egypt do match iconographic representations of the same region and period, although some adjustment does need to be made if the bow is shown at full draw. As the first period under investigation immediately precedes that of the Hyksos invasion, and includes the region from which the Hyksos purportedly arrived (Mesopotamia and the Levant), there is a high likelihood that the New Kingdom composite artifacts represent a fair proxy for Mesopotamian artifacts during and slightly prior to the same period. This similarity applies not only to bow length, but also bow profile. While the images covered thus far in the current chapter have all been of double-concave profile, a number of images also depict bows of an angular profile, as can be seen in both the Darband-i-Gawr and Tar Lunni rock reliefs shown in figures 7.11-12. Both images are located in Mesopotamia, and are among the earliest depictions of bows with an angular profile known, potentially indicating a transition period in bow design, or at the very least an additional level of diversity to bow profile in the region during the third millennium BCE. Additionally, it shall be shown later that the relative length of these angular bows matches the length of New Kingdom Egyptian artifacts, thereby adding an additional level of consistency to the issue of validity regarding the use of proportional length.



7.11 Darband-i-Gawr relief, 2200 BCE.



7.12 Sketch of Tar Lunni Relief, 2250 BCE.

QUESTIONS OF CONSISTENCY

As mentioned previously, Hamblin has expressed two concerns with regard to the use of Mesopotamian and Elamite iconography. Both concerns deal with issues of consistency and as they call into question the validity of the entirety of the current chapter, need to be addressed.

The first issue raised by Hamblin deals with inconsistencies in bow profile between differing works of art in general (Hamblin, 2006, p. 92). Most particularly Hamblin asserts that because the Victory stele of Naram-Sin and the rock relief of Darband-i-Gawr show both show the same scene and yet have differing bow profiles, by default the bow depictions in Mespotamia and Elam of the third and fourth millennia BCE are unreliable. By extension then, according to Hamblin, iconographic claims made for the artwork of the region would be similarly suspect (Hamblin, 2006, pp. 92-3).

Throughout the thesis however it has been shown that differing bow profiles within a given culture and period *do* vary. This diversity is attested in both New and Middle Kingdom Egypt, but also in prehistoric Europe, and native tribes in North America, and as such finding a similar diversity should come as no surprise for Mesopotamia and Elam – particularly given the fact that the period in question covers approximately two thousand years (McLeod, 1981, p. 28; McLeod, 1970, p. 2; Rausing, 1967, pp. 38-9; Dams, 1984, p. 130). Further, the question of consistency between these two particular works is only of potential concern if both indeed are meant to portray Naram-Sin, a claim which is not undisputed. Nevertheless, some insights can be gained with regard to relative dating and who is portrayed with a more detailed examination.

The first published account of the Darband relief was done by C. J. Edmonds in 1925, but it remained unexamined archaeologically until Eva Strommenger managed a visit with a photographer in 1960 (Edmonds, 1925, pp. 63-64; Strommenger, 1963, p. 83). Like Hamblin, Meissner and Ebeling, and Meiroop claim the Darband relief depicts Naram-Sin (Hamblin, 2006, p. 86; Meissner and Ebeling, 1978, p. 339; Meiroop, 1999, p. 219). Orthmann et al., and Houtsma et al. however both attribute the Darband relief, like the later relief of Annubanini (2000-1900 BCE), to a Lullu King (Orthmann et al., 1975, pp. 202-203; Houtsma et al., 1993, p. 538). Strommenger takes a more cautious approach and states that *stylistically* the Darband relief matches the Naram-Sin stele in many respects, and in general follows the artistic trends and symbolism of Akkadian art in general with a heroic figure standing poised with left foot placed upon the vanquished. Each also carries a bow in their left hand, held with elbow bent such that the upper bow limb either rests on or touches the left shoulder (Strommenger, 1960, pp. 84, 88).

The single largest problem is that the Darband relief bears no inscription, the primary means of identification for monumental reliefs in the ancient Near East, making definitive dating or attribution to a particular king impossible (Debevoise, 1942, p. 76; Mieroop, 1999, p. 219; Strommenger, 1963, p. 88). Indeed, the Darband relief could as easily depict a Lullu king, a group similarly depicted on Annubanini relief discussed later herein (Speiser, 1952, p. 99; Debevoise, 1942, p. 80). Nor is bow profile the only difference between the two works. The helm worn in the Darband relief is a rounded cap with a wide rim, a feature which perhaps acts as reinforcement; in contrast, the Naram-Sin stele helm has a slightly conical, rather than rounded top, is slightly bulbous, has either little or no rim and is adorned by horns. The style of beards, knotting and display of the skirts are also different, as is the shape of the head of the axe held in each of the figures' right hands.

Of these differences the shift in headgear is potentially most important. Most notable is the fact that the Naram-Sin stele depicts Naram-Sin's helm with horns, a symbol of divinity, while the Darband relief (or any other monumental reliefs of the region during the third and fourth millennia BCE) does not (Ornan, 2004, p. 96; Hundley, 2013, p. 72; Cornelius, 1997, p. 31). The fact that one work of art depicts a figure with horns and another without is however not conclusive evidence that the two works represent different people, as several cylinder seals etched with the name Naram-Sin can be found in both styles, as seen in figures 7.13-14 (Deleporte, 1920, p. 11; Ball, 1989, p. 153). This particular symbol of godhood can at times be further used to distinguish between more powerful gods (shown with more than one set of horns) from lesser gods, with only a single set of horns (Hundley, 2013, p. 72; Börker-Klähn, 1928, pp. 41-2). While the lack of horns on the Darband relief does not discount the possibility that it may indeed depict Naram-Sin, if such is the case the difference can be used as a means of relative dating, as once godhood is proclaimed by a ruler it is unlikely (and potentially unwise) to later renounce it. This is perhaps particularly true within the genre of monumental art, which is often used as a medium to express a ruler's power. As such, *if* the Darband relief does depict Naram-Sin it would stand to reason that it was commissioned *before* his claims to godhood and the construction of the Naram-Sin stele. Taken as a whole however, the cumulative differences between the two scenes and lack of inscription on the Darband relief make the assertion that both works depict Naram-Sin unlikely.

Figure 7.13 Seal Impression depicting Naram-Sin (right), 2254-2218 BCE. Note crown (sans-horns).

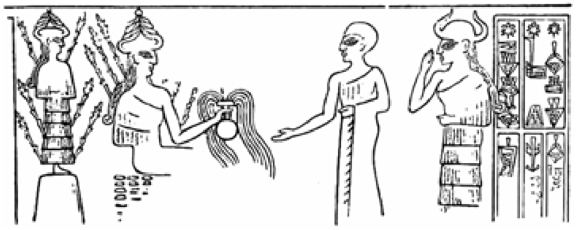


Figure 7.14 Seal sketch depicting Naram-Sin (right) 2254-2218 BCE. Note horned crown proclaiming his divine nature.

Hamblin’s second and more serious assertion is that bow profile varies not only from work to work within Mesopotamian art of the third millennium BCE, but also *within a given work of art*. Such an assertion would indeed call into question the accuracy of the depictions under review in general, and potentially render any analysis based upon such works invalid. As such this claim must be investigated in detail to ensure the validity of the analysis which follows.

For Mesopotamia and Elam during the third and fourth millennia BCE several examples of works depicting more than one bow exist, with the most famous of these works being the victory stele of Naram-Sin (2254-2218). The depiction of the bow held by Naram-Sin himself is clearly visible in the top register of figure 7.7, but as the second bow, held by an archer in the lower register is significantly smaller, both shall be examined in separate, closely cropped images (figures 7.15-716).

Much has been made of the shape of Naram-Sin's bow; while it does not have the much sought after "cupid" shape mistakenly believed by many as conclusive evidence of composite construction, it most certainly has a double-concave profile as can be seen in the close-up (figure 7.15). Also notable are the limb tips, which present as ears due to their straight nature which may potentially imply that they would not bend during the draw. More details on this particular point will be discussed later in the current chapter.

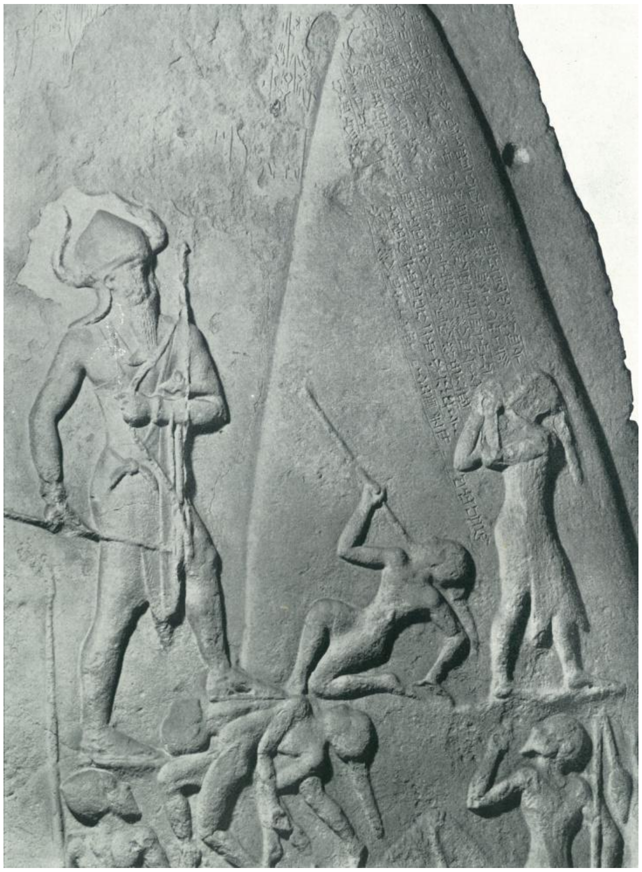


Figure 7.15 Victory stele of Naram-Sin, 2254-2218 BCE (close-up of upper register).

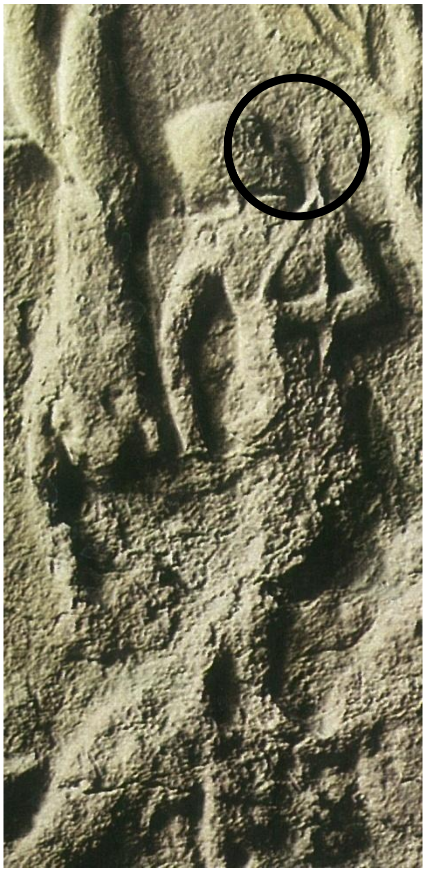


Figure 7.16 Naram-Sin stele, close-up of figure holding bow, lower register 2254-2218 BCE.

The second figure holding a bow stands just to the left of the single tree depicted in the lower register of the stele, as seen in figure 7.16. The bow is badly worn: the lower limb of the bow and indeed much of the lower half of the entire figure is only vaguely recognizable at best, if not damaged beyond recognition. Minor differences in relief height roughly outline the legs, and while much of the lower (right) foot is fairly clear, the upper (left) foot is barely distinguishable from the background making it difficult to determine an exact figure height.[38] The bow itself at first glance appears to be a short simple segment bow and just as Hamblin describes, is significantly different in profile than the bow held by Naram-Sin.

That being said, as king it would be entirely within reason that Naram-Sin could have different (superior) equipment than that of his troops or even his officers. Many of the composite bows from the tomb of Tutankhamen bear elaborate decoration (items #48f and #48h being the most elaborate) including stylized designs or inscriptions and even scenes in multiple colors or in gold leaf (Griffith Institute, 2004). Having a bow with a different profile than one's troops could potentially be an extension of this principle, a possibility also acknowledged by Hamblin

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[38] The left foot has been cropped from the picture shown herein. Thankfully this particular anatomical detail is superfluous with regard to determining both figure height and bow length.

(Hamblin, 2006, p. 93). That being said, judgment should be reserved until after examining the second bow in greater detail.

A closer examination shows a faint trace of a straight line extending vertically directly above the tip of the bow where the rock is raised slightly from that of the background as seen in figure 7.16 (circled). This raised area extends to a point even with the lower edge of the brim of the figure's helm, and could very well be the upper ear of the bow, in which case it too would present with a double-concave profile identical to that carried by Naram-Sin. Although it is difficult to be certain given the severity of damage, the available evidence appears to negate Hamblin's claims regarding internal inconsistencies. A somewhat rough estimate of relative length based upon the upper half of the bow (including the heavily damaged upper "ear") indicates that both bows are (proportionally) almost identical in length and in brace height (table 7.2).

While the Naram-Sin stele is the only work which Hamblin directly questions, other examples that similarly portray multiple bows are worth examination to ensure that the works under analysis continue to show internal consistency. The Rimush stele from Tello (2244-2236 BCE) also depicts multiple bows. In this case, three: two (heavily damaged) are shown in the top register, being held at brace in a manner similar to the Naram-Sin stele, and one in the middle register which is shown at full draw. Only fragments of the bows in the upper register (figure 7.17) remain visible, but the sections which do remain reveal two points: first, the depiction of the lower limb tips appear to be consistent with each other. Second, taking detail from both of these bows and combining them reveal that the shape of the limb tips strongly resembles those shown in the Naram-Sin stele.

The depiction of the bow in the middle register however is shown at full draw (figure 7.18). This immediately presents both a potential problem and an opportunity. The problem is that the bows in the top register cannot conclusively be proven to be of the same design as that shown in the middle register due to the fact that bow profile naturally shifts as draw progresses. That being said, the bows also cannot be proven to be of differing designs for the same reason. Given the consistency of other details throughout the stele, including quiver details and cut of clothing, particularly when combined with the uniform internal consistency in other works for the region there is no evidence to suggest that the two registers depict differing designs. If consistency is accepted between the top and middle registers, which while likely is not a guarantee, then we are presented a unique opportunity – the ability to correlate a given bow profile when shown both at full draw and at brace in the ancient world. As can be seen, both limbs of the bow appear to be nearly straight, presenting as if the bow was bending almost entirely at the handle. Looking at the elongated limb tips in the upper register we can see that there is a recurve in the substantial limb tips, meaning that these tips must then straighten as draw progresses. If correct, this implies that the bows shown in the Rimush stele are almost certainly a working recurve design, wherein the recurve limb tips bend during the draw, as opposed to a static recurve design where the limb tips (or ears) maintain a constant angle of recurvature (do not bend). This same profile occurs regularly throughout second half of the third millennium BCE and it is likely that they also utilize a working recurve design.

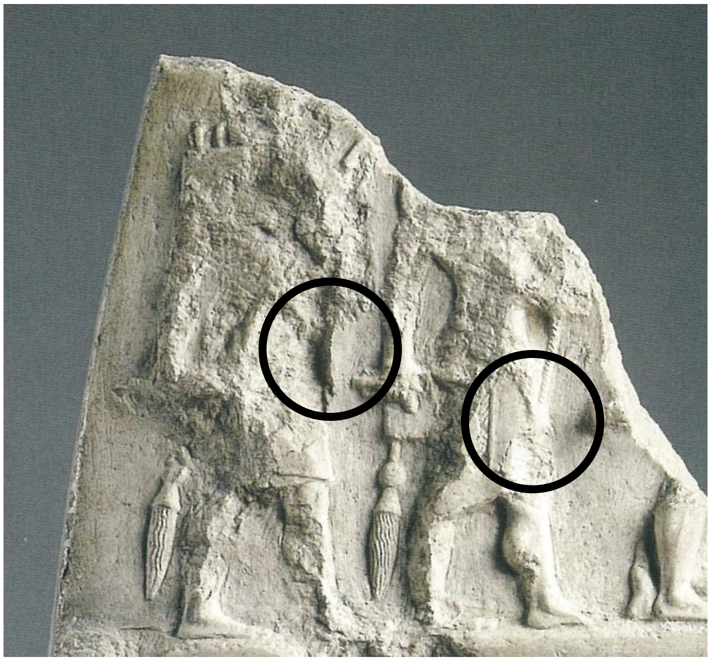


Figure 7.17 Rimush Stele, close-up of upper register, 2244-2236 BCE.

Figure 7.18 Rimush Stele, 2244-2236 BCE.

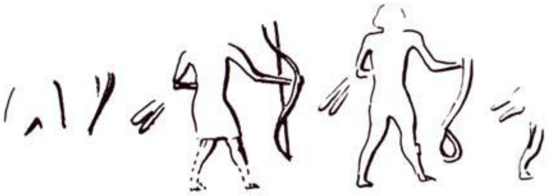


Figure 7.19 *Bulla* sketch, Susa, 3800-3100 BCE.

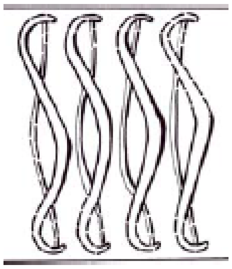


Figure 7.20 *Bulla* sketch, Susa, 3800-3100 BCE.

Finally, several *bullae* from the fourth millennium BCE show multiple bows. One, depicted in figure 7.19, does show some degree of variation in limb tip design between the bows held by the middle two figures. The others all maintain identical profiles, as can be seen in figure 7.20. Taken as a whole, while several differing bow profiles are present in Mesopotamian and Elamite art during the third and fourth millennia BCE, the art during this period shows a very high degree of internal consistency within each work. With Hamblin's concerns regarding consistency addressed, attention can now turn to the analysis itself focusing on the relative proportion of bow length to figure height, the first section of which covers the period from 2300-1850 BCE.

ICONOGRAPHIC ANALYSIS

The analysis which follows is divided into three sections. The first covers the period from 2300-1850 BCE, which links bows of an angular profile from New Kingdom Egypt to that of Mesopotamia and Elam during the period immediately preceding the Hyksos invasion, thereby linking the iconographic and artifact evidence of this event between Egypt and Mesopotamia (Ryholt, 1997, p. 5; Spalinger, 2009, p. 15).

The second section ranges from 2400-1900 BCE, and focuses on bows of double-concave profile with long ears which are most likely of a working recurve design, but which appears to have lost popularity with the introduction of the angular design. The start and end points of this first section were chosen as a natural break point in the available artwork, with a shift occurring sometime shortly before the start of 2400 BCE. The other end date of 1900 BCE represents the last known depiction of a bow with a double-concave profile prior to the Hyksos invasion.

The third section covers the period prior to 2400 BCE. While the bows during this period continue to sport a double-concave profile (at times with a set-back grip), the imagery is marked by several iconographic differences which includes depictions of the bow string *crossing* the bow limb, a feature which is indicative of a static (rather than working) recurve design combined with long nock loops. Additionally, several of the bows are longer in relative proportion, potentially indicating that they are of self, rather than composite construction.

ANGULAR PROFILE: 2300-1850 BCE

The section begins with an examination of iconographic evidence from Mesopotamia and Elam that most closely corresponds to the period immediately prior to the Hyksos invasion of Egypt. The purpose of this is to minimize the chronological gap between the period for which both artifact and iconographic evidence exists (New Kingdom Egypt), to the period and region for which there is abundant iconographic evidence but no artifacts (the early second millennium BCE Mesopotamia and Elam).

As such, the section will first focus on images of bows with the same profile as found in composite bow artifacts from New Kingdom Egypt – that is to say, bows with an angular profile. The first example shown in figure 7.21 dates to 1850 BCE, and is a cylinder seal from Sippar. To date no other published works have undertaken an evaluation of this source other than a general description and dating from its discovery in 1855 (Collon, 2005, p. 47; Werr, 1980, pp. 41, 63). As such, this is the first in-depth examination of the seal as it pertains to archery. It should be noted that in this case, the highest level of detail can be found in a photograph of the seal *itself* rather than in an impression. Because of this the details appear reversed with the bow held in the figure's right hand (which would reverse to the left hand when rolled, as typically found throughout the third millennium BCE). The figure wears headwear matching that of both the Darband and Annubanini reliefs (Collon, 2005, p. 47; Werr, 1980, pp. 41, 63).

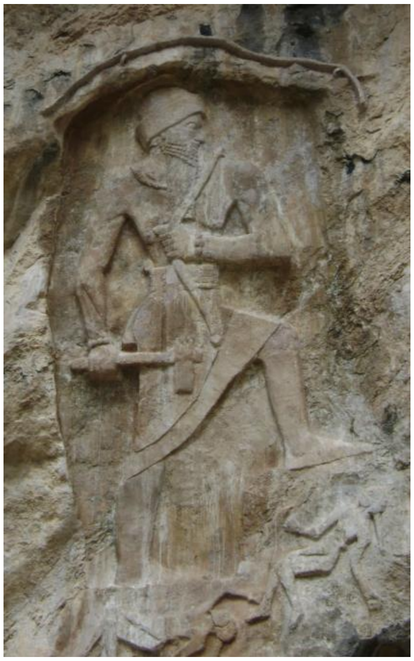
Figure 7.21 Cylinder Seal, Sippar, ca 1850 BCE.

7.22 Seal Impression (cropped), Kish, 2334-2193 BCE.

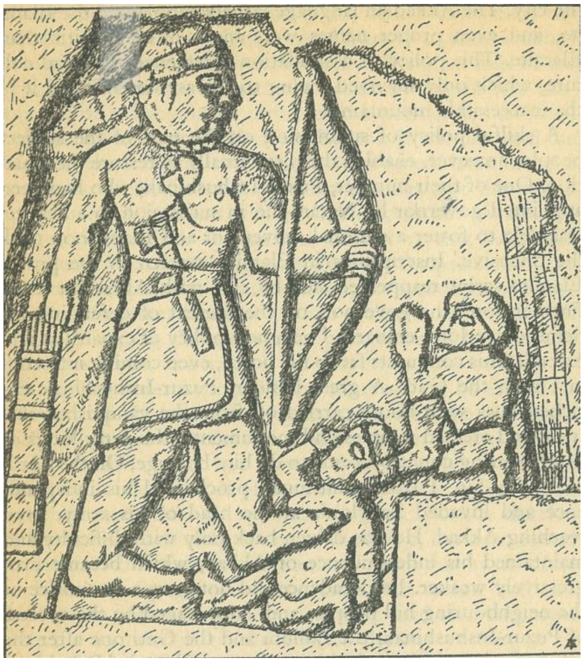
As the subject is wearing a helm, proportional measurement was done from feet to the jaw line, as inclusion of the helm could potentially skew figure height. The results show that based on a figure height of 170cm, the bow would then be 73cm in length measured from tip to tip, 83cm along the arc, and have an abnormally high brace height of 28cm. The high brace height may be artistic convention designed to ensure that the bow string does not overlay the arm.

While the overall length along the arc matches several of the bow artifacts from the tomb of Tutankhamen, it is significantly shorter than the median average length of 111cm (McLeod, 1970, pp. 22, 24). The depiction here of such a short bow tends to indicate that these shorter bows (of 80cm or less) were not unusual, and the overall length indicates composite construction.

Only three other works from Mesopotamia depict bows with an angular profile prior to 1850 BCE: the rock relief of Darband-i-Gawr (2200 BCE), the much less well-known Tar Lunni relief (2250BCE), and a cylinder seal from Kish (2334-2193 BCE). Both reliefs show bows held in hand at brace, and are composed of the stereotypical “conquering” or “victory” pose shown on the Naram-Sin stele, with figures facing right, bows held in the left hand and with left foot stepping upon one or more fallen foes. The cylinder seal differs significantly in its composition, and shows a bow in the process of being fired, as can be seen by the faint impression delineating an arrow (figure 7.22, circled).



7.23 Darband-i-Gawr relief, 2200 BCE.



7.24 Sketch of Tar Lunni Relief, 2250 BCE.

A number of differences present themselves between the reliefs despite the compositional similarities. First and foremost while the Tar Lunni relief is Akkadian or at an attempt at an Akkadian design, stylistically it is much more crudely executed (Ghirshman, 1954, p. 54; Wilkinson, 1991, p. 83). The head is overly round, the right arm is unnaturally short, and is depicted such that it does not appear to have an elbow joint; the right hand is similarly diminutive. The legs and feet are overly thick compared to the body, and the left knee remains unbent despite the difference in elevation between the left and right feet. The bow is angular in profile, but the bow limbs are overly thick. A bow with these proportions would likely be significantly higher in draw weight than average, but given the low level of artistic execution throughout the work, the limb thickness is likely an exaggeration.

In contrast, the Darband relief approaches the quality of execution of the Naram-Sin stele (Mieroop, 1999, p. 219; Strommenger, 1963, p. 88). It also was originally carved with, and maintains, a much greater amount of fine detail in comparison to the Tar Lunni relief, including curls in the beard, significant muscular definition, and numerous small touches such as the beaded bracelets on both wrists, and a realistic drape to the lower edge of the skirting. The bow limbs are also proportionately slimmer. Both reliefs are dated close to that of the Naram-Sin stele, but only the Tar Lunni relief has an accompanying inscription, making dating more certain than that of the Darband relief (Ghirshman, 1954, p. 54; Meissner and Ebeling, 1978, p. 339).

The seal from Kish differs from both of these examples in both style and composition. Stylistically, the figures are exceptionally thin, having an almost stretched appearance. Like the Darband relief, it presents an impression having been somewhat crudely done, but manages to maintain a greater level of fine detail: beards are shown with individual hairs, muscles have slightly greater definition, and the feet clearly show arches. The various elements depicted on the seal itself and their composition are also different from both the reliefs and the Sippar seal, and depicts a group of gods hunting a demon (cropped) (Collon, 2005, p. 180; Hamblin, 2006, p. 92). The leftmost god is in the process of firing a bow, and the seal is the only image from Elam and Mesopotamia from the third millennium or before to show a bow as it is being fired, a conclusion made as the draw (left) hand of the figure is not holding the string, which remains at partial draw while the arrow is in the process of being launched from the bow (circled). The relative measurements indicate a bow length of 70cm measured from tip-to-tip, or 74cm along the arc. As the bow is shown at partial draw, an exact measurement for brace height is not possible, but measurement from the interior of the bow handle to the string yields a figure of 19cm, meaning that when at brace this figure must be somewhat shorter, and is estimated by the author to be approximately 16cm.

The bows in all four works present an angular profile, but differ slightly in proportional length. The bow in the Darband relief (based on the standard of a figure height of 170cm) is 68cm in length from tip to tip, and 74cm along the arc, almost identical to that of the seals from Sippar and Kish. The brace height of the Darband relief is lower, at 13cm (table 7.1). In contrast, the bow in the Tar Lunni relief is proportionately longer, with a length of 116cm from tip to tip, and 129cm when measured along the arc with a brace height of 16cm. This places the bow above the median average of the composite bow artifacts from the tomb of Tutankhamen (111cm), but is comparable in length to a larger number of existing artifacts than the shorter length displayed by the Sippar and Kish seals and Darband relief (McLeod, 1970, pp. 8-10).

Table 7.1 Angular Bows: 2300-1850 BCE*

Figure	Name	Date (BCE)	Bow Depiction	Bow Length (tip-to-tip)	Bow Length (along the arc)	Brace Height
7.21	Sippar Seal	1850	Brace	73cm	83cm§	28cm
7.22	Kish Seal	2334-2193	Brace	70cm	74cm	19cm
7.23	Darband Relief	2200	Brace	68cm	74cm	13cm
7.24	Tar-Lunni Relief	2250	Brace	116cm	129cm	16cm

* Based upon a figure height of 170cm (not including height provided by headwear).
§ Length is likely an overestimation due to the depiction of unrealistically high brace height.

Taken together, these four images show a continuation of the angular bow profile from New Kingdom Egypt to approximately 2300 BCE in Mesopotamia, at which point evidence for this particular design ends. While the two rock reliefs are both Akkadian with regard to styling and composition, at least one of these works (Tar Lunni) is definitively not Akkadian, and the other remains in question. The lack of earlier evidence for bows with an angular profile potentially implies that it was a recent innovation to the region, but as the origins of the monumental works remain in question, it also could mean that the angular profile was perhaps either more popular with or originated from an outlying ethnic group such as the Lullu. All of the examples however correspond to lengths of actual physical artifacts of identical profile from New Kingdom Egypt, starting shortly after the Hyksos invasion, thereby providing supporting evidence for the validity of the initial analysis and all are of a length consistent with composite construction (Betteridge, 1995, p. 34).

DOUBLE-CONCAVE PROFILE: WORKING RECURVE DESIGN, 2400-1900 BCE

Attention now turns to bows with a double-concave profile. The bows presented herein tend to show some amount of variation. In some cases, such as the Annubanini relief (2000-1900 BCE), it is likely that the bow shows an exaggerated curvature in the handle, resulting in a very high brace height. In others, such as the Naram-Sin stele, substantial ears are present, and as discussed previously within the current chapter, it is likely that this represents a working recurve design, wherein the ears gradually come into line with the rest of the bow limb as the draw progresses.

The most recent examples from Mesopotamia or Elam for the period under investigation include the monumental bas-relief of Annubanini at Sar-i-Pul (2000-1900 BCE) and the so called “Adda” cylinder seal from Sippar (2200-2159 BCE) (Hamblin, 2006, p. 92; Barnett and Wiseman, 1960, p. 88; De Lapérouse, 2003, pp. 213-4). Both images (figures 7.25-26) show a shallow degree of recurvature at the limb tips compared to earlier examples of working recurve bows, and a high brace height compared to bow length (Hamm, 1993, p. 171). Both depict a compositional variation of the “victory” pose reminiscent of the Naram-Sin stele, with a king or god as an archer presenting captured foes to a deity. The bows in both images are held in the left hand, with left arm bent and one leg forward and slightly raised. Stylistically however, the images vary significantly. The figures in the Annubanini relief have limbs comparable in thickness to the Naram-Sin stele, but the clothing has an unusual “layered” appearance. In contrast, the Adda seal has the stretched detailed previously in the cylinder seal from Kish (figure 7.22) and vertical folds to the clothing, although the god the left also features clothing with a layered appearance in addition to the vertical folds (Amiet, 1980, pl. 410; Ghirshman, 1954, p. 55).

The proportionality of tip to tip, arc lengths, and brace heights of the bows are similar to each other, but the Adda seal is longer. The bow depicted in the Annubanini relief measures 83cm from tip to tip, and 113cm along the arc, an unnaturally large difference more typical of Egyptian art when presenting bows at full draw. The resulting brace height (distance from the interior of the handle to the string) is correspondingly high at 34cm. The Adda seal has a tip to tip length of 114cm, a length of 144cm along the arc, and brace height of 32cm. While the tip to tip lengths bow fall within the range both of other artwork from Mesopotamia and Elam, the brace heights are unnaturally high, calling the accuracy of both of these images into question.

Figure 7.25 Annubanini relief, Sar-i-Pul, 2000-1900 BCE.

Figure 7.26 Adda Seal Impression (cropped), Sippar, 2200-2159 BCE.

The uniquely deep curvature in the handle of these two images may represent a transitory period where earlier representations with longer ears have begun to be replaced by bows with a more angular profile with and that these images are potentially an attempt at imitating the earlier, and perhaps by that point, anachronistic (and hence less familiar) style. While this explanation could potentially explain the inaccurate representation in both of these images, it remains conjectural without further examples of artwork to draw from. What can be said is that immediately prior to this, bow representations undergo a shift toward longer ears as seen on the Naram-Sin stele, and that by the time both of these images were made bows with an angular profile had begun to appear, a style that eventually came to be the accepted standard for composite construction in later New Kingdom Egypt as well as within Mesopotamia during the Hittite empire (1600-1180 BCE) (Rausing, 1967, pp. 38-9; Betteridge, p. 1995, p. 33).

A comparison can be seen in the Kalki and Lugal-Sha seals (figures 7.27-28), both of which show substantially longer ears. The Kalki seal in particular remains in virtually pristine condition and shows a high level of naturalistic realism, with differing styles of hair and beards (Collon, 2005, p. 148). Early interpretations of the seal presumed that the warrior (shown with bow) was the leader and that the scene represented an “expedition” (Layard, 1853, p. 538; Ward, 1910, p. 140). Later investigations however revealed that the owner of the seal was Kalki, a scribe and servant of Ubil-Eshtar, who in turn was "brother of the king (Sargon)" (Nigro, 1998, p. 94; Collon, 2005, p. 148). This revised interpretation puts the central figure, which all the other figures are facing, as the leader indicating that the figure would likely be Ubil-Eshtar. Relative length indicates a bow length of 98cm measured from tip to tip and 112cm along the arc. Brace height is a very reasonable 18cm.

Like the Kalki seal, the Lugal-Sha seal also presents a bow with a double-concave profile and pronounced ears, this time depicted at partial draw (Collon, 2005, p. 183; Hamblin, 2006, p. 93). The figure of a god (note the single pair of horns) is shown kneeling in the process of shooting a bull (Ornan, 2004, p. 96; Hundley, 2013, p. 72). The styling is less realistic than the Kalki seal, but identical to both the Adda and Sippar seals, with a thin, stretched figure appearance.

Figure 7.27 Kalki seal impression (cropped), Akkad, 2200-2159 BCE.

Figure 7.28 Seal Impression inscribed "Lugal-Sha" (cropped), 2334-2193 BCE

Unlike most other works of art from the period, the bow appears somewhat asymmetric with a distinctly longer upper limb, although this could potentially be due to the layout of the scene, as making the lower limb of the bow longer would mean that it would overlay the right leg at the knee. Rather than deal with the difficulties involved with overlapping detail, the artist may very well have consciously chosen to shorten the lower limb and/or ear, but could also indicate foreshortening, as the bow would be held at an angle such that the lower limb passed to the outside of the right knee (Wilkinson, 1991, pp. 90-1). The bow also shows significant curvature in the handle like the Annubanini relief, and unlike the Rimush stele described in the iconography section, the ears appear to be much more “static” meaning that they have partially bent in-line with the remainder of the bow limbs, but not as much as expected given the draw length shown. Relative measurement for the Lugal-Sha seal, again assuming a figure height of 170cm, yields a bow length of 79cm measured tip to tip at partial draw (likely equating to a tip to tip length of 85cm at brace), with a length along the arc of 105cm, consistent with the relative size of other works of the period, and strongly indicative of composite construction; estimation of brace height is impossible given the fact that the bow is shown at either full or partial draw.

Figure 7.29 Cylinder seal impression (cropped), Akkadian, 2334-2193 BCE.

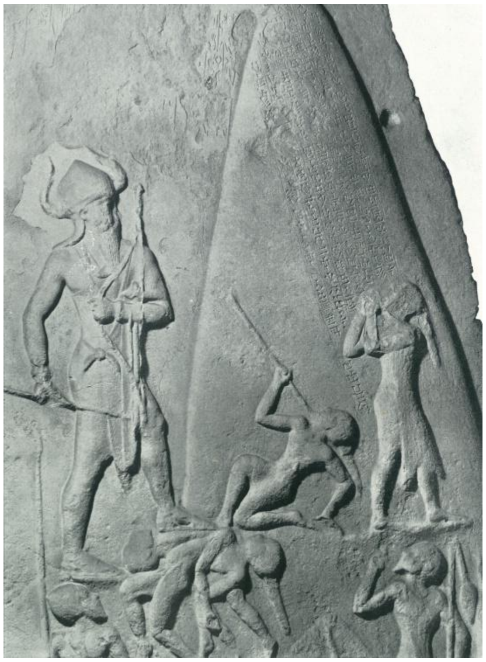


Figure 7.30 Naram-Sin stele, upper register, 2254-2218 BCE.

The presentation of a double-concave profile with pronounced ears continues in four additional works until approximately 2400 BCE, two large and two small. While working recurve bows in the modern day typically have less pronounced ears, the longer ear design would still be highly functional. The first of these depictions is another hunting scene is depicted in figure 7.29. Unlike most art form Mesopotamia and Elam, the figure notably does *not* take up the entirety (or nearly the entirety) of the register (Kantor, 1966, p. 174).

Like the Lugal-Sha seal, it too shows a hunter in a kneeling position, and while the impression is quite faint, it also bears the distinctive stretched appearance common to the Akkadian empire (Collon, 2005, p. 155; Hamblin, 2006, p. 93). In contrast to the Lugal-Sha seal, the limbs are shown almost completely straight, making it look as if the bow only bends in the handle. While some bend in the handle is possible with certain bow designs the degree of flex shown in here, if it were truly confined only to the grip would be highly inefficient compared to a bow which bends along the length of the limb, and would potentially tax the materials strength of even composite construction. This particular profile however is a match to the bow shown in the middle register of the Rimush stele (figure 7.32) as previously mentioned, lending strong support to the possibility that the bow in question is of a working recurve design shown at full (rather than partial) draw (Hamm, 1993, p. 171).

The bow itself measures 92.5cm along the arc. No trace of a string can be seen, but a measurement from upper tip to the figure’s right hand and back to the lower limb tip indicates a length of 121cm. While this is comparable in length to a number of bow artifacts from New Kingdom Egypt, it is a mismatch when compared to the along the arc length in the same manner as discussed in Egyptian artwork show at full draw as discussed previously in Chapter Five (McLeod, 1970, p. 15). A direct tip to tip measurement while at full draw shows a length that would proportionately equate to 69cm in length. Overall, the measurements present some degree of inconsistency, but no matter if the bow is measured via string length, tip to tip or along the arc, all of the resulting lengths are short enough that they indicate composite construction.

Use of less than the entire register is also seen in both the upper and lower registers of the Naram-Sin stele, in which both bows show identical double-concave profiles with sizable ears. As these bow lengths, as well as that shown in figure 7.29, are consistent with other examples where the figures take up the entire register height, this tends to support the belief that substantial foreshortening was not a regular feature of bow depictions in Mesopotamian and Elamite art.

Depicting Naram-Sin’s victory over the Lullu, the stele was later captured by the Elamite King Shutruk-Nahhunte and taken to the Elamite city of Susa, where it was uncovered during excavations (De Morgan, 1900, pp. 144-5; Amiet, 1976, pp. 29-32). As the Naram-Sin stele is perhaps the best known image under evaluation for the period between 2400-1900 BCE, it has attracted the most attention regarding claims both for and against composite construction, again up to this point based exclusively on the basis of its profile (Yadin, 1963, p. 150; Rausing, 1967, p. 83; Gabriel and Metz, 1991, p. 9; Hamblin, 2006, p. 86; Gabriel, 2007, p. xiv).

The bows are nearly identical in length, showing a high degree of consistency, with the bow carried by Naram-Sin having a tip to tip length of 101cm, or 110cm along the arc and a brace height of 17cm. Length of the bow in the lower register takes some computation. First, the length of the badly worn but still visible ear (circled, figure 7.31) was included in the length of the upper limb, which was measured from the top of the worn tip to the middle of the forearm. This length was then doubled to determine the length of the entire weapon. The resulting figures show that, again assuming a figure height of 170cm, that the bow in the lower register would have a tip to tip length of 106cm, an along the arc length of 111cm, and a brace height of 17cm.

Hamblin performs his own evaluation of bow length for the Naram-Sin stele, but restricted his efforts to the bow presented in the upper register, and came up with nearly identical figures – a bow length of 95cm (as opposed to 101cm for the author), with the variation owing to differing assumptions in figure height (Hamblin, 2006, p. 92). Hamblin however confines his analysis largely to an evaluation of profile consistency, and does not make further use of his measurements.

The bows depicted on the Rimush stele from Tello continue the depiction of nearly identical bow profiles (figures 7.32 and 7.33), with the middle register mating the profile of both the Akkadian seal shown in figure 7.29 (also at full draw) while what is left of the bows in the top register appear identical to the Naram-Sin stele, Kalki and Lugal-Sha seals which are shown at brace (Feldman, 2007, p 278; Nadali and Verderame, 2005, p. 316). Dating on the Rimush stele varies, the most conservative dating (used herein) is between 2244-2236 BCE, but the stele has also been dated to between 2415-2290 BCE (Moortgat, 1969, pl. 117; Wallenfels, 2003, p. 201).

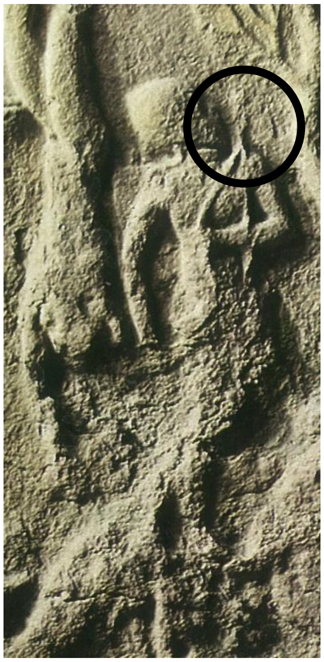


Figure 7.31 Naram-Sin stele, close up of archer, lower register, 2254-2218 BCE.

Figure 7.32 Rimush Stele, Tello, 2244-2236 BCE.

Measurements for the bow in the middle register are easier to determine than those in the upper register, as it has suffered less damage, and shows an along the arc length of 126cm. String length, like that depicted in figure 7.29, is exaggerated, at 123cm again matching the exaggerated length shown in Egyptian art from both the New and Middle Kingdoms. Tip to tip length is 82cm, and brace height is of course impossible to determine as the bow is shown at full draw.

The figures in the upper register have been very heavily damaged as can be seen in figure 7.33 (Nigro, 2003, p. 72). Only by taking details from both figures and combining them can an estimate of lower limb length be made, with the figure on the left providing detail on details on the extended limb tip, while in the figure on the right provides (faint) detail of hand and arm positioning, allowing an estimate of bow midpoint to be made. Taken together and using proportional anatomy to estimate total figure height, these details would yield an estimated bow length of approximately 99cm when measured tip to tip and a brace height of 16cm. This figure is particularly interesting when compared to the measurements gathered from the bow in the middle register, as it lies almost exactly at the mid-point between the tip to tip length measured while at full draw (82cm), and the length of the string (123cm). As a means of crosschecking potential iconographic error it is imprecise, but the results are nevertheless indicative that a tip to tip bow length (corresponding perhaps to an along the arc length of 110cm) is a realistic average. It is also almost exactly equal to the measurements of the bows shown in the Naram-Sin stele.

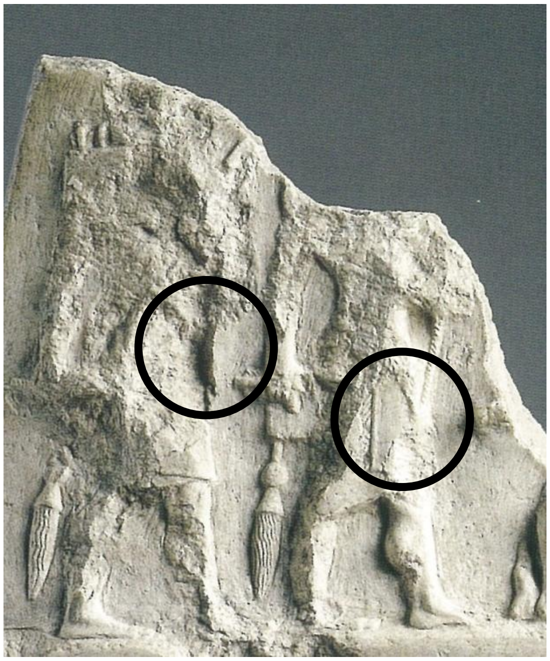


Figure 7.33 Rimush Stele, top register, Tello, 2244-2236 BCE.

Looking at the data provided from these works as a group (table 7.2), and comparing them to those of the previous section (table 7.1) several trends become evident. First is that while both angular and double-concave profiles co-existed for some time, it appears that there was a general transition from bows of a double-concave profile (with a working recurve design) to bows with an angular profile between 2400 and 1850 BCE. Further, the proportional lengths of all of the examples presented in both tables 7.1 and 7.2 are significantly less than the length of 150cm determined (within the limitations previously outlined earlier in the chapter) to be indicative of composite construction. The longest proportional example is the 144cm along the arc length given for the Adda seal, which has already been determined to have an unrealistically high brace height, indicating that the length as measured from tip to tip (114cm) is likely more accurate. While the double-concave profile continues to be seen well into the fourth millennium BCE for Mesopotamia and Elam, sometime at or near 2400 BCE the iconography shows a significant shift in bow design as discussed below.

Table 7.2 Double-Convave Bows: Working Recurve Design, 2400-1900 BCE*

Figure	Name	Date (BCE)	Bow Depiction	Bow Length (tip-to-tip)	Bow Length (along the arc)	Brace Height
7.25	Annubanini Relief	2000-1900	Brace	83cm	113cm§	34cm
7.26	Adda Seal	2200-2159	Brace	114cm	144cm§	32cm
7.27	Kalki Seal	2200-2159	Brace	98cm	112cm	18cm
7.28	Lugal-Sha Seal	2334-2193	Brace	79cm	105cm	N/A
7.29	Akkadian Seal	2334-2193	Full or Partial Draw	N/A	92cm	N/A
7.30	Naram-Sin Stele (upper register)	2254-2218	Brace	101cm	110cm	17cm
7.31	Naram-Sin Stele (lower register)	2254-2218	Brace	106cm	111cm	17cm
7.32	Rimush Stele (middle register)	2244-2236	Full Draw	N/A	126cm	N/A
7.33	Rimush Stele (upper register)	2244-2236	Brace	99cm	N/A	16cm

* Based upon a figure height of 170cm (not including height provided by headwear).
§ Length is likely an overestimation due to the depiction of unrealistically high brace height.

DOUBLE-CONCAVE PROFILE: STATIC RECURVE DESIGN, 3800-2400 BCE

A number of sources available for the period prior to 2400 BCE have survived in Mesopotamia and Elam. Unlike later periods however, the works tend to be smaller in size - the largest being the Lion Hunt stele. The remaining sources consist of cylinder seals from both Uruk and Susa, a number of *bullae* from Susa, and an incised plaque from Mari. Throughout this period works continue to present a double-concave profile albeit in a different style, and many of the sources depict the bow string crossing the limb tips, as seen in figures 7.34-5, 7.38, and 7.41-44.

Chronologically, the most recent of the works for the period is the incised plaque from Mari (figure 7.34) which dates to between 2500-2250 BCE, and was recovered during the early 1930's as part of the excavations done by Parrot (Parrot, 1971, p. 269; Margueron, 2003, p. 137). The image depicts an archer about to fire from behind a large pavise with an inward curving top, held by a shield-bearer. A third figure, presumably dead, accentuates the scene. Thus far, only two authors have expressed an opinion with regard to bow construction, with Hamblin questioning the lack of analysis to date by scholars which support an early development date of composite construction (Hamblin, 2006, p. 218). In contrast, Miller supports the likelihood that is shows a bow of composite construction (again based upon bow profile), but the main focus of his work is on the depiction of the arrow, which he believes may be the first recorded use of a fire arrow

(Miller, 1982, pp. 10-11). If correct, it would help explain the vertical portrayal of the arrow, such that it would not set either the bow or string alight by accident.

Figure 7.34 Stone plaque, Mari, 2500-2250 BCE.

Figure 7.35 Limb tip partially protruding through elongated nock loop.

The bow is clearly double-concave in profile, but differs significantly in style from earlier works, with ears that curve outwards (as opposed to straight, as seen in the Naram-Sin stele) even while at partial draw. Additionally, like the Lugal-Sha seal described earlier, the bow string appears to be overly long compared to the amount of curvature shown by the bow limbs, which present a profile indicative of brace. Indeed, the bow string does not in fact appear to connect directly with the limb tips, but instead crosses to the *outside* of the limb first, a feature that is common in the works for this period. This feature is unique to some static recurve designs (with unbending ears) when used in combination with long nock loops, such that it would allow some portion of the ear within the loop as seen in figure 7.35 (Pavlović, 2013, p. 52). At a lower brace height significantly more of the ear would protrude until the nock loop met the point at which the ear meets the working portion of the limb (the portion wrapped in brown cordage, figure 7.35).

The bow in the Mari Plaque is partially obscured by both the pavise and shield-bearer. Using the hand as the mid-point of the bow and measuring outward to the one visible tip, doubling the result and comparing it to the height of the archer shows a bow length of 81cm when measured from tip to tip and 99cm when measured along the arc, with an unrealistically low brace height of 4cm. This estimate of brace height makes the assumption that the bow at brace would normally have a taut string, but the bow string as depicted in the Mari plaque, if accurate, would have some degree of slack.

The actual use of a slack string is not only highly inefficient, but presumes that the bow would have identical profiles both when unstrung and at brace. The use of an overly long string is of course possible, but would reduce the amount of stored energy at any given draw length considerably. Additionally, the use of long nock loops which could result in the bow string crossing the limb as shown in the Mari plaque would only occur in a taut string while at brace, as an overly long string would immediately pull away from the bow limbs, rather than cross them (Baker, 1992, p. 48; Anglim et al., 2002, p. 13; Rausing, 1967, p. 17). In consideration of these points, the conclusion then is that the depiction of an overly long string on the Mari plaque and other works is almost certainly an artistic convention.

While computation of proportional measurement is not problematic given the presentation of the full figure of the archer and almost complete depiction of the bow, several features in the body call into question the proportional accuracy of the scene as a whole. Most notably, the positioning of the right arm and hand is unnatural. The left arm drawing the bow is correct for an archer with a left hand draw positioned for an upward shot, but the right hand is shown with a pronated, rather than a supinated grip. Additionally, the arrow itself is positioned at the bottom, rather than the top of the hand. Furthermore, the presentation of the bow in an overhead position, such that it protrudes significantly above the height of the figure, increases the likelihood that the image has been subjected to some degree of foreshortening. Taken together, the proportional measurements are potentially unreliable. As such, while the proportional lengths for the image can potentially be of value to *confirm* measurements in a preexisting set of data, they should be excluded from an initial formation of a data set, and have been noted as such in table 7.3.

Other works for the period are more realistic with regard to string attachment, as can be seen in figure 7.36, showing an anthropomorphic lion in a hunting scene (Collon, 2005, p. 192, Amiet, 1972, pl. 1014; Roach, 2008, pl. 1063). Unlike the Mari plaque or the Susa *bullae* (detailed later herein in figures 7.41-4), the Lion seal has comparatively smaller recurved limb tips. Even more importantly however, the point of attachment of the string to the bow is to the limb *tips*, and does not cross the bow limbs, making it in this regard a more accurate portrayal, as does the minor detail of wedge-shaped arrowhead typical of stone points from both Egypt and Mesopotamia for the period (Spalinger, 2009, p. 20; Wilkinson, 2003, p. 96).

The string is again overly long, but bow itself is shown with a degree of bend which indicates that unlike the Mari plague, it is not at brace. Bow profile would normally be impossible to determine at draw, but the unbending recurved tips indicate that at brace it would have a double-concave profile (albeit lacking the set-back grip seen in figure 7.34). Additionally, the bow is unrealistically thick in the handle, a feature also shared in the Lion Hunt stele (figure 7.37). Proportional measurement based as always on a 170cm figure height yields a bow length of 130cm measured tip to tip and 142cm along the arc.

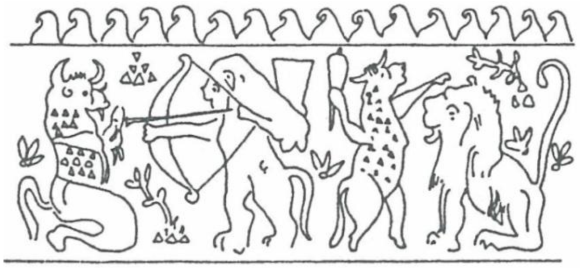


Figure 7.36 Lion seal sketch, Susa, 3000-2400 BCE.

Figure 7.37 Lion Hunt Stele, Uruk, 3250-3000 BCE.

The bow shown on the Lion Hunt (or Warka) stele closely resembles that of the Lion seal, with comparatively smaller hooked limb tips and overly thick bow, but also has features similar to the Mari plaque, with a string attachment point at draw at a position low on the bow limbs (closer to the grip). The stele, which was excavated during the 1933/34 excavation season dates to between 3250-3000 BCE, and depicts a lion hunt with either two separate figures or perhaps a single figure twice; once killing a lion with a spear, once with a bow (Basmachi, 1949, p. 87). The imagery has been interpreted as a "priest-king" shown in the role of a defender or protector, a theme common to Mesopotamian art through the period (Breniquet, 1992, p. 72; Hansen, 2003, p. 23).

Hamblin makes no particular claim with regard to the bow depicted on the Lion Hunt stele, but Rausing claims that the relative length of the bow is "much too much for the bow stave to have been a simple one" in conjunction with the length to which the bow is drawn (Rausing, 1967, p. 82). The bow is shown at full draw, but the unbending limb tips again allow identification of bow profile at brace as double-concave. String length is not overly long, but is shown as an arc, rather than an angle formed at the point of draw, a detail likely done to ensure that the figure’s face remains unobstructed (Wilkinson, 1991, pp. 90-1). Brace height is impossible to determine as the bow is at draw, but proportional measurement indicates that the bow would have a length of 115cm from tip to tip, and 135cm along the arc.

Other works from the period prior to 2400 BCE show variation with the double-concave profile, with individual features largely depicting a mixture of influences that can be matched to either the Mari plaque or the Lion seal. A new feature can however be discerned in figure 7.38. The image is a seal from Uruk, dating to between 3300-3000 BCE. Both Collon and Wallenfels mention the seal briefly, stating dates and the fact that it represents a hunt, making the present study the first in-depth investigation of the work (Collon, 2005, p. 155; Wallenfels, 2003, p. 23). Like the Mari plaque, the bow string in the Uruk seal touches the bow on both the upper and lower limbs significantly closer to the handle than would normally be expected. Both bows are similarly shown with recurved tips that bend outward even at draw, and both depict identical double-concave profiles with set-back grips.

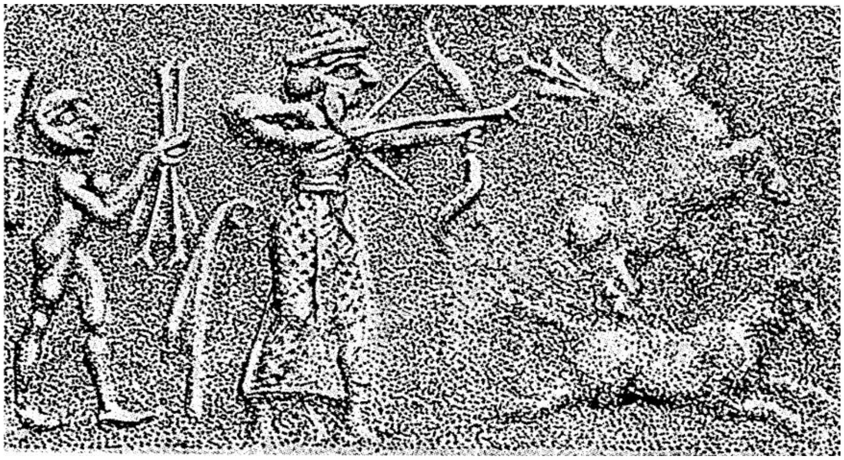


Figure 7.38 Seal impression of hunt (cropped), Uruk, 3300-3000 BCE.

Unlike the Mari plaque however, and indeed unlike any of the works surveyed thus far in the analysis, the depiction of the bow in the Uruk seal appears to vary in thickness. The profile begins narrow in the handle, and then rapidly widens as the limbs progress outwards, then narrowing again toward the limb tips. If the bow follows standard artistic conventions for both Mesopotamia and Egypt, this would indicate variations in bow thickness (Benzel et al., 1998, p. 43). As a bow design however, the resulting weapon would only bend at the very tips and in the handle, and almost certainly lead to breakage at the grip. Given that a literal interpretation of the variance in bow limb dimensions as thickness would result in a non-functional weapon, an alternative explanation is that the artist was attempting a partially oblique perspective, and that the image is intended to convey differences in limb *width*. While such a design would require the use of wood with larger dimensions, it is an efficient design that can be seen in the Mere Heath artifact, the Sudbury Bow and modern recurves, including the composite bow used herein for the materials testing in section of Chapter Six (Herrin, 1993, p. 64; Soar, 2005, p. 5; Allely and Hamm, 1999, p. 34).

Again, like the Mari plaque, the bow is shown in a position consistent with being at brace despite the depiction that it is at full draw. Proportional measurement shows that the bow would have a tip to tip length of 98cm or 107cm along the arc. Brace height was measured on both limbs from the point of recurvature closest to the archer rather than tip to tip, as this would allow for the string to lay aside the limbs (in the case of large nock loops and narrow, stiff ears) resulting in a brace height of 14cm.

Evidence for a design with flat, wide-limbs continues in figures 7.39-40, which depict a siege and a bowyer’s shop, respectively. The Siege seal (3300-3000 BCE, city wall cropped) is mentioned by Hamblin as an early depiction of a Priest-King shooting his enemies, but neglects to mention the fact that both Collon and Amiet, the two authors who previously catalogued this particular seal, describe the bow on the basis of its profile as composite (Hamblin, 2006, p. 93; Collon, 2005, p. 162; Amiet, 1972, pl. 695). Although the upper limb of the bow is damaged, the profile is clearly double-concave with a set-back grip with variations in limb width. Again, like the Uruk seal and Mari plaque the bow is shown without the expected curvature for being at partial draw. Proportional measurement indicates that the bow has a tip to tip length of 128cm, and a length along the arc of 151cm, a length which would make non-composite construction possible. Brace height is impossible to determine as the bow is shown at draw.

Figure 7.39 Siege seal sketch (cropped), Susa, 3300-3000 BCE.

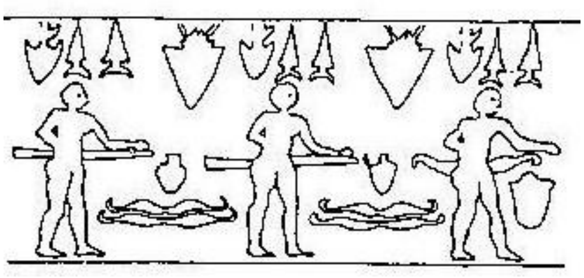


Figure 7.40 Bowyer’s seal sketch, Uruk, 3500-3000 BCE.

The Bowyer’s seal shown in figure 7.40 (3500-3000 BCE) provides the strongest support for flat, wide-limbed construction shown previously. The four (presumably completed) bows shown in the lower portion of the seal are not held in hand, and as such their measurement *vis-à-vis* the figures is questionable, as unattended objects are often not depicted proportional in size in Egyptian and Mesopotamian artwork, and instead are made to fit the scene. Both Hamilton and Collon mention this seal; Hamilton describes the shape of the bows and their unstrung profile, concluding that they are likely to be of self construction while Collon provides dating information (Collon, 2005, p. 163; Hamblin, 2006, p. 90).

Hamblin’s determination of self construction is based again on an evaluation of bow profile – in this case focusing on the fact that if the bows had a sinew backing they would show a significant degree of reflex when unstrung (Hamblin, 2006, p. 90). While correct in essence, physical testing in Chapter Six showed that the amount of reflex is not in fact significant unless the bow is intentionally pulled into reflex prior to the application of the sinew, or unless numerous layers of sinew were applied in succession and allowing each layer to dry completely prior to the application of the next layer. Chapter Six also showed that the primary benefits of composite construction are twofold – one, correctly identified by Hamblin is bow reflex. The other is the ability to decrease bow mass by shortening the bow. In such a case, a single layer of sinew would be adequate to prevent bow breakage, but would *not* result in a highly reflexed profile when unstrung. This means that while a highly reflexed bow with no string would strongly support the notion of composite manufacture, the lack of reflex does not necessarily preclude it. Indeed, if composite manufacture had only recently been discovered, then the development of a highly reflexed design would have required some degree of experimentation. In contrast, the increased durability would be readily apparent to an archer when a bow is inadvertently subjected to abuse. Personal experience by the author has shown that, barring a limb reversal (figure 4.2), the application of a single layer of sinew has minimal impact on limb reflex, but makes the bow virtually immune to failure under tension (Hamm, 1992b, p.213; Comstock, 1992, p. 233).

The limb tips of the Bowyer's Seal are similarly compatible with the other works in the current section also of double-concave profile. All four of the bows in 7.40 rapidly narrow as the limbs progress past the mid-point towards the tips. In combination with long nock loops, the recurved tips result in a double-concave profile when strung, and would allow at least a portion of the recurved tips to protrude behind the string in a manner consistent with both the Mari plaque and the Susa *bullae* (figures 7.41-4).

The four remaining images for the period all show this same feature wherein the bow string crosses to the outside of the limb in a manner consistent with extended nock loops and static recurve design, and have a double-concave profile (with no set-back in the handle). The collected images are all *bullae* recovered from Susa, and date to between 3800-3100 BCE (Roach, 2008, pp. 76-7). This is the first time any of these images have been analyzed in detail, but the existence of multiple *bullae*, each bearing the imprint of multiple bows supports the possibility that archery formed an important part of Elamite warfare as early as the fourth millennium BCE (Schneider, 1952, p. 73). Unlike the Uruk seal, none of the Susa *bullae* show an attempt at depicting an oblique perspective. The bows in figure 7.44 however do show a level of slackness. While the depiction of loose bow strings in theory could be matched to the Mari plaque and the Uruk seal, which show little or no curvature in their bow limbs despite being at either full or partial draw, the images in the three remaining *bullae* tend to dissuade this notion, as they have bows held in hand (at brace) and have taut strings. As such, bows in the *bulla* shown in figure 7.44 most likely are not intended to depict bows at brace, but rather bows at rest but with strings loosely attached (Baker, 1992, p. 49).

All of the *bullae* clearly show the bow strings attached to the limb tips, which then cross the bow limbs. In all of the cases where sufficient detail remains, the bow string is shown crossing *behind* the bow limb. While the potential for extended nock loops to allow a portion of a narrow limb tip to protrude has already been discussed, this would require that the bow string cross the limb tips on *both* sides. Having a string cross a bow limb to only one side however is heretofore unknown;

the *bullae* remain the first documented examples of such imagery, but as the crossing of the bow string on only one side would be highly unstable in use, this particular detail should be considered an artistic convention rather than an accurate portrayal.

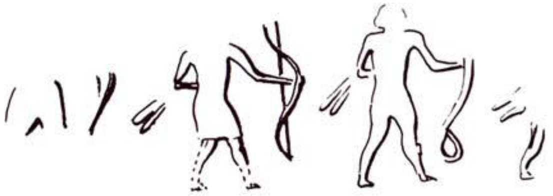


Figure 7.41 *Bulla* sketch, Susa, 3800-3100 BCE.

Figure 7.42 *Bulla* sketch, Susa, 3800-3100 BCE.

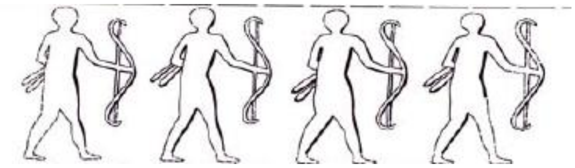


Figure 7.43 *Bulla* sketch, Susa, 3800-3100 BCE.

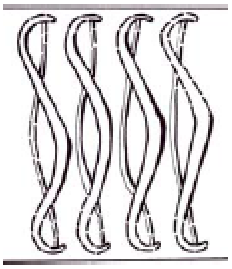


Figure 7.44 *Bulla* sketch, Susa, 3800-3100 BCE.

Proportional measurement is not possible for all of the bows shown in figures 7.41-44. Most notably, length estimates for the bows depicted in figure 7.44 are impossible, as the *bulla* in question does not show a figure which the bows can be measured against. Similarly, the *bullae* in figures 7.41-2 have been damaged such that insufficient detail remains to accurately measure all of the figures and bows. That being said, enough detail remains that bow length can be determined for one or more of the bows depicted in each of the *bullae* shown in figures 7.41-3.

For figure 7.41, the bow held by the middle figure proportionately measures 81cm from tip to tip or 91cm along the arc, and has a brace height of 16cm. In the same image, the figure on the right however holds a bow 164cm in length tip to tip and an along the arc length of 245cm. The discrepancy between these two figures is almost certainly exaggerated as the lower limb tip curls completely back on itself. Brace height is impossible to gauge as no string is shown, but the figure sports a bow length that, like the Siege seal, would not require composite construction.

In figure 7.42, the figures are all damaged, and additionally are all slightly different in height. Proportional measurement from shoulder to knee (or shoulder to waist in the case of the fourth figure from the left) was performed so that proportional measurements for each bow continue to be based on the assumption of a figure height of 170cm to ensure consistency. Starting from the left, the first bow has a tip to tip length of 109cm or 113cm along the arc, with an unrealistically low brace height of 6cm. The second bow has a tip to tip length of 85cm, a length along the arc of 100cm and a higher, but still low brace height of 11cm. For the third figure from the left, the bow proportionately measures almost identically to the second figure, with a length of 86cm from tip to tip, 101cm along the arc, and an 11cm brace height. The fourth figure from the left holds with more pronounced curvature, and has a length of 93cm from tip to tip, 109cm along the arc, and a brace height of 7cm. The final figure on the right is shown holding a bow which proportionately would be 97cm from tip to tip, 121cm along the arc, and a brace height of 10cm.

The imagery shown in figure 7.43 is remarkably consistent, with only minute variations in figure height and bow length. As such, they shall be presented as a single entry representing four bow images. Each of the four figures holds a bow with a double-concave profile in their right hand held forward, while the left hand (reserved) holds a pair of arrows. Each of the bows has a tip to tip length of 121cm, a somewhat exaggerated along the arc length of 170cm, and a brace height of 14cm.

Additionally, the degree of curvature of the limb tips in all of the *bullae* is somewhat exaggerated. The limb tip of the figure on the right in figure 7.41 is a clear example of this phenomenon, to the point that it curls back onto itself. Finally, while the use of long nock loops and deep, unbending static ears could account for some degree of protrusion, as seen in figure 7.35, the degree of protrusion shown in figures 7.41-4 is most likely magnified to some degree.

Taken together the proportional measurements, shown in table 7.3, continue to indicate that composite construction was commonly expressed in the iconography of the time and region. Both the Siege seal and the bows shown in figure 7.41 however are of a length that would *not* require the use of composite construction. The bows depicted in figure 7.43 are similarly long, making self construction a possibility there as well. The evidence for the period between 3800-2400 BCE then supports the notion that composite construction was likely introduced to the region at some point during this range of time, and that at some point prior to the end of the fourth millennium BCE composite construction was not yet fully assimilated into the iconography of the region. It should be noted that adoption of composite construction into iconography does not necessarily equate to the complete abandonment of self construction. Indeed, bows of self construction continued amongst the elite of New Kingdom Egypt centuries after the adoption of composite technology, and it is likely that Mesopotamia and Elam were the same (McLeod, 1981, p. 38).

Table 7.3 Double-Concave Bows: Static Recurve Design, 3800-2400 BCE*

Figure	Name	Date (BCE)	Bow Length (tip-to-tip)	Bow Length (along the arc)	Brace Height
7.34	Mari Plaque	2500-2250	81cm§	91cm§	N/A
7.36	Lion Seal, Susa	3300-2400	130cm	142cm	N/A
7.37	Lion Hunt Stele	3250-3000	115cm	135cm	N/A
7.38	Uruk Seal	3300-3000	98cm	107cm	14cm
7.39	Siege Seal	3300-3000	128cm	151cm†	N/A
7.40	Bowyer's Seal	3500-3000	125-137cm§	N/A	N/A
7.41	*Bulla* Sketch (middle figure)	3800-3100	149cm	174cm†	16.2cm
7.41	*Bulla* Sketch (right figure)	3800-3100	164cm†	245cm†	N/A
7.42	*Bulla* Sketch (leftmost figure)	3800-3100	109cm	113cm	6cm
7.42	*Bulla* Sketch (second from left)	3800-3100	85cm	100cm	11cm
7.42	*Bulla* Sketch (third from left)	3800-3100	86cm	101cm	11cm
7.42	*Bulla* Sketch (fourth from left)	3800-3100	93cm	109cm	7cm
7.42	*Bulla* Sketch (rightmost figure)	3800-3100	97cm	121cm	10cm
7.43	*Bulla* Sketch (all figures)	3800-3100	121cm	170cm†	14cm
7.44	*Bulla* Sketch (rightmost figure)	3800-3100	N/A	N/A	N/A

* Based upon a figure height of 170cm (not including height provided by headwear).
§ Bow lengths are estimates.
† Bow length sufficient to *not* require composite construction.

CONCLUSION

The works reviewed in this chapter represent the most complete collection to date of archery-related images for Mesopotamia and Elam during the third and fourth millennium BCE. Arranged as they are both by profile and in reverse chronological order, a number of trends can be identified. First and foremost, the period between 3800-3100 BCE appears to represent a transitional period during which the adoption of composite construction into the region's iconographic tradition was nearly complete, as can be seen by the mixture of mostly shorter weapons less than 150cm interspersed by the occasional depiction of longer examples. This tradition of depiction of shorter weapons then continues throughout the third millennium BCE and into the second millennium and beyond. This identification of a point of transition fulfills the fourth and final goal of the thesis and validates the use of proportional length as a viable system of evaluating bow construction so long as it is correctly applied. A great deal of additional information can also be gleaned with a firm understanding of bow design and mechanics as presented in Chapters Four and Six, particularly with regard to details in bow design, and is outlined below.

The bow profile common during this period of transition (3800-3100 BCE) is double-concave, at times with a set-back grip and consists of a static recurve design (with unbending limb tips), the use of wide, flat limbs, and narrow ears in combination with long nock loops, as shown by the recurrent depiction of bow string crossing limb tips. Additionally, the Bowyer’s seal provides evidence that suggests bows of the period did not have a large amount of reflex when unstrung, indicating that the addition of a thin layer of sinew (or other backing material) was used primarily as a means of preventing breakage, rather than as a means to shift unstrung bow profile. This allowed the adoption of a shorter overall length, but also implies that the full potential of composite construction, which combines both shorter bow limbs with limb reflex, had not yet been unlocked. As such, advantages in bow efficiency described in Chapter Six would apply, but the benefits of profile differential potentially would not. Bows of self manufacture certainly existed for a portion of the period, but iconographic expression of these longer weapons was phased out by the end of the fourth millennium BCE.

By the year 2400 the double-concave profile continued, but the static recuve design had by this point or shortly thereafter given way to a working recurve design with long, straight ears which would gradually come in-line with the remainder of the limb as draw progressed. While working recurves in the modern day tend to sport wide, flat limbs it remains uncertain if this particular design feature was carried over from the previous static recurve design or not (Hamm, 1993, p. 171; Baker, 1992, p. 67; Hoyt, 2012, p. 15). Sometime prior to the year 1850 BCE iconographic representations of bows sporting a double-concave profile cease to exist, and were replaced by bows of an angular profile. The last evidence for bows with a double-concave design in Mesopotamia and Elam, which date to between 2000-1900 BCE are poorly proportioned, which could potentially indicate that by this point in time they were less familiar and hence poorly executed in the artwork.

Angular bows make their first appearance in the iconographic record at approximately 2300 BCE, but it remains unclear if this particular design innovation was developed locally or if it was imported from elsewhere. By the time of the Hyksos invasion, this shift to an angular profile and composite construction was accompanied by a change in limb design from wide to narrower bow limbs, and an increased emphasis on limb reflex. The combination of shorter overall length combined with an increased degree of limb reflex further increased potential bow performance such that comparable weapons with a draw weight of between 18-23kg and draw length 73cm or more of both self and composite construction would have shown a range differential of perhaps 45%, as seen in Chapter Six.

CHAPTER EIGHT

CONCLUSION

This thesis was originally inspired by the author’s personal interest in dating the arrival or development of composite technology in Mesopotamia and Elam, and this desire was in part fueled by Hamblin’s assertion that no evidence for the composite bow pre-dates the second millennium BCE (Hamblin, 2006, p. 94). Hamblin’s discourse is certainly both more detailed and utilizes a wider base of source material than any of the proponent works which advocate an earlier point of development, but focuses largely on identifying inconsistencies in existing arguments rather than performing any kind of analysis of his own (Hamblin, 2006, pp. 92-4). In this regard the current effort owes Hamblin a great debt, as he highlighted issues with regard to consistency and profile evaluation that otherwise might have been overlooked.

The initial intention was to utilize the same source material as Hamblin, supplemented by additional sources, and write a counter-refutation as a journal article. As research into the topic of archery progressed, it quickly became clear that the accomplishment of this goal was not possible given the current base of knowledge in the fields of archery, history, or archaeology. In response, the modest task of the initial goal expanded, and expanded again, eventually becoming the four thesis goals stated in the introduction such that it encompassed bow mechanics from both a theoretical and practical standpoint, physical testing, engineering, physics, art history, and the development of a new method of iconographic evaluation of bow-related imagery. These goals specifically entail: (one) the identification and (two) the quantification of variables which account for the improved performance of composite construction, (three) the development of a new methodology by which composite construction could be identified from artwork and (four) the application of this improved methodology to the artwork of Mesopotamia and Elam during the third and fourth millennia BCE.

That this degree of expansion was necessary to accomplish what originally what would have represented a single chapter of the current work says much about the state of archery research as it applies to history, anthropology and archaeology. This is not to say that the field suffers from a lack of data: a bounty of information and source material is available related to archery, including ancient artifacts, texts and iconographic source material, highly technical mathematical modeling, records from archery competitions of various natures the world over and the experience of modern bowyers. Rather, these sources tend to give disparate results that cannot be easily resolved with each other, and in a number of cases appear to be outright contradictory. The thesis shows that this is *not* because these studies were somehow erroneous or poorly designed.

The vast majority are well thought out and executed. Rather, the studies *appear* to provide disparate data because they fail to provide sufficient information such that they can be placed in a larger framework. Indeed, prior to the current thesis such a larger framework did not yet exist and several key points of research remained unexamined and in need of investigation before it could be created.

This is largely understandable when compared to the slightly lager field of armor and weapon studies in the ancient world. Unlike the thrust or cast of a spear, study of the bow and arrow encompasses a wider number of variables which also take into account bow design. This additional level of complexity has resulted in some aspects of bow history and performance being more widely examined than others, leaving several holes in existing research. This has led to a distinct dichotomy within the field: more generalized works typically repeat minimal information with regard to bow performance and iconographic evaluation. In contrast, specialized works provide a wealth of in-depth detail – but much of this information cannot be easily or accurately applied outside of their particular region and time period without a larger framework from which proper context could be drawn. As such, the role of archery in history, anthropology and archaeology has been both highly fractured in its study and exceptionally opaque to the non-specialist. Because of this, scholars whose work touch upon or include archery in an ancillary or tangential fashion have been able to utilize only a fraction of the total amount of information that could otherwise be gleaned if such a framework existed and was easily accessible.

These gaps in the field were substantial: prior to this effort, the specific factors which provide increased performance (as measured in arrow velocity or range) for composite over self construction were essentially guesses unsupported by physical testing, and ranged from increased draw weight, to profile to differences in string mass, to material properties (Gabriel, 2004, p. 27; Kosiorek, 2002, p. 51; Denny, 2007, p. 44). Comparative performance estimates similarly suffered, ranging from 13% to up to 600% (Baker, 1992, p. 115; Anglim et al., 2002, p. 10). Answers to these basic questions were needed, as only with a firm understanding of the reasons for and degree of advantage of composite construction over an otherwise equal bow of self construction could a reliable method of iconographic evaluation be developed.

And an improved methodology was needed, for the *de facto* method iconographic evaluation for bow images was until this point based upon bow profile (Hamblin, 2006, p. 86-87; Yadin, 1963, p. 81; Gabriel, 2007, p. xvi). Originally developed using classical Greek depictions of a “cupid-shaped” bow as a standard of evaluation, this method worked well within a Greco-Roman context, but gives both false positive and false negative results when matched against physical artifacts from other periods and cultures (Hamm, 2000, p. 127; Mason, 2007, pl. lxi; Allely and Hamm, 1999, p. 31). For Mesopotamian and Elamite artwork of the third and fourth millennia BCE, the evaluation of bow profile devolved into individual opinion of how “cupid-like” a given bow representation was, without understanding that bow of any given profile can be made using any given construction method – if made sufficiently long. Rausing was the first scholar to specifically note this deficiency, and was also the first to propose the use of proportional length as a possible substitute (Rausing, 1967, p. 20). Rausing however never refined this new method of evaluation rendering it highly subjective, and prior to the current work it has only been used by one other scholar (Collon, 1983, p. 53).

The current thesis then has attempted to provide a larger, unified framework by filling a number of the gaps in existing research such that a non-specialist can better place specialized data in a larger context, while simultaneously acting as a baseline of knowledge for further research within the field. That being said the research points covered herein, while they are substantial and original contributions unto themselves and essential for an understanding of bow performance in general, were originally designed as stepping stones to enable the accomplishment of the initial purpose: iconographic evaluation of bow-related artwork in Mesopotamia and Elam during the third and fourth millennia BCE. Because of this, not every aspect of bow performance was examined: throughout the thesis both arrow and arrowhead mass and design was rendered constant. In reality both have a significant impact bow performance and effectiveness, a topic that is potentially worthy of a separate doctorate unto itself.

With the thesis goals and main problems within the field identified, the thesis next turned to the issue of nomenclature at the start of Chapter Two, as a number of systems of terminology co-exist with regard to both profile and method of construction. Each of these systems has its benefits and drawbacks, but none are both comprehensive and accurate with regard to their ability to describe the differing shapes and methods of possible manufacture. To address these issues, the thesis uses two entirely new nomenclature systems, one dealing with bow profile, the other with construction method. Of the two nomenclature systems developed, the organization of bow manufacture techniques is by far more important as it defines details that cannot be quickly or easily conveyed pictorially (a technique often used when describing bow profile) (Rausing, 1967, p. 20; Anglim et al., p. 13). Taken together, the new nomenclature systems are the first to provide a complete and accurate descriptive means that can clearly describe any bow of either modern or historic origin using a standardized naming system (Randall, 2015, pp. 44-6).

The new nomenclature systems eliminated descriptive confusion, allowing the thesis to progress to an evaluation of existing research. In particular, the work of modern bowyers working in traditional materials (horn, wood and sinew) were instrumental in understanding bow mechanics on a theoretical level, and also provided some range and velocity examples which could be used on a comparative basis. These range estimates were bolstered by both historical records and world archery championship flight archery (distance) records, and provided a frame of reference for the evaluation of testing performed in Chapter Six (McLeod, 1969, p. 13; World Archery Federation, 2014).

The different claims to potential reasons for improved performance relating to composite manufacture were similarly gathered. Some, including recurrent claims that composite bows inherently have a higher draw weight than a bow of self construction were immediately discounted, as both historical artifacts as well as the author’s personal experience clearly show that bows made with any construction method can be made with a range of draw weights. Judgment on other claims which could not be immediately and decisively discounted was reserved until a theoretical framework of bow mechanics was in place later in Chapter Four.

A survey of experimental archaeology results was done next, and revealed that while armor and weapon studies in the ancient world form a small but thriving niche, the vast majority of these efforts do not focus on bow capabilities (Coles, 1962, p. 185; Gabriel and Metz, 1991, pp. 59, 63; Matthew, 2012, p. 58). Those efforts which do feature bows more prominently do not provide useful data with regard to bow design outside of a narrow context of the culture and period under immediate study (Blyth, 1977, pp. 58-59).

A few select efforts come close to the focus of the current thesis, but these efforts were not designed to evaluate individual design characteristics, and do not test across a range of draw weight, a point which was later discovered to be key to understanding the performance variation of earlier research results (Godehardt et al., 2007, p. 139; Hulit and Richardson, 2007, pp. 58-60; McEwen et al., 1991, p. 82). While these works only skirted the issues under investigation in the thesis, their contribution was instrumental not only in determining the limits of research knowledge prior to the current endeavor but also in developing test design. In short, the review of current research found that while the particular goals of the thesis remained largely uninvestigated, enough research had been done to show that accurate testing of individual aspects of bow mechanics was indeed possible, and that an examination of bow mechanics on a theoretical model would be key to research efficiency as it could be used to identify variables worthy of further investigation.

Chapter Three continued the review of source material, this time focusing on the ancient world. Given the thesis goals of the current work, artifact evidence was the most useful with regard to identifying the differing profiles, methods of construction and distribution of bow use throughout the ancient world. Sadly, no known bow artifacts remain for Mesopotamia and Elam, and chronologically firm evidence for bow of composite construction ends in the ancient Near East and greater Mediterranean regions at the start of New Kingdom Egypt (Griffith Institute, 2004; McLeod, 1970, p. 2; Rausing, 1967, p. 81). Several partial artifacts from Europe dating to the second half of the third millennium are possibly *indicative* of composite construction, but thus far the evidence remains inconclusive. A set of bows identified specifically as being of composite construction from the Pribajkalja region of Siberia which has been varve dated to the end of the third millennium BCE however does exist (Rausing, 1967, pp. 119-20; Michael, 1958, p. 12). In the narrowest sense, this disproves Hamblin’s assertion that there is no conclusive proof of the composite bow prior to the start of the second millennium BCE, but these artifacts may represent a technological anomaly, and are geographically separated from Mesopotamia to the extent that direct contact cannot be proven.

Textual sources from the ancient world provided evidence and context for bow use throughout the ancient Near East, including direct support for the use of bows with different profiles in Middle Kingdom Egypt (Pyramid Texts, 219-220). While some of these sources are at times suggestive, none definitively identifies composite construction prior to the Hyksos invasion of Egypt (Gudea, A: 152-172; Jacobsen, 1987, pp. 395-396; Homer, *Illiad*, 2.4.105; Homer, *Odyssey*, 21.395; Rose, 1934, p. 343). A number of later texts from classical Greco-Roman period do however provide useful range information against which physical testing performed in Chapter Six could be compared (Polybius, 6.31.10-14; Strabo, *Geography*, 14.1.23; Vegetius, *Epitoma rei Militaris*, 2.23).

With a distinct lack of artifact and textual evidence, determination of composite construction for Mesopotamia and Elam therefore falls to an evaluation of iconographic evidence, making the creation of the new method of evaluation not based upon bow profile critical. A number of iconographic sources from the Egyptian New and Middle Kingdoms, Mesopotamia and Elam depicting bows exist. A study of Egyptian iconography showed that art for both the New and Middle Kingdom periods had an established standard of proportion, which was based upon the height of a human figure (James, 1985, p. 13; Benzel et al., 1998, p. 43). As a result, Egyptian artwork tended to have a high level of proportional accuracy, but only within certain limitations as it also utilized proportional hierarchy, and sizes of objects often did not remain consistent from one scene to the next (Spalinger, 2009, p. 77; Bleiberg, 2005, p. 266; Aldred, 1968, p. 11). As a result each individual figure, its clothing, and any objects worn, or held in hand were quite accurate proportionally, but comparison *between* figures or between a figure and an unattended object would likely be unreliable. Also, while these individual figures were proportionally accurate, they were not particularly realistic or naturalist by modern standards, nor were they intended to be as the painters and sculptures were craftsmen who adhered to a rigorous artistic canon rather than artists (Aldred, 1968, p. 4; Wilkinson, 1991, pp. 90-91).

Additionally, it was clear that the composite bow as it appears in New Kingdom artwork with its characteristic angular profile was rapidly assimilated into Egyptian iconography as it applied to the pharaoh, and this process of iconographic assimilation then spread to representations of Egyptian troops in general (Spalinger, 2009, p. 22). Despite the high degree of assimilation into artistic norms, the composite bow did not completely replace bows of self manufacture, as can be seen by the variety of both self and composite bows recovered from the tomb of Tutankhamen (Griffith Institute, 2004; McLeod, 1970, p. 2).

Comparison between bow artifacts from New Kingdom Egypt and artistic representations of bows from the same period also noted a heretofore undocumented pattern: bows depicted at brace yielded proportional measurements both when measured from tip to tip and along the arc which are consistent with artifacts from the same period. Bows shown at draw however as a rule had proportional measurements along the arc which were significantly *longer* than any known composite bow artifacts from Egypt. Proportional tip to tip length however remained accurate even when shown at draw, and closely matched artifact evidence. This pattern extended even to different representations shown on opposite sides of the same chariot, lending support to the possibility that this was a part of artistic canon. The author plans to pursue this phenomenon more closely in a separate journal article in the future.

As an in-depth review of Mesopotamian iconographic conventions was reserved for later in Chapter Seven, its coverage in Chapter Three was restricted to a description of similarities of conventions between Mesopotamian and Egyptian art, followed by a brief survey of source material from Mesopotamia and Elam for the third and fourth millennia BCE. Varying claims have been made by a number of authors as to composite construction in Mesopotamian art, but the single most commonly referred to image is the Victory Stele of Naram-Sin (2254-2218 BCE). Additionally, several different and distinct bow profiles can be seen in Mesopotamian and Elamite art (Rausing, 1967, pp. 82-3; Hamblin, 2006, p. 92). This variation in bow profile in ancient art is not unique to Mesopotamia however, and can also be seen in Egypt and Europe (Klochko, 1987, p. 19; McLeod, 1970, p. 22; McLeod, 1981, p. 38). Artifact evidence for both Egypt and Europe confirms this profile diversity, a point which supports the premise that some degree of profile variation was not unusual for a given period and culture, indicating that the diversity in bow profiles found in Mesopotamian and Elamite art is most likely accurate (Griffith Institute, 2004; Universitat Autonoma de Barcelona, 2013; Soar, 2005, pp. 3-5).

With a survey of source material complete, the thesis then turned in Chapter Four to the creation of a theoretical framework which explained bow mechanics in terms easily understood by an interested layperson. The purpose of this chapter was twofold. First, it was to provide a foundation of knowledge with regard to how bows work in general so that the reader could evaluate the logic of performance and testing claims both herein and in other publications for themselves. Second, it sought to identify which factors could potentially explain why bows made using composite construction generally outperform bows using self construction. To accomplish these goals, all the different factors which could influence bow performance were organized into one of two groups: factors influencing energy storage, and factors influencing energy transfer (inefficiencies). This theoretical framework was not the first of its kind, but is the first to specifically examine factors that could be responsible for the comparative performance advantage of composite construction.

Additionally, it is the first time such a framework has been presented in such a manner that it can be easily understood by the non-mathematician in a work focusing on history, rather than in a work dedicated to craft skills (Baker, 1992, p. 44; Kooi and Sparenberg, 1997, p. 291). The resulting examination revealed that bow performance variation between composite and non-composite manufacture could readily be isolated to one or more of three possible variables: variations in limb mass, differences in bow profile, and differences in material strength, all of which were examined in greater detail during physical testing performed in Chapter Six.

Other variables, including draw length, draw weight, brace height and the like and their affect on bow performance were also described, but were shown that they could be rendered constant when comparing bows of self and composite construction, and as such did not need to undergo further physical testing. Finally, Chapter Four concluded that bow length, independent of bow mass, was a variable worthy of further investigation with regard to bow use from within the confines of a chariot.

The question of physically testing the importance of bow length was the topic of Chapter Five. As a number of works present the reduction of bow length as a response to the need for bow use within the confines of a chariot, the possibility for causation of composite bow technology was investigated specifically with regards to bow length (Cotterell, 2005, p. 57; Drews, 2004, p. 49; Hamblin, 2006, p. 146). As Hamblin presents the most well developed argument against the early development of composite bow technology, and as one of his points asserted that the development of both the composite bow and chariot were co-dependent, an assessment of bow length with regard to chariot use was needed (Hamblin, 2006, p. 94).

A survey of source material as it related specifically to chariot archery was performed first. The survey showed that while modern experimental archaeology used bows of 145cm or less, no research has been done specifically with regard to the maximal length that *could* be used within the confines of a chariot. One study did note that now maximal length would have been limited, but the premise was not subjected to testing (Hulit and Richardson, 2007, p. 62). Likewise, ancient textual and iconographic sources from New Kingdom Egypt indicated that bow length was typically 130cm or less. Longer along the arc bow lengths were noted in bows shown at full draw, but the length mismatch between these longer lengths and extant artifacts first noted in Chapter Three made these depictions (averaging 170cm) unreliable. Artifact evidence did however provide detailed cab and railing height measurements for a number of chariots from New Kingdom Egypt which have survived to the modern day (Partridge, 1996, p. 122; Littauer and Crouwel, 1979, p. 97).

As existing research had no definitive answer to the question of maximal useable bow length within a chariot physical testing was needed, a process that required a set of bows of increasing length and a recreation of a chariot. Given the nature of testing, which focused on bow/railing interference, it was determined that functional replicas were required, but that they need not be made using traditional materials and methods (Mathieu, 2002, p. 3; Coles, 1977, p. 238). To meet this need a set of bows was created out of heat-molded PVC. The full-sized chariot mockup had a cab sized to match that of existing artifacts (100cm in width and 50cm in depth), and was constructed from welded rebar. The chariot design included two particular points: first, the bottom was woven, rather than solid so that it matched ancient artifacts as this was previously noted to be significant in existing research (Hulit and Richardson, 2007, p. 62). Second, the chariot railing was adjustable in height so that it could be raised and lowered to match the various railing heights seen in actual artifacts.

Testing revealed that bow length was not particularly restrictive, and that an archer 168cm in height could easily manage a bow of up to 170cm in length with a railing height of 90cm, or slightly higher than that of the highest chariot reviewed. This length can accommodate self construction, and as such it can be said with a high degree of certainty that use of a chariot as a mobile archery platform did *not* require a bow length that would mandate the use of composite construction. That being said, the improved performance typically associated with composite construction would certainly have *encouraged* its adoption for chariot use, as the added range combined with increased mobility would have acted as a powerful force multiplier on the battlefield of the ancient world.

Additional insights were also gained, some of which confirmed earlier beliefs while others were, like the question of bow/railing interference, completely new. First among these points was that the use of a woven floor added a great deal of stability, a fact confirmed by alternating foot placement on the edges of the frame and that of the woven panel (Hulit and Richardson, 2007, p. 62). Fields of fire estimates were also confirmed and while not clear in a full 360° when occupied by both archer and driver, remained extensive (Spalinger, 2009, p. 15).

Placement of driver and archer within the chariot was also revealing, and included a point not mentioned in other research to date. Notably, it was found that driver/archer interference was minimized when the archer had his draw arm on the *inside*. Given that the majority of humanity is right handed and that this is in turn results in a strong preference for a right-handed draw means that when standing in the cab facing forward, the archer would be placed on the *left*, while the driver would be on the right. As archers stand with the opposite foot forward to that of their draw hand, the placement of archers on the left – with their left foot forward and right reserved explains the use of a rectangular chariot bed, as the left (front) foot of the archer would be placed as close to the front outside corner as possible. This has strong implications for the Florence chariot artifact, in that given its unique U-shaped cab bed, it was likely designed for either a single person, or at most a driver and non-archer passenger, as the curved front would have required a decisively sub-optimal placement of passengers if used as an archery platform (Littauer and Crouwel, 1979, p. 76). With the impact of bow length examined and the purported need for composite construction for use while in a chariot disproven, the remaining performance variables were examined in Chapter Six.

The first variable subjected to physical testing in Chapter Six was differing materials. Starting with a bow of all wood construction, layers of horn and sinew were added successively and the increases in draw weight compared. These results were then compared with increases of draw weight caused by the addition of an equally thick layer of wood, which both acted as a control test, and proved the validity of the predictive draw-force curve model. The results were not as expected: once the variations in bow profile caused by the addition of the sinew backing had been taken into account, both sinew and horn increased draw weight *less* than a comparable amount of wood. The reason for this was determined to be the fact that while both sinew and horn have a much higher ultimate breaking strength (under tension and compression, respectively) than wood, the *stiffness* of both of these materials is substantially less than wood of equal thickness (Baugh, 1994, p. 119; Gordon, 1987, p. 321; Kooi, 1991, p. 28). The implications cannot be understated as it applies to understanding bow performance. Namely, that while the addition of sinew and/or horn has the *potential* to improve bow performance, that potential is only realized if the resulting design exceeds the capacity of the wood being used (which would result in either complete or partial material failure) (Kooi, 1994, p. 18). In essence, sinew and horn can keep a bow from breaking, and allows the use of higher draw weights and/or a shorter length than wood alone: taking a functional bow and adding horn and sinew would result in some increase in performance, but less than if the bow had been made only out of wood but thicker. Strictly speaking then, the variable of materials was disproven as a direct contributor to increased bow performance, but rather allowed a greater flexibility in bow design. These findings however cannot be applied to other, less common materials used in composite construction, such as bone, and antler, which have a substantially higher stiffness than either horn or sinew (Chen et al., 2009, p. 702; Currey, 1988, p. 136; Currey et al, 2009, p. 43).

The process of material testing also revealed several points, the first of which is that while the addition of a sinew backing will pull bow limbs into some degree of reflex, it does *not* change a bow’s braced profile, as the curvature will be a smooth arc along the entire limb length. This means that all double-concave bows and angular bows (and double-convex bows as well) owe their unique profile at brace to the introduction of either splices or steam bending.

Additionally, while the degree of reflex will increase with the addition of successive layers of sinew which are allowed to dry between applications, the amount of reflex imparted by each layer of sinew is small. This indicates that to achieve a significant degree of reflex necessitates that the bow limbs be pulled into reflex *prior* to the application of the sinew backing. The implications for images of unstrung bows therefore are that while a significant degree of reflex would indeed mandate composite construction, a flat or slightly reflexed profile is ambiguous with regard to its method of construction.

Finally, despite claims to the contrary by a number of scholars, the construction of a composite bow does not take five to ten years, but can rather be accomplished in a matter of several months, with the majority of this time dedicated to drying (Drews, 1993, p. 110; Howard, 2011, p. 8; Rausing, 1967, p. 157; Luschan, 1899, p. 3; Archer, 2010, p. 61). This extended time period of years is not necessary incorrect, but likely includes the time needed to season the wood, with production performed in a dedicated shop wherein individual production steps are done *en masse* on a seasonal basis. In such a situation production could indeed take years, but unless this larger context is properly presented, a manufacture period of “years” presents a skewed view of composite construction.

Profile testing was similarly insightful, and was accomplished by comparing two separate sets of bows with nearly identical draw weight, but different profiles. Each set of bows included examples with draw weights of 25, 50, 75, and 100 pounds (11.3, 22.6, 34, and 45.4kg). To ensure that results were valid, minor variations in draw weight were then corrected for by mathematically adjusting the final force draw curve results on a percentage basis such that the final draw weight for each pair of bows was equal. As profile testing depended exclusively upon comparison of stored energy rather than energy release, differences in bow mass were unimportant.

As expected, bows with a higher degree of reflex (wherein the bow limbs bend away from the archer while held in hand but not strung) did indeed have increased energy storage as measured by the total area beneath the draw-force curve. The increase in energy storage varied to some extent with draw weight, but this was caused primarily by profile variations in the segment profile bows of self construction. Once these variations are taken into account, the vast majority of this variation disappeared. The resulting increase in energy storage then can be expressed fairly simply as follows.

- When comparing bows of equal draw weight and draw length but different unstrung profile, the percent difference in stored energy (and range) will equal *half* the amount of profile differential (expressed as a percentage of bow length).

Larger or smaller differences in unstrung bow profile would yield different results in direct proportion the difference in stored energy; i.e. a 20% profile difference would show a 10% increase in energy storage. Theoretically this difference in bow profile could continue indefinitely, but this would quickly result in a bow too unstable to use, somewhat akin to trying to uncoil a watch spring. Practical considerations therefore limit the degree of reflex to approximately 40% reflex when compared to a bow with absolutely straight limbs, at which point the unstrung limb tips would cross. This additional 20% increase in stored energy translates to a 20% increase in range (ignoring the effects of drag). While the theoretical model in Chapter Four predicted an increase in stored energy, this is the first time that this energy increase has been quantified in a general form such that the energy storage to two bows with different profiles could be directly compared.

In comparison to profile testing, mass testing focused on energy transfer efficiency due to the fact that bow mass (and string mass) act as an impediment to energy transfer rather than as factor of energy storage unto itself. Mathematically, a perfect bow would operate with 100% efficiency, but such a feat would require that both string and bow limb mass be zero. To test the effect of increased mass, each of the bows used for profile testing were fired to provide baseline velocity results, and then subjected to additional rounds of testing with additional weight added at the midpoint of each bow limb. The results showed that increased limb mass did indeed result in decreased velocity (decreased energy transfer efficiency), again confirming predictions of theoretical modeling in Chapter Four. Results further showed that the vast majority of energy inefficiency can be directly attributed to the energy required to accomplish limb return (from draw to brace). Indeed, the amount of predicted energy needed for bow return exceeded total actual energy loss, indicating that the measurement of other sources of inefficiency combined were too small to detect with the equipment available for testing.

The efficiency results showed that a well designed bow of self construction can be up to 70% efficient in some cases depending on its design and draw weight – results comparable to preexisting research (Karpowicz, 2006). Bow efficiency for self construction however decreased as draw weight increased, reaching 60-65% efficiency at draw weights common in the ancient world (18-23kg) and eventually declining to 45% at draw weights of 45kg. In contrast, the fiberglass bows showed a remarkably consistent efficiency of approximately 75% across the range of draw weights tested. Evidence for composite bows made of horn, wood, and sinew shows that bow mass (and limb travel) could remain quite low up through a draw weight of 59kg, indicating even higher levels of energy transfer efficiency of 80% or more (Karpowicz, 2005). It was further found that energy transfer efficiency changed proportionately with changes in bow mass, but proportionately with the *square* of limb travel (the distance a limb moves from full draw to brace), indicating that shorter bow limbs are an important consideration in bow design. Indeed from an efficiency standpoint, limb travel is significantly more important than bow mass.

As bow efficiency is tightly bound with that of bow design as well a choice of materials, differences in efficiency cannot be as neatly summed up as with bow profile. Nevertheless, the comparative advantage of composite over self construction remains simple to understand even if an exact numerical expression is unattainable, and is as follows…

- Presuming a comparison of bows with *identical* profiles, and at draw weights seen throughout the majority of history (between 18-23kg), energy transfer efficiency is 80% or higher efficiency for composite construction compared to roughly 60% efficiency for self construction with limbs having a round or D-shaped cross section. This equates to a 35% difference in both increased energy and range.

- This difference increases with draw weight: at a draw weight of 45kg, composite bows will maintain an 80% efficiency while self manufacture will have a 45% energy transfer efficiency, again assuming a equal profiles. This yields an energy transfer and range differential of 75%

- The benefits obtained from both profile (differences in energy storage) and changes in limb mass and limb travel (differences in energy transfer efficiency) are *additive* when expressed as a percentage, and represent both the comparative difference in arrow energy and arrow range. For a draw weight of between 19-23kg then this would be a range increase of 45%, which gradually increases to 85% at 45kg.

The result is that the comparative performance advantage of composite versus self bows increases with draw weight. The fact that the comparative performance of these two construction methods does not remain constant with draw weight was speculated upon earlier herein, but has now been proven, and explains the vast majority of variation in range results in different research efforts. It also means that these various range comparisons need to be understood within their individual context.

Within the ancient world, draw weights ranged on average between 18-23kg, a contention supported by both modern and ancient range estimates (Spotted-Eagle, 1998, pp. 15-16; Baker, 1992, p. 115; McLeod, 1965, pp. 4-7). Additionally, the ancient world shows no evidence for differentiation in draw weight between hunting and war (Rausing, 1967, p. 29; Baker, 1992, p. 115). Given these draw weights a composite bow in the ancient world from New Kingdom Egypt, Classical Greece or the Roman Empire would likely have a range advantage of perhaps 45% over a self bow of equal draw weight. This estimate presumes a difference in profile of approximately 20% (yielding a range increase of 10%), with additional gains due to the composite bow’s higher efficiency. Early bows as displayed in the Bowyer’s Seal in Chapter Seven (figure 7.40) would likely show a smaller range increase of perhaps 35% as they do not show any reflex.

While a 45% increase in range is significant, it remains a far cry from the 200-300% increase commonly cited in many works (Anglim et al., 2002, p. 10; Drews, 1993, p. 110; Hamblin, 2006, p. 95; Archer, 2010, p. 61). This does not mean that these comparative ranges are unto themselves wrong, but rather that they are being applied to the incorrect time period. Both world archery distance records and historical records from the Middle Ages and Renaissance record differences in range of 200-300%, but these records are substantially different from records in the ancient world on two points. First, the bows in all of these records were substantially higher in draw weight, with historical records using bows designed specifically for war (Karpowicz, 2008, p. 41; Hardy, et al., 2011, p. 627; World Archery Federation, 2012; Payne-Gallwey, 2007, p. 14). Modern archery distance records use bows of similar draw weight, at times reaching upwards of 90kg. Second, the bow ranges achieved in Medieval and Renaissance records utilized significantly different arrows, with the composite bow typically having light arrows specifically designed for distance shooting while the longbows of self construction used heavier arrows more suitable for war (Karpowicz, 2007, p. 682; Strickland and Hardy, 2005, p. 409).

As it has just been shown that the comparative range advantage of composite construction increases with draw weight increased performance is only to be expected, but to apply these expectations from bows having perhaps four times the draw weight of those used for the ancient world is erroneous. While the range increases of 200% or more are certainly possible, they can only occur at draw weights in excess of the 45kg tested herein, which would result in an 85% range increase (again assuming a 20% profile differential). The result then is that numerous scholars have been assigning a much greater advantage to composite construction in the ancient world than actually existed. With this inflated performance assumption has come some degree of expectation.

Hamblin in particular uses these expectations to question the early development of the composite bow, asking that if it was indeed developed prior to 2000 BCE, why is it that it did not leave a more notable trace in the historical record in either the form of physical artifacts or military tactics (Hamblin, 2006, p. 94)?

The first of these points is easily explained for the same reason that the preservation of *any* bow artifact is uncommon, namely that wood, horn, and sinew is all biodegradable making the preservation of such materials over even a few centuries exceptionally rare (Hills, 2005, p. 103; Blanchette, et al., 1994, p. 55; Florian, 1989, p. 5). Additionally, bows historically were typically considered, much like shields in the Anglo-Saxon culture, to be more or less disposable objects; as such, a bow was considered no more than firewood once it became damaged beyond use (Strickland and Hardy, 2005, p. 41; Stephenson, 2002, p. 126).

The lack of military revolution requires more consideration, but can also be explained both by the nature of ranged combat and performance results found during physical testing. First and foremost ranged units unto themselves only remain effective so long as the enemy can be *kept* at range (Randall, 2012, p. 2; Kern, 1999, pp. 9-10). As such, throughout most of history ranged units needed the protection of melee-based infantry (Anglim et al., 2002, p. 14; Maurice, 12.7). In such cases where ranged units could act without the protection of melee troops the act of keeping enemy units at range was typically accomplished through the use of favorable terrain and/or fortifications which prevented the enemy from closing range, or increased mobility accomplished by using a chariot (and later the horse *sans* chariot) as a mobile archery platform (Anglim et al., 2002, pp. 82, 94; McNab, 2011, pp. 18-20; Nossov, 2005, p. 3; Vitruvius, 1.5.2). Improvements in power (increasing the lethality of missiles) and range (increasing the distance that must be crossed allowing archers to subject enemies to a greater amount of missile fire) are also beneficial.

Taking these factors into account, while the primary advantage for the use of the composite bow was increased range, the amount of range increase presumed by many scholars (200-300%) has been overstated, in large part due to failure to understand that this range advantage is not a constant but rather varies both with bow design and draw weight. The actual 45% increase in range was significant enough that the composite bow was rapidly incorporated into the iconographic record of Mesopotamia, Elam and New Kingdom Egypt, was not enough to result in a revolution in military tactics until it was combined with the chariot as a mobile archery platform early in the second millennium BCE. In short, while fortifications such as a substantial town or castle wall would have provided a similar multiplying effect defensively in siege situations, the *offensive* effect of added mobility was needed before the composite bow was able to substantially influence battlefield tactics and strategy (Drews, 1993, p. 105; Powell, 1990, pp. 2, 5; Pinheiro, 2010, p. 1).

Finally, it should be noted that powerful ranged weapons were not a panacea for all things military. In time the supremacy of chariot-based archers was brought down by the Sea Peoples who typically used spears, swords and javelins (Wente, 1963, p. 171; Booth, 2007b, p. 98; Davies, 1933, pl. VII). Indeed, the choice to adopt archery as a culture's primary military weapon even after the advent of both the composite bow and chariot (and later, mounted archers) was far from universal, and depended upon a great variety of factors, including climate, local terrain, and cultural values. The city states of Classical Greece and Rome are two notable examples that focused on the use of heavy infantry despite the substantial but imperfect protection that the associated armor provided against the composite bow (Tyrtaeus, 11.35-38; Plutarch, *Crassus*, 25.6; Coulston, 2007, p. 35; Cagniart, 2007, p. 89).

With the causes and quantities of the variables responsible for the increased range of composite bows both identified and quantified, thereby fulfilling the first two thesis goals, the problem of evaluating composite construction from artwork could begin. Physical testing combined with preexisting research showed that Rausing’s premise for a method of evaluating the likelihood of composite construction focused upon bow *length*, rather than profile was sound, and based upon the understanding that the shorter a bow is, the greater amount of stress placed upon the limbs to achieve a given draw length (Galilie, 2000; p. 159; Middleton, 2007, p. 44). At some point then the use of self construction becomes impractical as bow length continues to shorten as it would result in partial failure (typically resulting in the bow taking on a permanent deflex), and eventually complete failure (breakage). Research has identified this break point at approximately 160cm, with some degree of variation depending upon the type of wood used and limb design (Baker, 1992, pp. 92-93; Kooi, 1994, p. 17). The thesis then added a margin of safety by shortening this by 10cm to allow for a more conservative estimate, setting the break point at 150cm.

As bow design includes a wide range of variables however the length of 150cm *unto itself* would be potentially flawed as the previous system based on profile, and as such a number of qualifying factors were also be taken into consideration, including an assumption of a minimum draw weight of 18kg, and a minimum draw length of 73cm. The use of these added factors allowed for a more accurate measure, as it would not provide false positives for bows with exceptionally low draw weights (as seen in bows used by the Bushmen of Africa) or shortened draw lengths (seen both in Bushmen bows and short double-convex bows from Middle Kingdom Egypt) (Hayes, 1990a, p. 279; Baker, 2000, p. 58). This length could then be applied to artwork by using proportional measurement of bow length against the height of a figure.

Further caveats were outlined: the proportional length of the bow must be held in hand or worn, and only compared to the height of that particular figure. Bows which were unattended or otherwise not held or worn by a figure were deemed to be unreliable. It was also noted that the new methodology was only as valid as the proportional accuracy of the image to which it is applied. As such, it should not be applied to works with a high degree of abstraction.

The collective works of Mesopotamia and Elam of the third and fourth millennia were then examined as a body to establish their level of proportional accuracy and identify trends and their implications for the analysis which followed. It was found that Mesopotamian art was quite similar to Egyptian art in a number of major aspects, including the depiction of figures in three quarter profile, the existence of a canon of proportionality, use of registers and standard of figure height within a given register, occasional use of proportional hierarchy and spatial relationship between registers (Tomabechi, 1983, p. 125; Benzel et al., 1998, p. 43; Kantor, 1966, p. 147). It was found that overall, Mesopotamian and Elamite art of the third and fourth millennia BCE had a level of proportional accuracy comparable to that of Middle and New Kingdom Egypt, but that it on average had higher overall naturalistic realism (Westendorf, 1968, p. 12; Bleiberg, 2005, p. 266; Kantor, 1966, p. 146).

With an acceptable level of proportionate accuracy established, the thesis then proceeded with the analysis proper, which was organized by bow profile and then by reverse chronological order. The analysis itself, like the methodology, was very mechanistic and focused on determining the proportional length of bows depicted in the images under investigation.

Proportionately accurate iconography that feature bows in Mesopotamia and Elam begins at approximately 3800 BCE. Prior to this point several works do contain depictions of bows, but as covered previously in Chapter Three, they are sufficiently abstract that they cannot be accurately evaluated by the new methodology developed in Chapter Seven. In the period from 3800-2400 BCE, bows were found to be universally of double-concave profile having a static recurve design with narrow, unbending limb tips. Works of this period commonly show the bow string crossing the bow limbs, a feature only possible with deep, narrow, unbending limb tips used in combination with long nock loops and wide, flat limbs; the resultant combination of design elements allows a portion of the limb tip to protrude behind the string. Several of the images analyzed had a proportional length that was over 150cm in length, meaning that they were long enough that non-composite construction was viable. The appearance of these longer bows, at times appearing on the same work as shorter bows of the same profile, represented a minority of the images surveyed, potentially indicating that a portion of the time between 3800 BCE and 3100 BCE represented a transitional period during which composite bow manufacture was still not fully integrated into the iconographic tradition of Mesopotamia and Elam. The analysis concluded then that the arrival or development of composite construction to Mesopotamia and Elam occurred sometime during the fourth millennium BCE and that by the start of the third millennium BCE shorter bows indicative of composite construction had become fully integrated into the iconography of the region.

From 3000 BCE forward, all iconography from the region found to date shows that bows had a proportional length of less than 150cm. This length, combined with iconographic evidence of draw lengths equating to an anchor point at the archer’s mouth or ear indicates, at least within iconography, no further evidence for bows of self construction for the region. This should not be taken to mean that bows of self construction did not continue to be used however. As can be seen by the continued presence of self bows in the tomb of Tutankhamen, self manufacture likely continued to some extent even if it no longer appeared in the art of the period. Along similar lines, while the available evidence currently points to the first appearance of the composite bow having occurred in Mesopotamia, it is not necessarily its first and is certainly not its only point of development (Mason, 2007, pl. 61; Sonneborn, 2007, p. 17).

Double-concave bows continued to dominate Mesopotamian and Elamite iconography through much of the third millennium, but at approximately 2400 BCE bow design underwent a shift from a static recurve to a working recurve design. This new design featured limb tips that gradually bent as the draw progressed. Limb tips no longer protruded through the nock loop, indicating that nock loops had become smaller and that this change was accompanied by limb tips had either shifted to a wider design, or that narrow tips were accompanied with a *siyah,* or string bridge – a rest designed to prevent the string from slipping off to either side of the limb tip upon return. No attempts at an oblique perspective have been found for this later period, and so it is impossible to determine if limbs retained their wide design as found in the period prior to 2400 BCE.

Iconographic evidence for double-concave profile bow use continued in Mesopotamia and Elam up to 1900 BCE, but at approximately 2300 BCE a new design featuring an angular profile with narrow limbs and little or no recurvature in the limb tips emerged which gradually replaced double-concave bows in the iconography of the region. While the two profiles co-existed for several centuries in artwork, the two most recent images depicting the double-concave, working-recurve design dating to 2000 BCE and 1900 BCE were unrealistic in proportion, with overly high brace heights and too-long lengths when measured along the arc. This may indicate that the double-concave profile had already been replaced, and that the resulting images were anachronistic and hence somewhat less familiar to the artisans. Like the bows with an angular profile however, the working-recurve bows were all of a length under 150cm, again indicating composite construction. Bows of the new angular profile continued to be used in Mesopotamia and Elam through the year 1850 BCE, by which point this particular style had likely spread into the Levant, when it was later introduced to Egypt via the Hyksos (Spalinger, 2009, p. 15; Gabriel, 2007, p. 87; Casson, 1969, p. 54).

CONCLUSION

The sheer amount of new information brought to light throughout the thesis is considerable, and is matched by the number of points which had previously been suspected, but now have been supported by physical testing. Most importantly however is that, taken together, the combined results have filled gaps in previous research efforts to a sufficient degree that a larger contextual framework can be applied to both pre-existing and future research efforts. It is hoped that this framework can then be used by the non-specialist to reliably extract and independently evaluate a greater amount of data from archery-related source material, whether it be artifact, textual or iconographic in nature.

The benefits from this framework are wide-ranging, and can be connected to almost any area of study which touches upon archery or bow use even in an ancillary fashion. First among these benefits is the ability to re-examine artwork of other cultures and periods now that a more accurate methodology for the evaluation composite construction has been developed. The results can shed light not only on when and where composite construction may have occurred, but also potentially delineate when and where it did *not* occur, and can potentially do so for areas where artifact evidence no longer exists. While image seriation of the adoption of composite construction does not necessarily indicate the abandonment of bows of self manufacture, it outlines the desired adoption of composite technology for the elite of a given culture, who are often the only members of a society who can afford the expense of elaborate burials and associated artwork (Wilkinson, 1982, p. 26; Gorelick and Gwinnett, 1990, pp. 49, 53).

The vast majority of these applications can be applied across a range of periods and cultures, and as such the thesis in many ways a foundational work with regard to bow design, performance and iconographic evaluation methodology. Research in these areas has typically been considered to be inaccessible to the non-specialist. Such no longer need be the case, for the current framework provides sufficient information for the non-specialist to develop and assess these connections for themselves and as such has the potential to impact the field of history as a whole wherever evidence of bow use may be found.

The thesis in essence provides a unified framework for archery research. It provides not only a unified system of nomenclature for describing both bow profile and construction, but also the first definitive identification of factors that allow composite construction to result in increased performance. It also is the first to isolate and quantify these factors, not just at a single draw weight, but across a range of draw weights that allows existing data that previously appeared contradictory to be smoothly integrated. Test results show that the many claims of comparative performance are overstated, but also provide a means by which this performance can be easily understood and independently applied by the non-specialist in future research efforts. Further, the thesis clearly identifies the impact of bow length with regard to chariot use, and provides insight into the relative placement of archer and driver impossible to glean from ancient art. Finally, it introduces a more accurate method of evaluating bow construction from artwork, and then applies this process to iconography of Mesopotamia and Elam, pushing back the date of introduction of composite construction by a full millennium and then tracing changes in bow design from the fourth millennium BCE down to the introduction of composite construction to Egypt by the Hyksos.

Appendix A

Table A.1 Cross-Sectional Measurements: Joined Wood Bow (400g)

	Upper Limb		Lower Limb	
Distance from Grip (mm)	Width (mm)	Thickness (mm)	Width (mm)	Thickness (mm)
0	38.0	15.5	38.0	15.0
50	38.0	9.5	38.0	9.5
100	38.0	7.9	38.0	8.0
150	38.0	7.5	38.0	7.5
200	38.0	7.5	38.0	7.5
250	37.5	7.5	37.4	7.5
300	36.5	7.5	36.7	7.5
350	35.5	7.5	35.4	7.5
400	34.0	7.5	34.1	7.3
450	32.2	7.5	32.2	7.5
500	30.3	7.5	30.3	7.5
550	28.6	7.5	28.8	7.5
600	27.7	7.3	27.6	7.4
650	25.0	7.2	24.5	7.2
700	21.7	7.1	21.4	7.1
750	18.0	7.0	18.1	7.0

Table A.2 Cross-Sectional Measurements: Wood/Sinew Bow (526g)

	Upper Limb		Lower Limb	
Distance from Grip (mm)	Width (mm)	Thickness (mm)	Width (mm)	Thickness (mm)
0	38.0	16.7	38.0	19.7
50	38.0	10.9	38.0	11.2
100	38.0	9.5	38.0	9.5
150	38.0	9.5	38.0	9.5
200	38.0	9.4	38.0	9.5
250	37.5	9.3	37.4	9.4
300	36.5	9.5	36.7	9.5
350	35.5	9.5	35.4	9.6
400	34.0	9.5	34.1	9.5
450	32.2	9.5	32.2	9.5
500	30.3	9.5	30.3	9.5
550	28.6	9.4	28.8	9.4
600	27.7	9.3	27.6	9.2
650	25.0	9.2	24.5	9.2
700	21.7	9.1	21.4	9.1
750	18.0	9.0	18.1	9.0

Table A.3 Cross-Sectional Measurements: Wood/Sinew/Wood Bow (591g)

	Upper Limb		Lower Limb	
Distance from Grip (mm)	Width (mm)	Thickness (mm)	Width (mm)	Thickness (mm)
0	38.0	16.7	38.0	19.7
50	38.0	11.5	38.0	11.5
100	38.0	11.5	38.0	11.5
150	38.0	11.5	38.0	11.5
200	38.0	11.5	38.0	11.5
250	37.5	11.5	37.4	11.5
300	36.5	11.5	36.7	11.5
350	35.5	11.5	35.4	11.5
400	34.0	11.5	34.1	11.5
450	32.2	11.5	32.2	11.5
500	30.3	11.5	30.3	11.5
550	28.6	11.5	28.8	11.5
600	27.7	11.5	27.6	11.5
650	25.0	11.5	24.5	11.5
700	21.7	11.5	21.4	11.5
750	18.0	11.5	18.1	11.5

Table A.4 Cross-Sectional Measurements: Wood/Sinew/Horn (687g)

	Upper Limb		Lower Limb	
Distance from Grip (mm)	Width (mm)	Thickness (mm)	Width (mm)	Thickness (mm)
0	38.0	17.5	38.0	17.9
50	38.0	12.9	38.0	13.7
100	38.0	12.2	38.0	12.2
150	38.0	12.2	38.0	12.2
200	38.0	12.2	38.0	12.2
250	37.5	12.2	37.4	12.2
300	36.5	12.2	36.7	12.2
350	35.5	12.2	35.4	12.2
400	34.0	12.2	34.1	12.2
450	32.2	12.2	32.2	12.2
500	30.3	12.2	30.3	12.2
550	28.6	12.2	28.8	12.2
600	27.7	12.2	27.6	12.2
650	25.0	12.2	24.5	12.2
700	21.7	12.2	21.4	12.2
750	18.0	12.2	18.1	12.2

Table A.5 Draw-Force Curve Computations: Wood/Sinew (Predicted)

Draw Length	**Wood Baseline**	**Predicted Multiplier $(9.5/7.5)^3$**	**Total Product, Sinew/Wood, Flat Profile (Predicted)**
18cm	0	2.0	0
23cm	0.1	2.0	0.2
28cm	0.5	2.0	1.0
33cm	0.8	2.0	1.6
38cm	1.1	2.0	2.2
43cm	1.5	2.0	3.0
48cm	1.8	2.0	3.6
53cm	2.1	2.0	4.2
58cm	2.5	2.0	5.0
63cm	3.0	2.0	6.1
68cm	3.5	2.0	7.1
73cm	4.2	2.0	8.5

Table A.6 Draw-Force Curve Data: Wood, Sinew/Wood (Actual) and Sinew/Wood (Predicted)

Draw Length	Wood Baseline (Actual)	Sinew/Wood, Flat Profile (Predicted)	Sinew/Wood, Flat Profile (Actual)	Sinew/Wood, Reflexed Profile (Actual)
18cm	0	0	0	0
23cm	0.1	0.2	0.6	1.0
28cm	0.5	1.0	1.1	1.6
33cm	0.8	1.6	1.5	2.4
38cm	1.1	2.2	2.0	2.9
43cm	1.5	3.0	2.4	3.4
48cm	1.8	3.6	2.9	4.0
53cm	2.1	4.2	3.5	4.4
58cm	2.5	5.0	3.9	5.0
63cm	3.0	6.1	4.5	5.6
68cm	3.5	7.1	5.1	6.4
73cm	4.2	8.5	5.9	7.1

Table A.7 Draw-Force Curve Computations: Sinew Residual, Reflexed Profile (Actual)

Draw Length	Sinew/Wood, Reflexed Profile (Actual)	Wood Baseline	Sinew Residual, Reflexed Profile (Actual)
18cm	0	0	0
23cm	1.0	0.1	0.9
28cm	1.6	0.5	1.1
33cm	2.4	0.8	1.6
38cm	2.9	1.1	1.8
43cm	3.4	1.5	1.9
48cm	4.0	1.8	2.2
53cm	4.4	2.1	2.3
58cm	5.0	2.5	2.5
63cm	5.6	3.0	2.6
68cm	6.4	3.5	2.9
73cm	7.1	4.2	2.9

Table A.8 Draw-Force Curve Computations: Sinew/Wood/Slat (Predicted)

Draw Length	Sinew Residual, Reflexed Profile (Actual)	Wood/Slat Bow, Flat Profile (Predicted)	Total Sum, Sinew/Wood/Slat, Reflexed Profile (Predicted)
18cm	0	0	0
23cm	0.9	0.2	1.1
28cm	1.1	1.0	2.1
33cm	1.6	1.6	3.2
38cm	1.8	2.2	4.0
43cm	1.9	3.0	4.9
48cm	2.2	3.6	5.8
53cm	2.3	4.2	6.5
58cm	2.5	5.0	7.5
63cm	2.6	6.1	8.7
68cm	2.9	7.1	10.0
73cm	2.9	8.5	11.4

Table A.9 Draw-Force Curve Data: Sinew/Wood, Sinew/Wood/Slat (Predicted), and Sinew/Wood/Slat (Actual)

Draw Length	Sinew/Wood, Reflexed Profile (Actual)	Sinew/Wood/Slat, Reflexed Profile (Predicted)	Sinew/Wood/Slat, Flat Profile (Actual)
18cm	0	0	0
23cm	1.0	1.1	1.0
28cm	1.6	2.1	1.6
33cm	2.4	3.2	2.3
38cm	2.9	4.0	3.0
43cm	3.4	4.9	3.6
48cm	4.0	5.8	4.5
53cm	4.4	6.5	5.2
58cm	5.0	7.5	6.0
63cm	5.6	8.7	7.0
68cm	6.4	10	8.1
73cm	7.1	11.4	9.5

Table A.10 Draw-Force Curve Computations: Sinew Residual, Flat Profile (Actual)

Draw Length	Sinew/Wood, Flat Profile (Actual)	Wood Baseline	Sinew Residual, Reflexed Profile (Actual)
18cm	0	0	0
23cm	0.5	0.1	0.4
28cm	0.9	0.5	0.4
33cm	1.4	0.8	0.6
38cm	1.9	1.1	0.8
43cm	2.0	1.5	0.5
48cm	2.4	1.8	0.6
53cm	2.9	2.1	0.8
58cm	3.3	2.5	0.8
63cm	3.9	3.0	0.9
68cm	4.4	3.5	0.9
73cm	5.2	4.2	1.0

Table A.11 Revised Draw-Force Computations: Sinew/Wood/Slat (Predicted)

Draw Length	Sinew Residual, Flat Profile (Actual)	Wood/Slat, Flat Profile (Predicted)	Total Sum, Sinew/Wood/Slat, Flat Profile (Predicted)
18cm	0	0	0
23cm	0.4	0.2	0.6
28cm	0.4	1.0	1.4
33cm	0.6	1.6	2.2
38cm	0.8	2.2	3.0
43cm	0.5	3.0	3.5
48cm	0.6	3.6	4.2
53cm	0.8	4.2	5.0
58cm	0.8	5.0	5.8
63cm	0.9	6.1	7.0
68cm	0.9	7.1	8.0
73cm	1.0	8.5	9.5

Table A.12 Revised Draw-Force Curve Data: Sinew/Wood, Sinew/Wood/Slat (Predicted), and Sinew/Wood/Slat (Actual)

Draw Length	Sinew/Wood, Flat Profile (Actual)	Wood/Sinew/Slat, Flat Profile (Predicted)	Wood/Sinew/Slat, Flat Profile (Actual)
18cm	0	0	0
23cm	0.5	0.6	1.0
28cm	0.9	1.4	1.6
33cm	1.4	2.2	2.3
38cm	1.9	3.0	3.0
43cm	2.0	3.5	3.6
48cm	2.4	4.2	4.5
53cm	2.9	5.0	5.2
58cm	3.3	5.8	6.0
63cm	3.9	7.0	7.0
68cm	4.4	8.0	8.1
73cm	5.2	9.5	9.5

Table A.13 Draw-Force Curve Computations: Wood/Horn (Predicted)

Draw Length	Wood Baseline	Predicted Multiplier $(10.2/7.5)^3$	Total Product, Wood/Horn Flat Profile (Predicted)
18cm	0	2.52	0
23cm	0.1	2.52	0.25
28cm	0.5	2.52	1.26
33cm	0.8	2.52	2.02
38cm	1.1	2.52	2.77
43cm	1.5	2.52	3.78
48cm	1.8	2.52	4.54
53cm	2.1	2.52	5.29
58cm	2.5	2.52	6.30
63cm	3.0	2.52	7.56
68cm	3.5	2.52	8.82
73cm	4.2	2.52	10.58

Table A.14 Draw-Force Computations: Sinew/Wood/Horn (Predicted)

Draw Length	Sinew Residual, Flat Profile (Actual)	Wood/Horn, Flat Profile (Predicted)	Total Sum, Sinew/Wood/Horn, Reflexed Profile (Predicted)
18cm	0	0	0
23cm	0.4	0.25	0.65
28cm	0.4	1.26	1.66
33cm	0.6	2.02	2.62
38cm	0.8	2.77	3.57
43cm	0.5	3.78	4.28
48cm	0.6	4.54	5.14
53cm	0.8	5.29	6.09
58cm	0.8	6.30	7.10
63cm	0.9	7.56	8.46
68cm	0.9	8.82	9.72
73cm	1.0	10.58	11.58

Table A.15 Draw-Force Curve Data: Sinew/Wood, Sinew/Wood/Horn (Predicted), and Sinew/Wood/Horn (Actual)

Draw Length	Sinew/Wood, Flat Profile (Actual)	Wood/Sinew/Horn, Flat Profile (Predicted)	Wood/Sinew/Horn, Flat Profile (Actual)
18cm	0	0	0
23cm	0.5	0.65	1.2
28cm	0.9	1.66	2.0
33cm	1.4	2.62	2.6
38cm	1.9	3.57	3.2
43cm	2.0	4.28	4.0
48cm	2.4	5.14	4.5
53cm	2.9	6.09	5.3
58cm	3.3	7.10	6.0
63cm	3.9	8.46	6.8
68cm	4.4	9.72	8.9
73cm	5.2	11.58	9.2

Table A.16 Segment Longbow Draw Weights (kg, at 73cm draw)

25 Pound		50 Pound		75 Pound		100 Pound	
Expected Draw Weight	Actual Draw Weight	Expected Draw Weight	Actual Draw Weight	Expected Draw Weight	Actual Draw Weight	Expected Draw Weight	Actual Draw Weight
11.34	15.0	22.73	21.0	34.09	31.0	45.45	38.6

Table A.17 Double-Concave Bow Draw Weights (kg, at 73cm draw)

25 Pound		50 Pound		75 Pound		100 Pound	
Expected Draw Weight	Actual Draw Weight	Expected Draw Weight	Actual Draw Weight	Expected Draw Weight	Actual Draw Weight	Expected Draw Weight	Actual Draw Weight
11.34	12.4	22.73	24.1	34.09	36.0	45.45	48.0

Table A.18 Bow Profiles

	Unworked Profile	Worked-In Profile	Recovered Profile	Bow Mass
25 Pound Segment	2.5cm Deflex	5.5cm Deflex	3.5cm Deflex	398g
50 Pound Segment	2.5cm Deflex	6.5cm Deflex	5.4cm Deflex	507g
75 Pound Segment	2.5cm Deflex	6.0cm Deflex	4.0cm Deflex	792g
100 Pound Segment	2.5cm Deflex	8.5cm Deflex	6.0cm Deflex	836g
25 Pound Double-Concave	21.0cm Reflex	21.0cm Reflex	21.0cm Reflex	881g
50 Pound Double-Concave	21.0cm Reflex	21.0cm Reflex	21.0cm Reflex	940g
75 Pound Double-Concave	21.0cm Reflex	21.0cm Reflex	21.0cm Reflex	1017g
100 Pound Double-Concave	21.0cm Reflex	21.0cm Reflex	21.0cm Reflex	1061g

Table A.19 Draw-force Curve Data: Segment Longbows (kg)

Draw Length	25 Pound	50 Pound	75 Pound	100 Pound
18cm	0	0	0	0
23cm	1.5	2.4	3.0	3.5
28cm	2.9	4.0	5.6	6.5
33cm	4.0	5.4	8.0	9.5
38cm	4.9	7.0	10.2	11.9
43cm	6.0	8.5	12.5	14.5
48cm	7.3	10.0	14.8	17.5
53cm	8.5	11.8	16.5	21.3
58cm	10.0	13.6	20.0	24.4
63cm	11.6	15.8	23.0	28.2
68cm	13.1	18.2	26.0	33.0
73cm	15.0	21.0	31.0	38.6

Table A.20 Draw-force Curve Data: Double-Concave Bows (kg)

Draw Length	25 Pound	50 Pound	75 Pound	100 Pound
18cm	0	0	0	0
23cm	0.4	2.1	3.0	6.9
28cm	2.1	5.1	7.8	12.0
33cm	3.4	7.5	11.0	16.1
38cm	4.7	9.5	14.9	21.0
43cm	6.1	11.4	17.3	24.0
48cm	6.5	13.2	19.8	26.0
53cm	7.6	15.2	23.5	32.0
58cm	8.7	17.0	26.8	33.7
63cm	9.5	19.3	28.4	38.5
68cm	11.1	21.5	32.3	43.0
73cm	12.4	24.1	36.0	48.0

Table A.21 Bow Reflex/Deflex as a Percentage of Bow Length

	Worked-In Profile	Bow Length Along the Arc	Percent Reflex/Deflex to Bow Length
25 Pound Segment	5.5cm Deflex	184.5cm	2.98% Deflex
50 Pound Segment	6.5cm Deflex	183.5cm	3.54% Deflex
75 Pound Segment	6.0cm Deflex	191.5cm	3.13% Deflex
100 Pound Segment	8.5cm Deflex	191.5cm	4.44% Deflex
25 Pound Double-Concave	21.0cm Reflex	166.0cm	12.65% Reflex
50 Pound Double-Concave	21.0cm Reflex	166.0cm	12.65% Reflex
75 Pound Double-Concave	21.0cm Reflex	166.0cm	12.65% Reflex
100 Pound Double-Concave	21.0cm Reflex	166.0cm	12.65% Reflex

Table A.22 Difference in Profile between Bow Pairs

	Segment Bow Profile	Double-Concave Bow	Percent Difference
25 Pound	-2.98%	12.65%	15.63%
50 Pound	-3.54%	12.65%	16.19%
75 Pound	-3.13%	12.65%	15.78%
100 Pound	-4.44%	12.65%	17.09%

Table A.23 Additional Energy Stored in Bow Pairs (10% Profile Differential)

	Percent Profile Differential	Additional Energy Stored (J)	Additional Energy Stored for 10% Profile Differential (J)	Additional Energy Stored for 10% Profile Differential
25 Pound	15.63%	1.074J	0.6871401	2.78%
50 Pound	16.19%	3.618J	2.2347128	4.72%
75 Pound	15.78%	7.702J	4.8808619	7.02%
100 Pound	17.09%	10.539J	6.1667642	6.7%

Table A.24 Arrow Velocity Data: 25# Segment Bow (m/s)*

Shot No. / Added Mass	**0g**	**50g**	**100g**	**200g**	**400g**	**600g**
1	40.5	40.2	39.6	31.4	~~36.6~~	26.2
2	~~481.9~~	39.9	37.7	33.5	29.9	25.3
3	40.2	38.1	39.0	31.4	30.5	~~30.2~~
4	~~48.8~~	38.7	38.7	33.5	29.0	28.0
5	~~102.7~~	37.5	~~1061.0~~	33.5	30.5	25.9
6	41.5	36.9	36.2	33.2	~~32.3~~	27.7
7	39.9	~~11.3~~	38.4	~~9.1~~	~~27.1~~	25.6
8	~~16.8~~	37.8	37.5	32.3	~~156.1~~	27.1
9	42.0	39.0	37.2	~~26.2~~	~~36.6~~	26.2
10	41.5	~~30.2~~	35.7	34.1	29.6	25.3
11	39.9	39.3	37.8	34.4	31.1	26.8
12	~~6.7~~	37.2	36.0	36.0	~~36.3~~	26.8
13	40.8	39.0	38.4	32.3	29.6	27.1
14	40.5	39.6	39.3	34.1	30.2	26.2
15	39.9	~~11.3~~	37.2	34.1	30.5	26.2
Mean	**40.5**	**38.6**	**37.76**	**33.37**	**30.1**	**26.46**
Median	**39.9**	**38.85**	**37.75**	**33.5**	**30.2**	**26.2**
Standard Deviation	0.72	1.04	1.18	1.23	0.6	0.8
Data Points	10	12	14	13	9	14
Outlier Iterations	1	1	1	1	4	1

*** All data was converted from feet per second and rounded to the first decimal place. Data points which have been struck through were considered to be either outliers and have not been included in mean, median and the data range of velocity computations.**

Table A.25 Arrow Velocity Data: 50# Segment Bow (m/s)*

Shot No. / Added Mass	**0g**	**50g**	**100g**	**200g**	**400g**	**600g**
1	32.3	43.6	41.1	~~21.3~~	33.5	29.9
2	33.5	34.1	31.1	38.7	15.8	~~23.5~~
3	43.3	39.9	45.4	35.4	22.9	25.4
4	45.1	42.7	37.2	37.5	9.4	29.9
5	32.9	43.0	43.0	39.0	23.8	30.8
6	39.9	46.3	44.8	~~23.2~~	19.5	28.0
7	46.9	29.9	36.9	37.8	21.6	29.0
8	47.9	44.2	43.6	~~24.4~~	33.0	29.9
9	37.2	22.6	39.0	36.9	36.6	29.6
10	30.2	23.2	41.5	38.1	32.0	28.3
11	38.4	43.9	31.7	~~33.5~~	33.5	28.0
12	59.4	~~64.6~~	40.8	38.4	29.0	~~35.1~~
13	17.4	45.4	41.5	38.1	34.4	27.4
14	39.0	~~93.8~~	41.8	38.7	33.5	~~23.5~~
15	43.3	45.1	40.8	36.9	33.8	~~129.8~~
Mean	**39.11**	**38.76**	**40.01**	**37.77**	**27.49**	**28.75**
Median	**39.00**	**43.00**	**41.10**	**38.10**	**32**	**29**
Standard Deviation	9.28	8.13	4.09	1.0	7.87	1.46
Data Points	15	13	15	11	15	11
Outlier Iterations	1	1	1	2	1	1

*** All data was converted from feet per second and rounded to the first decimal place. Data points which have been struck through were considered to be outliers and have not been included in statistical computations.**

Table A.26 Arrow Velocity Data (Revised): 50# Segment Bow (m/s)*

Shot No. / Added Mass	**0g**	**50g**	**100g**	**200g**	**400g**	**600g**
1	~~32.3~~	43.6	41.1	~~21.3~~	33.5	29.9
2	~~33.5~~	~~34.1~~	~~31.1~~	38.7	~~15.8~~	~~23.5~~
3	43.3	39.9	45.4	35.4	~~22.9~~	25.4
4	45.1	42.7	37.2	37.5	~~9.4~~	29.9
5	~~32.9~~	43.0	43.0	39.0	~~23.8~~	30.8
6	39.9	46.3	44.8	~~23.2~~	~~19.5~~	28.0
7	46.9	~~29.9~~	36.9	37.8	~~21.6~~	29.0
8	47.9	44.2	43.6	~~24.4~~	33.0	29.9
9	~~37.2~~	~~22.6~~	39.0	36.9	~~36.6~~	29.6
10	~~30.2~~	~~23.2~~	41.5	38.1	32.0	28.3
11	~~38.4~~	43.9	~~31.7~~	~~33.5~~	33.5	28.0
12	~~59.4~~	~~64.6~~	40.8	38.4	~~29.0~~	~~35.1~~
13	~~17.4~~	45.4	41.5	38.1	34.4	27.4
14	~~39.0~~	~~93.8~~	41.8	38.7	33.5	~~23.5~~
15	43.3	45.1	40.8	36.9	33.8	~~129.8~~
Mean	**44.4**	**43.79**	**41.34**	**37.77**	**33.39**	**28.75**
Median	**44.2**	**43.9**	**41.5**	**38.10**	**33.5**	**29**
Standard Deviation	2.63	1.76	2.47	1.0	0.69	1.46
Data Points	6	9	13	11	7	11
Outlier Iterations	2	2	1	2	2	1

*** Revised data from table 3.26 after iteratively identified highlighted data points were removed.**

Table A.27 Arrow Velocity Data: 75# Segment Bow (m/s)*

Shot No. / Added Mass	**0g**	**50g**	**100g**	**200g**	**400g**	**600g**
1	47.5	~~12.2~~	43.9	42.1	36.3	32.6
2	46.6	~~10.1~~	43.3	40.8	36.3	33.5
3	49.7	46.3	44.5	40.8	37.5	33.8
4	48.2	~~48.2~~	44.5	41.5	36.6	34.1
5	46.0	~~47.5~~	44.8	41.5	36.3	32.6
6	49.1	45.1	43.6	41.5	37.2	33.5
7	44.8	~~39.9~~	43.9	40.8	36.0	32.9
8	48.5	45.7	44.2	41.1	36.0	34.1
9	43.3	46.6	43.9	40.8	37.5	~~38.7~~
10	46.6	46.3	43.0	40.2	36.3	~~128.9~~
11	~~604.7~~	45.7	42.7	43.9	~~9.8~~	32.6
12	46.9	45.7	44.8	42.1	~~26.8~~	32.0
13	47.5	45.7	45.7	42.1	~~53.9~~	32.3
14	46.0	45.1	41.5	43.9	~~39.0~~	~~9.1~~
15	47.5	45.5	43.9	41.1	36.6	~~9.1~~
Mean	**47.01**	**45.77**	**43.88**	**41.61**	**36.6**	**33.09**
Median	**47.2**	**45.7**	**43.9**	**40.8**	**36.6**	**32.9**
Standard Deviation	1.63	0.47	0.97	1.09	0.53	0.70
Data Points	14	10	15	15	11	11
Outlier Iterations	1	2	1	1	2	1

*** All data was converted from feet per second and rounded to the first decimal place. Data points which have been struck through were considered to be outliers and have not been included in statistical computations.**

Table A.28 Arrow Velocity Data: 100# Segment Bow (m/s)*

Shot No. / Added Mass	0g	50g	100g	200g	400g	600g
1	51.8	49.4	48.2	47.5	42.7	~~43.0~~
2	50.0	~~6.1~~	47.9	~~42.4~~	43.9	~~43.0~~
3	13.7	50.6	49.7	46.6	~~11.9~~	~~35.1~~
4	14.3	49.1	~~21.3~~	47.0	43.3	~~43.0~~
5	14.3	~~17.7~~	~~198.7~~	47.2	42.4	~~31.7~~
6	14.3	~~577.6~~	47.9	~~38.1~~	43.3	38.7
7	44.8	50.0	50.0	48.8	43.0	~~39.3~~
8	51.2	51.2	48.2	50.0	43.3	~~39.6~~
9	54.2	~~33.5~~	50.3	48.5	42.4	38.4
10	~~283.8~~	50.9	50.0	~~42.4~~	43.9	38.4
11	53.0	49.1	48.5	~~12.8~~	44.2	38.1
12	52.7	48.4	50.0	48.2	43.6	38.7
13	43.0	49.1	48.2	47.2	42.1	38.7
14	51.5	50.0	48.2	46.6	43.3	38.4
15	52.1	49.7	47.9	46.9	43.3	~~36.0~~
Mean	**40.06**	**49.77**	**48.85**	**47.68**	**43.19**	**38.49**
Median	**50.6**	**49.7**	**48.2**	**47.2**	**43.3**	**38.4**
Standard Deviation	16.68	0.82	0.93	1.02	0.60	0.21
Data Points	14	11	13	11	14	7
Outlier Iterations	1	1	1	2	1	2

*** All data was converted from feet per second and rounded to the first decimal place. Data points which have been struck through were considered to be outliers and have not been included in statistical computations.**

Table A.29 Arrow Velocity Data (Revised): 100# Segment Bow (m/s)*

Shot No. / Added Mass	0g	50g	100g	200g	400g	600g
1	51.8	49.4	48.2	47.5	42.7	~~43.0~~
2	50.0	~~6.1~~	47.9	~~42.4~~	43.9	~~43.0~~
3	~~13.7~~	50.6	49.7	46.6	~~11.9~~	~~35.1~~
4	~~14.3~~	49.1	~~21.3~~	47.0	43.3	~~43.0~~
5	~~14.3~~	~~17.7~~	~~198.7~~	47.2	42.4	~~31.7~~
6	~~14.3~~	~~577.6~~	47.9	~~38.1~~	43.3	38.7
7	~~44.8~~	50.0	50.0	48.8	43.0	~~39.3~~
8	51.2	51.2	48.2	50.0	43.3	~~39.6~~
9	54.2	~~33.5~~	50.3	48.5	42.4	38.4
10	~~283.8~~	50.9	50.0	~~42.4~~	43.9	38.4
11	53.0	49.1	48.5	~~12.8~~	44.2	38.1
12	52.7	48.4	50.0	48.2	43.6	38.7
13	~~43.0~~	49.1	48.2	47.2	42.1	38.7
14	51.5	50.0	48.2	46.6	43.3	38.4
15	52.1	49.7	47.9	46.9	43.3	~~36.0~~
Mean	**52.06**	**49.77**	**48.85**	**47.68**	**43.19**	**38.49**
Median	**51.95**	**49.7**	**48.2**	**47.2**	**43.3**	**38.4**
Standard Deviation	1.19	0.82	0.93	1.02	0.60	0.21
Data Points	8	11	13	11	14	7
Outlier Iterations	2	1	1	2	1	2

*** Revised data from table 3.29 after iteratively identified highlighted data points were removed.**

Table A.30 Arrow Velocity Data: 25# Double-Concave Bow (m/s)*

Shot No. / Added Mass	**0g**	**50g**	**100g**	**200g**	**400g**	**600g**
1	~~33.5~~	40.2	~~29.9~~	37.2	33.2	32.3
2	38.7	37.8	36.0	36.0	33.2	32.0
3	40.8	36.6	37.2	35.4	34.4	31.7
4	~~26.5~~	40.2	36.6	35.7	33.8	32.0
5	36.6	38.4	35.4	35.7	34.4	32.9
6	39.0	38.4	37.8	36.0	~~41.8~~	32.0
7	~~10.1~~	38.1	38.4	36.6	35.4	31.4
8	37.8	38.1	39.9	35.4	32.9	~~34.1~~
9	~~49.4~~	~~46.3~~	38.7	36.0	~~42.4~~	32.3
10	40.2	36.6	36.0	36.0	32.9	31.7
11	38.7	34.7	38.1	36.9	33.5	32.6
12	~~10.1~~	36.3	39.9	36.0	~~40.5~~	32.6
13	38.4	36.3	~~44.8~~	37.8	34.4	32.9
14	37.5	36.9	37.5	36.3	32.6	32.0
15	~~47.5~~	38.4	37.2	~~32.6~~	34.4	32.6
Mean	**38.6**	**37.6**	**37.59**	**36.21**	**33.76**	**32.21**
Median	**38.7**	**37.95**	**37.5**	**36.0**	**33.65**	**32.15**
Standard Deviation	1.22	1.47	1.36	0.67	0.81	0.45
Data Points	9	14	13	14	12	14
Outlier Iterations	3	1	1	1	1	1

*** All data was converted from feet per second and rounded to the first decimal place. Data points which have been struck through were considered to be outliers and have not been included in statistical computations.**

Table A.31 Arrow Velocity Data: 50# Double Concave Bow (m/s)*

Shot No. / Added Mass	**0g**	**50g**	**100g**	**200g**	**400g**	**600g**
1	54.3	52.4	53.0	~~57.3~~	46.6	43.0
2	54.9	53.3	53.9	~~56.7~~	46.0	43.0
3	51.8	53.6	~~46.3~~	50.6	46.9	43.3
4	55.2	54.3	53.0	50.9	47.2	~~59.7~~
5	~~30.5~~	52.7	52.7	50.3	48.8	46.9
6	~~14.0~~	53.6	54.9	~~21.9~~	47.5	45.1
7	55.2	51.8	51.8	50.3	47.9	44.2
8	55.8	53.0	55.5	52.1	47.5	45.4
9	54.3	53.3	53.3	51.2	45.7	47.5
10	~~14.6~~	53.3	52.4	51.5	47.5	46.3
11	57.9	53.0	52.4	49.7	47.2	45.4
12	50.3	52.7	50.9	50.3	46.3	45.4
13	52.4	51.8	53.3	50.6	46.9	45.4
14	50.0	53.0	49.7	51.8	45.4	45.1
15	52.4	53.3	51.5	~~32.9~~	46.9	46.0
Mean	**53.71**	**53.00**	**52.74**	**50.85**	**46.95**	**45.14**
Median	**54.3**	**53**	**52.85**	**50.6**	**46.9**	**45.4**
Standard Deviation	2.25	0.41	1.46	0.70	0.85	1.32
Data Points	12	15	14	11	15	14
Outlier Iterations	1	1	1	1	1	1

*** All data was converted from feet per second and rounded to the first decimal place. Data points which have been struck through were considered to be outliers and have not been included in statistical computations.**

Table A.32 Arrow Velocity Data: 75# Double-Concave Bow (m/s)*

Shot No. / Added Mass	0g	50g	100g	200g	400g	600g
1	61.6	60.7	58.2	56.4	50.9	51.2
2	62.5	60.4	57.9	56.1	~~14.3~~	49.4
3	61.9	62.2	59.4	53.3	53.9	47.5
4	62.2	~~54.3~~	59.7	57.3	52.7	51.8
5	~~64.3~~	60.7	60.7	56.1	53.3	~~14.3~~
6	62.5	60.4	59.4	57.9	49.7	50.0
7	62.2	62.5	59.7	53.6	~~14.6~~	~~61.6~~
8	63.1	~~55.8~~	59.4	57.0	53.6	53.9
9	~~362.4~~	60.7	~~44.2~~	~~16.8~~	42.4	~~13.7~~
10	~~17.1~~	60.7	61.0	57.9	45.1	~~57.3~~
11	~~48.2~~	59.7	~~69.5~~	57.3	43.6	47.2
12	61.9	62.2	56.7	53.3	~~14.3~~	49.7
13	61.6	64.0	57.6	57.3	54.9	49.4
14	62.8	60.7	57.3	57.3	51.8	~~311.2~~
15	~~7.9~~	~~33.2~~	~~288.3~~	~~349.9~~	53.6	49.4
Mean	**62.23**	**61.24**	**58.92**	**56.22**	**50.46**	**49.95**
Median	**62.2**	**60.7**	**59.4**	**57.0**	**52.25**	**49.55**
Standard Deviation	0.47	1.17	1.30	1.64	4.16	1.87
Data Points	10	12	12	13	12	10
Outlier Iterations	2	1	1	1	1	3

*** All data was converted from feet per second and rounded to the first decimal place. Data points which have been struck through were considered to be outliers and have not been included in statistical computations.**

Table A.33 Arrow Velocity Data (Revised): 75# Double-Concave Bow (m/s)*

Shot No. / Added Mass	0g	50g	100g	200g	400g	600g
1	61.6	60.7	58.2	56.4	50.9	51.2
2	62.5	60.4	57.9	56.1	~~14.3~~	49.4
3	61.9	62.2	59.4	53.3	53.9	47.5
4	62.2	~~54.3~~	59.7	57.3	52.7	51.8
5	~~64.3~~	60.7	60.7	56.1	53.3	~~14.3~~
6	62.5	60.4	59.4	57.9	49.7	50.0
7	62.2	62.5	59.7	53.6	~~14.6~~	~~61.6~~
8	63.1	~~55.8~~	59.4	57.0	53.6	53.9
9	~~362.4~~	60.7	~~44.2~~	~~16.8~~	~~42.4~~	~~13.7~~
10	~~17.1~~	60.7	61.0	57.9	~~45.1~~	~~57.3~~
11	~~48.2~~	59.7	~~69.5~~	57.3	~~43.6~~	47.2
12	61.9	62.2	56.7	53.3	~~14.3~~	49.7
13	61.6	64.0	57.6	57.3	54.9	49.4
14	62.8	60.7	57.3	57.3	51.8	~~311.2~~
15	~~7.9~~	~~33.2~~	~~288.3~~	~~349.9~~	53.6	49.4
Mean	**62.23**	**61.24**	**58.92**	**56.22**	**52.71**	**49.95**
Median	**62.2**	**60.7**	**59.4**	**57.0**	**53.3**	**49.55**
Standard Deviation	0.47	1.17	1.30	1.64	1.54	1.87
Data Points	10	12	12	13	9	10
Outlier Iterations	2	1	1	1	2	3

*** Revised data from table 3.33 after iteratively identified highlighted data points were removed.**

Table A.34 Arrow Velocity Data: 100# Double-Concave Bow (m/s)*

Shot No. / Added Mass	0g	50g	100g	200g	400g	600g
1	77.7	75.9	73.1	64.6	55.2	53.9
2	75.0	71.3	~~45.7~~	~~78.6~~	56.1	51.5
3	78.0	74.7	70.1	64.3	55.5	~~40.8~~
4	77.4	~~13.7~~	71.3	~~63.7~~	~~14.6~~	51.8
5	77.7	75.0	69.8	~~65.5~~	57.6	~~72.2~~
6	77.4	68.0	71.3	~~32.6~~	~~42.1~~	55.2
7	76.6	~~22.2~~	72.5	64.6	52.4	55.8
8	77.7	87.2	~~464.5~~	64.6	55.2	55.2
9	~~21.9~~	74.4	70.7	64.6	55.2	56.1
10	~~20.7~~	73.5	71.0	~~66.8~~	52.7	53.3
11	76.2	92.4	~~41.8~~	64.3	53.3	~~68.9~~
12	76.2	93.3	71.6	~~62.2~~	54.3	52.4
13	78.9	95.4	70.4	64.3	~~43.3~~	54.6
14	~~21.0~~	74.4	~~92.0~~	~~19.8~~	54.6	~~488.3~~
15	~~103.9~~	73.5	70.1	~~68.6~~	~~15.2~~	~~202.4~~
Mean	**77.16**	**79.15**	**71.08**	**64.47**	**54.74**	**53.98**
Median	**77.4**	**74.7**	**71.0**	**64.6**	**55.2**	**54.25**
Standard Deviation	1.02	8.97	1.03	0.15	1.45	1.58
Data Points	11	13	11	7	11	10
Outlier Iterations	1	1	1	2	2	2

*** All data was converted from feet per second and rounded to the first decimal place. Data points which have been struck through were considered to be outliers and have not been included in statistical computations.**

Table A.35 Arrow Velocity Data (Revised): 100# Double-Concave Bow (m/s)*

Shot No. / Added Mass	0g	50g	100g	200g	400g	600g
1	77.7	75.9	73.1	64.6	55.2	53.9
2	75.0	~~71.3~~	~~45.7~~	~~78.6~~	56.1	51.5
3	78.0	74.7	70.1	64.3	55.5	~~40.8~~
4	77.4	~~13.7~~	71.3	~~63.7~~	~~14.6~~	51.8
5	77.7	75.0	69.8	~~65.5~~	57.6	~~72.2~~
6	77.4	~~68.0~~	71.3	~~32.6~~	~~42.1~~	55.2
7	76.6	~~22.2~~	72.5	64.6	52.4	55.8
8	77.7	~~87.2~~	~~464.5~~	64.6	55.2	55.2
9	~~21.9~~	74.4	70.7	64.6	55.2	56.1
10	~~20.7~~	73.5	71.0	~~66.8~~	52.7	53.3
11	76.2	~~92.4~~	~~41.8~~	64.3	53.3	~~68.9~~
12	76.2	~~93.3~~	71.6	~~62.2~~	54.3	52.4
13	78.9	~~95.4~~	70.4	64.3	~~43.3~~	54.6
14	~~21.0~~	74.4	~~92.0~~	~~19.8~~	54.6	~~488.3~~
15	~~103.9~~	73.5	70.1	~~68.6~~	~~15.2~~	~~202.4~~
Mean	**77.16**	**74.49**	**71.08**	**64.47**	**54.74**	**53.98**
Median	**77.4**	**74.4**	**71.0**	**64.6**	**55.2**	**54.25**
Standard Deviation	1.02	0.78	1.03	0.15	1.45	1.58
Data Points	11	7	11	7	11	10
Outlier Iterations	1	3	1	2	2	2

*** Revised data from table 3.35 after iteratively identified highlighted data points were removed.**

Table A.36 Comparison of Ideal to Observed Arrow Velocities and Energy Efficiencies*

Bow	Stored Energy (J)	Ideal Arrow Velocity (m/s)	Mean Observed Arrow Velocity (m/s)	Transferred Energy	Energy Transfer Efficiency (%)
25 Pound Double-Concave	25.816	44.456	38.6	19.36948	75.02%
50 Pound Double-Concave	50.97	62.616	53.71	37.5019333	73.58%
75 Pound Double-Concave	77.2	77.061	62.23	50.3434477	65.20%
100 Pound Double-Concave	102.578	88.829	77.16	77.3976528	75.45%
25 Pound Segment	29.910	47.966	40.50	21.32325	71.3%
50 Pound Segment	41.261	56.338	44.40	25.62768	62.11%
75 Pound Segment	59.845	67.849	47.01	28.7292213	48.01%
100 Pound Segment	74.016	75.456	52.06	35.2331668	47.6%

***Arrow mass remained constant throughout testing at 26g.**

Table A.37 Limb Return Velocity: Segment Bows (m/s)

Shot No.	25 Pound Segment Bow	50 Pound Segment Bow	75 Pound Segment Bow	100 Pound Segment Bow
1	32.004	39.3192	47.244	53.6448
2	31.0896	39.9288	46.9392	53.6448
3	31.6992	39.624	48.3768	53.34
4	29.2608	40.2336	45.72	54.5592
5	31.6992	40.2336	47.8536	52.4256
6	31.0896	39.0144	47.244	54.2544
7	29.2608	39.624	47.5488	53.0352
8	29.8704	~~41.7576~~	46.3296	53.34
9	31.3944	40.2336	46.6344	52.1208
10	31.0896	39.3192	48.3768	51.5112
Mean	**30.84576**	**39.724584**	**47.30496**	**53.1876**
Median	**31.0896**	**39.624**	**47.244**	**53.34**
Standard Deviation	**0.96193**	**0.43105**	**0.81555**	**0.89644**
Data Points	**10**	**9**	**10**	**10**
Outlier Iterations	**1**	**1**	**1**	**1**

Table A.38 Limb Return Velocity: Double-Concave Bows (m/s)

Shot No.	25 Pound Double-Concave Bow	50 Pound Double-Concave Bow	75 Pound Double-Concave Bow	100 Pound Double-Concave Bow
1	30.1752	40.2336	46.9392	52.7304
2	31.0896	40.5384	49.3776	53.0352
3	28.6512	39.624	46.3296	51.816
4	29.2608	41.148	46.9392	52.7304
5	29.2608	40.2336	46.3296	53.34
6	28.6512	40.8432	47.5488	53.34
7	30.1752	41.4528	44.8056	52.1208
8	29.5656	40.5384	49.0728	52.4256
9	28.956	39.624	45.72	54.5592
10	28.6512	40.2336	46.02448	53.34
Mean	**29.44368**	**40.44696**	**46.90869**	**52.94376**
Median	**29.2608**	**40.386**	**46.6344**	**52.8828**
Standard Deviation	**0.7735**	**0.56285**	**1.35937**	**0.53977**
Data Points	**10**	**10**	**10**	**10**
Outlier Iterations	**1**	**1**	**1**	**1**

Table A.39 Limb Return Energy Expenditure - 25# Segment Bow

25 Pound Segment Bow	Segment Volume (ml)	Segment Density (ρ)	Segment Mass (kg)	Segment Travel (m)	Travel Time (s)	Energy(J) = $kg*m^2/s^2$
Section 1	1304.23847	0.87	0.01134687	0.200	0.01783	1.4275845
Section 2	1521.61155	0.87	0.01323802	0.170	0.01783	1.2033348
Section 3	1521.61155	0.87	0.01323802	0.143	0.01783	0.851453
Section 4	1521.61155	0.87	0.01323802	0.113	0.01783	0.5316741
Section 5	1956.35771	0.87	0.01702031	0.087	0.01783	0.405202
Section 6	2173.73079	0.87	0.01891146	0.067	0.01783	0.2670178
Section 7	2173.73079	0.87	0.01891146	0.047	0.01783	0.1313973
Section 8	2608.47695	0.87	0.02269375	0.030	0.01783	0.0642413
Section 9	2608.47695	0.87	0.02269375	0.016	0.01783	0.0182731
Section 10	2608.47695	0.87	0.02269375	0.005	0.01783	0.0017845
Limb Total	19998.3233	0.87	0.17398541	-	0.01783	4.9019623
Bow Total	-	0.87	-	-	-	9.8039246

Table A.40 Limb Return Energy Expenditure - 50# Segment Bow

50 Pound Segment Bow	Segment Volume (ml)	Segment Density (ρ)	Segment Mass (kg)	Segment Travel (m)	Travel Time (s)	Energy(J) = $kg*m^2/s^2$
Section 1	1304.238473	0.87	0.011347	0.200	0.013845	2.367716
Section 2	1521.611552	0.87	0.013238	0.170	0.013845	1.995787
Section 3	1956.35771	0.87	0.01702	0.143	0.013845	1.815653
Section 4	2608.476947	0.87	0.022694	0.113	0.013845	1.511668
Section 5	2391.103868	0.87	0.020803	0.087	0.013845	0.82139
Section 6	3260.596183	0.87	0.028367	0.067	0.013845	0.664292
Section 7	3043.223104	0.87	0.026476	0.047	0.013845	0.3051
Section 8	3260.596183	0.87	0.028367	0.030	0.013845	0.133184
Section 9	3477.969262	0.87	0.030258	0.016	0.013845	0.040409
Section 10	3477.969262	0.87	0.030258	0.005	0.013845	0.003946
Limb Total	26302.14255	0.87	0.228829	-	0.013845	9.659146
Bow Total	-	0.87	-	-	-	19.31829

Table A.41 Limb Return Energy Expenditure - 75# Segment Bow

75 Pound Segment Bow	Segment Volume (ml)	Segment Density (ρ)	Segment Mass (kg)	Segment Travel (m)	Travel Time (s)	Energy(J) = $kg*m^2/s^2$
Section 1	1521.612	0.87	0.013238	0.210	0.011627	4.318666
Section 2	2391.104	0.87	0.020803	0.172	0.011627	4.552632
Section 3	3043.223	0.87	0.026476	0.130	0.011627	3.309998
Section 4	3912.715	0.87	0.034041	0.097	0.011627	2.369349
Section 5	3912.715	0.87	0.034041	0.067	0.011627	1.130408
Section 6	4782.208	0.87	0.041605	0.041	0.011627	0.517373
Section 7	4782.208	0.87	0.041605	0.022	0.011627	0.148964
Section 8	5216.954	0.87	0.045387	0.009	0.011627	0.027196
Section 9	5651.7	0.87	0.04917	0.004	0.011627	0.00582
Section 10	5651.7	0.87	0.04917	0.000	0.011627	0
Limb Total	40866.14	0.87	0.355535	-	0.011627	16.38041
Bow Total	-	0.87	-	-	-	32.76081

Table A.42 Limb Return Energy Expenditure - 100# Segment Bow

100 Pound Segment Bow	Segment Volume (ml)	Segment Density (ρ)	Segment Mass (kg)	Segment Travel (m)	Travel Time (s)	Energy(J) = $kg*m^2/s^2$
Section 1	1738.985	0.87	0.015129	0.210	0.010341	6.239489
Section 2	2173.731	0.87	0.018911	0.172	0.010341	5.232115
Section 3	3043.223	0.87	0.026476	0.130	0.010341	4.184419
Section 4	3912.715	0.87	0.034041	0.097	0.010341	2.995273
Section 5	4347.462	0.87	0.037823	0.067	0.010341	1.587815
Section 6	5216.954	0.87	0.045387	0.041	0.010341	0.713509
Section 7	5434.327	0.87	0.047279	0.022	0.010341	0.213996
Section 8	5869.073	0.87	0.051061	0.009	0.010341	0.038678
Section 9	6303.819	0.87	0.054843	0.004	0.010341	0.008206
Section 10	5869.073	0.87	0.051061	0.000	0.010341	0
Limb Total	43909.36	0.87	0.382011	-	0.010341	21.2135
Bow Total	-	0.87	-	-	-	42.427

Table A.43 Limb Return Energy Expenditure - 25# Double-Concave Bow

25 Pound Double-Concave Bow	Segment Volume (ml)	Segment Density (ρ)	Segment Mass (kg)	Segment Travel (m)	Travel Time (s)	Energy(J) = $kg*m^2/s^2$
Section 1	2173.731	0.4	0.00869492	0.227	0.01868	1.284033
Section 2	2608.477	0.4	0.01043391	0.197	0.01868	1.160482
Section 3	3043.223	0.4	0.01217289	0.139	0.01868	0.674035
Section 4	4782.208	0.4	0.01912883	0.124	0.01868	0.842928
Section 5	2608.477	1.91	0.04982191	0.087	0.01868	1.080731
Section 6	17640	1.91	0.0336924	0.054	0.01868	0.281565
Section 7	17640	1.91	0.0336924	0.032	0.01868	0.098876
Section 8	17640	1.91	0.0336924	0.013	0.01868	0.016318
Section 9	17640	1.91	0.0336924	0.003	0.01868	0.000869
Section 10	2608.477	1.91	0.04982191	0.000	0.01868	0
Limb Total	88384.59	-	0.28484397	-	0.01868	5.439837
Bow Total	-	-	-	-	-	10.87967

Table A.44 Limb Return Energy Expenditure - 50# Double-Concave Bow

50 Pound Double-Concave Bow	Segment Volume (ml)	Segment Density (ρ)	Segment Mass (kg)	Segment Travel (m)	Travel Time (s)	Energy(J) = $kg*m^2/s^2$
Section 1	2173.731	0.4	0.008695	0.227m	0.013598	2.423058
Section 2	2608.477	0.4	0.010434	0.197m	0.013598	2.189908
Section 3	3043.223	0.4	0.012173	0.139m	0.013598	1.271949
Section 4	4782.208	0.4	0.019129	0.124m	0.013598	1.590663
Section 5	2608.477	1.91	0.049822	0.087m	0.013598	2.039413
Section 6	22745.8	1.91	0.043444	0.054m	0.013598	0.685123
Section 7	22745.8	1.91	0.043444	0.032m	0.013598	0.240592
Section 8	22745.8	1.91	0.043444	0.013m	0.013598	0.039707
Section 9	22745.8	1.91	0.043444	0.003m	0.013598	0.002115
Section 10	2608.477	1.91	0.049822	0.000m	0.013598	0
Limb Total	108807.8	-	0.323852	-	0.013598	10.48253
Bow Total	-	-	-	-	-	20.96506

Table A.45 Limb Return Energy Expenditure - 75# Double-Concave Bow

75 Pound Double-Concave Bow	Segment Volume (ml)	Segment Density (ρ)	Segment Mass (kg)	Segment Travel (m)	Travel Time (s)	Energy(J) = $kg*m^2/s^2$
Section 1	2173.731	0.4	0.008695	0.227	0.011725	3.259108
Section 2	2608.477	0.4	0.010434	0.197	0.011725	2.945511
Section 3	3043.223	0.4	0.012173	0.139	0.011725	1.710821
Section 4	4782.208	0.4	0.019129	0.124	0.011725	2.139504
Section 5	2608.477	1.91	0.050865	0.087	0.011725	2.800537
Section 6	24924.9	1.91	0.048604	0.054	0.011725	1.030948
Section 7	24924.9	1.91	0.048604	0.032	0.011725	0.362034
Section 8	24924.9	1.91	0.048604	0.013	0.011725	0.05975
Section 9	24924.9	1.91	0.048604	0.003	0.011725	0.003182
Section 10	2608.477	1.91	0.050865	0.000	0.011725	0
Limb Total	117524.2	-	0.346575	-	0.011725	14.31139
Bow Total	-	-	-	-	-	28.62279

Table A.46 Limb Return Energy Expenditure - 100# Double-Concave Bow

100 Pound Double-Concave Bow	Segment Volume (ml)	Segment Density (ρ)	Segment Mass (kg)	Segment Travel (m)	Travel Time (s)	Energy(J) = $kg*m^2/s^2$
Section 1	2173.731	0.4	0.008695	0.227	0.010388	4.151659
Section 2	2608.477	0.4	0.010434	0.197	0.010388	3.75218
Section 3	3043.223	0.4	0.012173	0.139	0.010388	2.179353
Section 4	4782.208	0.4	0.019129	0.124	0.010388	2.725436
Section 5	2608.477	1.91	0.050865	0.087	0.010388	3.567503
Section 6	26290.6	1.91	0.051267	0.054	0.010388	1.385246
Section 7	26290.6	1.91	0.051267	0.032	0.010388	0.486451
Section 8	26290.6	1.91	0.051267	0.013	0.010388	0.080283
Section 9	26290.6	1.91	0.051267	0.003	0.010388	0.004275
Section 10	2608.477	1.91	0.050865	0.000	0.010388	0
Limb Total	122987	-	0.357228	-	0.010388	18.33239
Bow Total	-	-	-	-	-	36.66477

Table A.47 Stored, Transferred and Predicted Energy

Bow	Stored Energy (J)	Transferred Energy (J)	Predicted Transferred Energy (J)
25 Pound Double-Concave	25.816	19.36948	14.93633
50 Pound Double-Concave	50.97	37.5019333	30.00494
75 Pound Double-Concave	77.2	50.3434477	48.57721
100 Pound Double-Concave	102.578	77.3976528	65.91323
25 Pound Segment	29.910	21.32325	20.1060754
50 Pound Segment	41.261	25.62768	21.94271
75 Pound Segment	59.845	28.7292213	27.08419
100 Pound Segment	74.016	35.2331668	31.589

***Arrow mass remained constant throughout testing at 26g.**

Table A.48 Ideal, Observed, and Predicted Arrow Velocities*

Bow	Ideal Arrow Velocity (m/s)	Observed Mean Arrow Velocity (m/s)	Predicted Arrow Velocity (m/s)#
25 Pound Segment	47.96	38.6	33.89
50 Pound Segment	56.34	53.71	48.04
75 Pound Segment	67.84	62.23	61.13
100 Pound Segment	75.46	77.16	71.21
25 Pound Double-Concave	44.56	40.50	39.33
50 Pound Double-Concave	62.62	44.40	41.08
75 Pound Double-Concave	77.06	47.01	45.64
100 Pound Double-Concave	88.83	52.06	50.42

***Arrow mass remained constant throughout testing at 26g.**

#Velocity after subtracting estimated amount of energy required for limb return.

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