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Faculty of Engineering and Physical Sciences

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Standardised Equipment or Specialist Groups? The Role of Archery Aboard Mary Rose

by

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Abstract

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Contemporary records uphold medieval English archers as among the most formidable opponents in European history. Equipped with the longbow, they defeated so many French soldiers throughout the period that after the naval battle of Sluys it was said that if fish could speak, they would do so in fluent French. Yet, what we know about the weapon itself is very little, and poorer understood still is the use of the longbow as a naval weapon.

The collection of 172 longbows recovered from Henry VIII's warship, *Mary Rose*, offers a unique opportunity to gain new insight into this important weapon. However, since the initial study of the bows, led by Robert Hardy, they have not been revisited, and many unanswered questions remain. Moreover, the bows have lost their maritime context; more often being discussed as examples of longbows used during the land battles of the Medieval Period, such as the ever-popular Battle of Agincourt.

Using a multidisciplinary approach, including the use of X-ray Computed Tomography, material science, and experimental archaeology, this research aimed to investigate some of the remaining questions about the longbows. Specifically focusing on the function of the longbows in terms of draw weight and range, and the tactical role of archery aboard the ship.

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Research Thesis: Declaration of Authorship

Print name: Abigail Christine Parkes

Title of thesis: Standardised Equipment or Specialist Groups? The Role of Archery Aboard *Mary Rose*

I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University.
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
3. Where I have consulted the published work of others, this is always clearly attributed.
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
5. I have acknowledged all main sources of help.
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.
7. None of this work has been published before submission.

Signature: Date:

Acknowledgements

Firstly, I would like to thank all those who contributed their knowledge and experience to this project. My supervisor, Professor Tomas Polcar, for your support of this project since it was just a rough idea off the back of a third-year dissertation, and for your feedback and help throughout. All of the muvis team for their help with the CT scanning for this project, but especially Dr Katy Rankin, who bore the brunt of my repeated questions. Dr. Alex Hildred, who provided access to the collection as well as Robert Hardy's notes throughout this thesis and the work leading up to it. Joe Gibbs, the bowyer who crafted the replicas used in this project. Daniel Hawley, who gave up his personal time to provide access to Fort Purbrook as well as providing valuable personal insight that allowed us to redesign the machine grip. Joff Williams, who provided arrows for the replica longbows and tonnes of helpful experiential information about arrows. Then came all the way to Southampton to spend two days shooting arrows with me in a moat. Bartosz Wawrzyniak, who built the shooting machine used in this project and continued to work on it after the required work for his degree in order to make improvements to the design that improved the function.

Secondly, I would like to thank everyone who supported me along the way. Between worldwide and personal dramas, the path to completing this thesis has not been an easy one. I could not have done it without the people who believed in me, struggled with me, and laughed with me. Whether I knew you before I started or met you along the way, thank you for being there.

Last but by no means least, I would like to give a special thanks to Dr. Bethany Harding (not quite official at time of writing but basically there). We have been on this crazy journey together literally since day one and I couldn't have done it without you. Thank you for your endless love and support.

And to word, no. This project is still not about bowls.

Chapter 1

Bows That Are Long: An Introduction to Longbows and the *Mary Rose* Collection

The English longbow is perhaps the most iconic weapon in English history. Well-known for leading England to victories over her enemies during the Medieval period, particularly the French during the Hundred Years War, the longbow has gained a reputation as a formidable and unbeatable weapon, with its importance remaining evident today in popular culture. From the Lord of the Rings to the King, to the newest rendition of Robin Hood, the longbow has become enshrined in myth and legend. Even flipping the bird is said to originate from English soldiers showing off and threatening the French with their ability to use a bow. Yet, what we know about the reality of the weapon is hardly anything at all.

Prior to the discovery of Henry VIII's favourite warship, *Mary Rose*, there were no surviving longbows from the Medieval or Tudor period, when the longbow was at its height. What was known about the weapon came mostly from historical literature and iconography, as well as much older artefacts from elsewhere in Europe. This changed during the excavations of *Mary Rose*, when 172 longbows were recovered, a majority of which were complete and appeared almost brand new, offering a unique opportunity to gain new insight into this important weapon. After being dried, the complete longbows were recorded, and a preliminary study of their dimensions was carried out. The results of which were published in an extensive two-part volume covering all *Mary Rose* weapons, Weapons of Warre. This study included testing of a select few longbows in an attempt to find their draw weight. However, this instead revealed that the longbows were more structurally degraded than they appear. Mathematical models and experimental archaeology were used in the place of this direct testing to gain an estimate of the longbows' draw weight, finding an average of 130 lbs (59 kg) at a 30 in draw length and maximum of 185 lbs (84 kg) for two very large longbows. However, these high draw weights have always been a controversial finding and many unanswered questions about the longbows remain, including about their place tactically aboard the ship and who the archers were that were using them. The main aim of this study was to begin to investigate these outstanding questions to further our understanding of the *Mary Rose* collection, as well as longbows in general.

While the importance of the collection in furthering our understanding of how the longbow came to be one of the most feared weapons in Europe cannot be overstated, it is also important to recognise the maritime context of the finds. As highlighted in Arnstad and Parkes (2021), the bow-and-arrow as a naval weapon is an understudied area of military history, despite a wealth of evidence for its use. The use of longbows specifically, is outshone by the famous land battles of the Hundred Years War. Since their discovery, the *Mary Rose* longbows have been the basis of replicas for many tests of performance to 'prove' their effectiveness against armour in these battles, while their use on the ship is left unstudied. Some scholars even suggest that the longbows found in chests aboard *Mary Rose* were merely in transit for the possibility of having to battle the French on land. By thinking tactically about the use of the longbow at sea, this thesis provides a much-needed reunion between the artifacts and their maritime context. Historical records show that longbows were valuable weapons for Henry VIII's navy. They were not just a relic from the past that can only help us understand the land battles of Agincourt or Crécy.

Through a combination of materials engineering techniques and experimental archery, data was collected from five replica longbows and a selection of *Mary Rose* longbows with the aim of addressing the question "were the longbows a standardised weapon everyone could use or were there specialist archers aboard the ship". In order to answer this question more information on the performance of the longbows was needed. In this thesis, the performance is considered to be the draw weight of the longbow and how this translates to initial arrow speed. Replica longbows were used to further understand the link between the physical characteristics of the longbow and its performance. This relationship that was then translated to the *Mary Rose* longbows, through the gathering of identical physical measurements, to analyse whether the observable differences in the collection relate to differences in their performance, potentially indicating different uses aboard the ship, or if the collection is made up of similar longbows all suitable for the average medieval soldier.

1.1 What is a longbow?

The longbow is a type of self-bow found mainly in North-western Europe. Self-bows are wooden bows crafted from a single stave of wood and not combined with other materials, as with the composite bow. Yew wood is considered to be the best wood for making longbows, however, bows of witch hazel and elm have also been found and classified as longbows. The wood is shaped so that the belly is rounded, and the back is flat, giving the longbow a characteristic D cross-section, which is generally measured using the depth-to-width ratio. In yew longbows, this shape also makes use of the different properties of the heartwood and sapwood, with the more flexible sapwood on the belly and the stronger heartwood on the back (Figure 1-1).

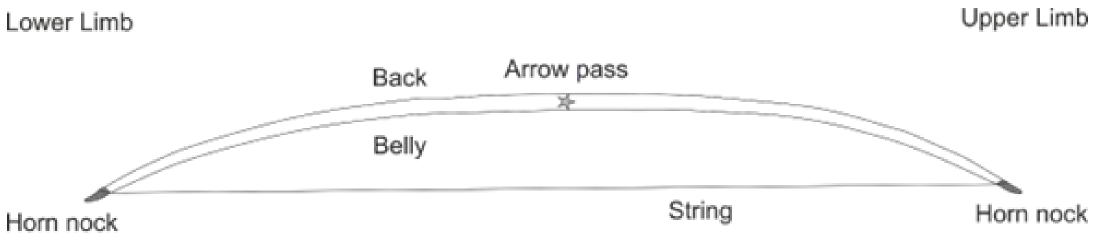


Figure 1-1 (Top) A diagram of a strung longbow showing belly and back, upper, and lower limb, horn nocks, and placement of an arrow. (Bottom) A photograph of a section of replica longbow showing the sapwood and heartwood components.

Their shape also distinguishes the longbow from other forms of self-bow, such as the flat bow, which has wide, flat limbs that are rectangular in cross-section (Figure 1-2). The longbow is also different from the flatbow and other bows in that it is designed to bend full compass. This means that the entirety of the longbow bends when it is drawn, rather than having a rigid centre where the bow is held, with limbs that bend. Although archers may have wrapped material around the longbow where it would be held, the wood itself is not usually shaped to have a defined grip area.

1.1.1 History and Origin

Edward I has often been credited for introducing the longbow to the English army after its “discovery” in Wales during his campaigns in the late thirteenth century. This was supposedly accompanied by a drastic change in military organisation and tactics from which the latter, more famous, victories of England in the Hundred Years War were built. However, this early 20th century view has more recently been revised, particularly in Strickland and Hardy’s ‘The Great Warbow’. The bow-and-arrow is an extremely old weapon, potentially dating back 50,000 years (Hardy, 2006), which has been used throughout six of the seven continents. The history of the longbow is similarly rich, as is the evidence of the use of the bow-and-arrow at sea. Extensive histories of the longbow have already been produced by other authors (For example: Heath, 1980; Bradbury, 1985; Hardy, 2006; Strickland & Hardy, 2005), so only a brief outline of its origin and use as a maritime weapon, and the rise and fall in English popularity will be given here. For a more complete history of the bow-and-arrow as a maritime weapon see Arnstad and Parkes (2021).

The earliest confirmed bow specimens come from European Mesolithic bog sites. Some fragmentary wooden pieces found alongside wooden arrow shafts in Stellmoor, Germany, are believed to be the remains of bows, dating to 9,000BCE. Complete elm self-bows have been recovered in Holmegaard, Denmark dating to around 6,000BCE (Grayson, et al., 2007). The first appearance of a yew longbow, similar to those found on *Mary Rose*, was found alongside the stone-age “iceman Ötzi”, who lived somewhere around 3400 BCE and 3100 BCE (Loades, 2019). Forty similar longbows were found during the excavations of the Nydam-boat, Denmark alongside over 100 arrows (Soar, 1996) showing that warships were well armed with bows by the 4th Century AD.

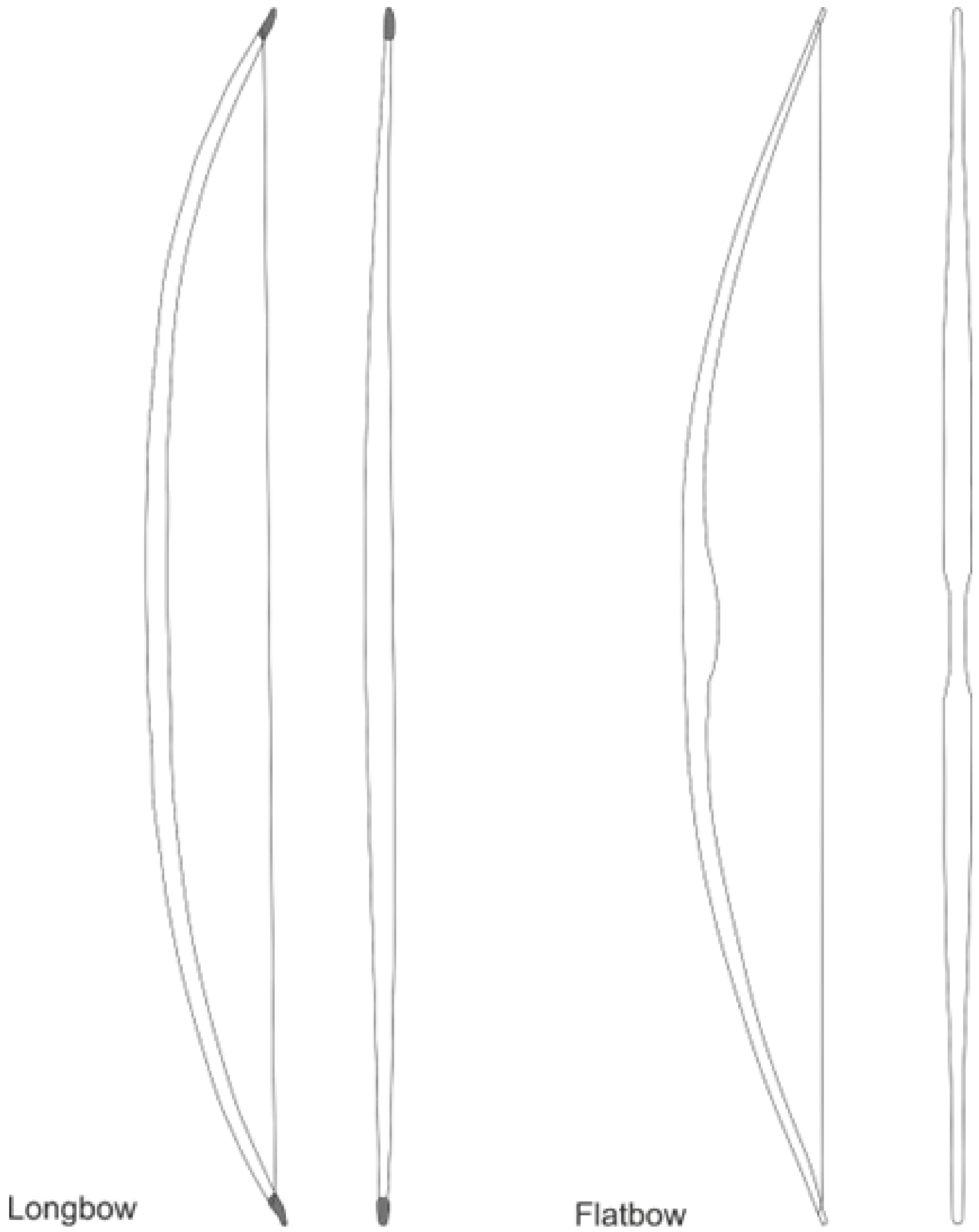


Figure 1-2 Diagram showing the overall shape the longbow (left) when strung and unstrung, and the flatbow (right) when strung and unstrung.

These same longbows continued to be used by their descendants in Anglo-Saxon Britain and in the Viking world. Although archaeological evidence of this is rare is it not non-existent. The most well-known finds are from Hedeby, a Viking Age trading settlement on the Jutland Peninsula, which revealed a complete yew longbow measuring 191cm, as well as 6 fragments (Geibig & Paulsen, 1999). With other bow finds from Germany, Netherlands, and Ireland spanning for the seventh to the thirteenth centuries CE (Haplin, 1997; Lanting, 1999; Flemming, et al., 2001; Haplin, 2008). Viking sagas and chronicles also indicate that bows were important weapons, especially in ship-to-ship combat (Soar, 1996). During the 1066 Norman conquest, it is an arrow to the eye which first wounds King Harold and ultimately leads to his demise (Strickland & Hardy, 2005).

The use of archery continued in Anglo-Norman England, with tactics similar to those employed in the Hundred Years War; foot soldiers flanked with archers in a defensive position. This was particularly true in the battles of Bourgtheroulde (1124) and Standard (1138) (Strickland & Hardy, 2005). Around the same time, Norman expansion in the Mediterranean lead to the development of the tactical use of archery at sea. After suffering defeat from the Venetian army at the Battle of Corfu in 1084, warships with higher platforms were developed to increase the efficiency of naval archers, a precursor to the fore and aft castles of the later medieval period (Stanton, 2015).

In the latter half of the twelfth century and into the thirteenth century, the longbow fell out of military use on land in England, with the crossbow and mounted knights favoured instead. However, the weapon remained in use for hunting and smaller scale battles, particularly in forested regions. It is from this that tales of the legendary Robin Hood likely developed (Strickland & Hardy, 2005). Additionally, the longbow seems to have remained an important weapon at sea. The cog, the most common ship type in Northern Europe, was highly suited to the use of naval archery with high freeboards as well as having additional elevated stern and forecastles installed for conflict. This vessel proved itself in battle in 1217 at the Battle of Sandwich – also known as the Battle of Dover (Stanton, 2015). The use of the longbow by the English to defeat the French is shown in the illustration of the Battle of Sandwich from Matthew Paris OSB, Chronica maiora II. Interestingly this image also shows a bag over the tip of the arrow, potentially indicating the use of fire arrows (Figure 1-3).

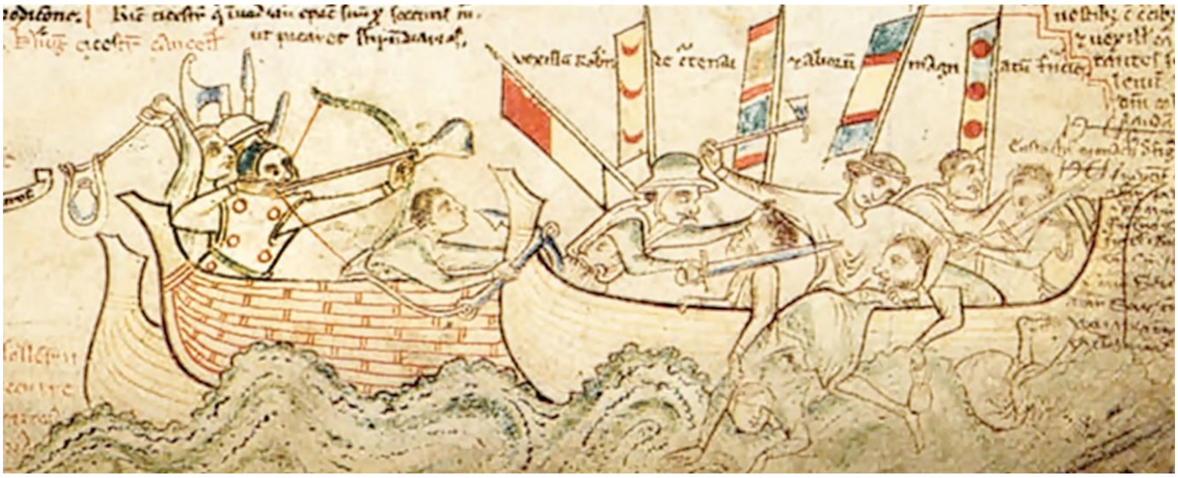


Figure 1-3 Illustration of the Battle of Sandwich from Matthew Paris OSB, Chronica maiora II showing an archer with arrow enclosed in a bag.

Thus, the idea of the discovery of the longbow in Wales falls apart because the longbow was already well-known in England. While Edward I can be credited for reintroducing archers in large numbers, they were largely ill-equipped and poorly organised. The real developments in the English army occurred in the thirty years after his reign, following many crushing defeats against the Scots lead by Robert Bruce. It is at this time tactics reverted back to dismounted armies flanked by defensive archers, paving the way for early victories in the Hundred Years war, such as Crecy (1346) and Poitiers (1356), which are commonly linked to English prowess with the longbow (Strickland & Hardy, 2005). However, it was not in these land battles that the longbow proved itself for the first time. In fact, it was at the naval Battle of Sluys in 1340 where an estimated 25,000 – 30,000 French and Genoese soldiers were killed by the English fleet. Despite the importance of the longbow in this victory being noted by multiple contemporary sources, such as the French writer Jean Froissart (c. 1337–c. 1405) (DeVries, 1995 and 2002), the Battle of Sluys is frequently ignored when talking about the efficacy of the weapon in this period.

The reign of Edward III also saw the beginning of the royal decrees that mandated regular practice with the longbow, which became a regular occurrence well into the sixteenth century. By Agincourt (1415), the most studied and well-known battle of the Hundred Years War, the English army had reached their peak, both in terms of tactics and organisation (Strickland & Hardy, 2005).

The start of the Tudor period (1485–1603) has previously been considered the end of the longbow’s career, its usage in decline as gunpowder weapons overtook it in efficiency (Heath, 1980, p. 152). However, particularly in terms of its use at sea, this does not appear to be accurate. Historical records show that Henry VIII (1509–1547) was a keen sport archer and passed laws to continue the tradition of training all young men to be proficient longbow archers. He had the highest quality European yew wood imported for his armies and paid bowyers handsomely for making the staves into longbows (Hardy, 2006). In terms of naval archery, records such as the Anthony Roll of 1545 show that all the ships in the Henrician fleet were equipped with a large number of longbows and arrows, the most famous of which was *Mary Rose*. Indeed, even towards the end of the period, the prospect of abandoning the longbow sparked a fierce debate (Tallet & Trim, 2010). Not only had the use of the longbow become a patriotic activity, but trades, such as longbow making and fletching, stood to suffer significantly from the removal of archers from the military (Esper, 1965). However, despite resistance, the longbow was officially abandoned in 1595, when the Privy Council mandated that only arquebusiers, caliver-men and musketeers be enrolled, and all longbows currently in use must be exchanged for these (Heath, 1980).

1.1.2 Variations

Variations of the longbow include the medieval warbow and the Victorian target bow. As discussed above, longbows have been used for millennia, however the earliest bows are considered to have been primarily used and designed for hunting instead of warfare. To contrast this, the longbows used by the English army during the Medieval and Tudor periods are often referred to as “warbows”. Many historians believe that these longbows were significantly more powerful than their predecessors and even contemporary longbows designed for hunting, allowing the arrows to fly further and penetrate armour.

In the seventeenth and eighteenth centuries, the longbow saw a renaissance of the weapon as a popular past time. However, this ‘longbow’ was typically lighter than the medieval warbow, with a draw weight around 30 to 60lbs, depending on the user. Additionally, they were often laminated with other woods, such as lemonwood, oak and osage orange, as suitable yew became more difficult to find. These bows did also not bend full compass, with a non-working handle in the centre of the bow. Although this sport became popular before her reign, Victoria was a keen archer and the craze came to its height during this time, meaning these bows are often referred to as Victorian longbows or Victorian Target Bows.

1.1.3 Does Length Really Matter?

The length of the longbow is commonly taken to be the most important defining feature of the weapon, as the name itself seems to suggest. The phrase “Longbows are bows that are long” appears in many texts on the subject and are in some cases the extent of the definition. However, there is not a minimum length requirement for a bow to be classed as a longbow. It is widely believed that the longbow was traditionally crafted to be two hands higher than the person that were to use it. Theoretically, this means that for the amount of variation in height in the population, there is an equal amount of variation in the length of longbows, which makes having a specific defined length difficult, especially when both women and children would have had them, not just adult men. However, there is still a large debate around the topic, as well as the possible existence of a similar but shorter bow; the shortbow.

Rogers (2011) attempts to define the length of a longbow, as well as four other ‘types’ of bow; the shortbow, the medium bow, the ordinary bow and the near longbow or transitional bow, which make up a large range of lengths. According to this definition, shortbows are bows that are up to the breastbone of the average man, around 3’9”. Medium bows are between breastbone and shoulder high, approximately 3’9” to 5’3”. The phrase ‘ordinary bows’ is used to encompass both medium and short bows. These are the prerequisite to the true longbow, which were supposedly used in the early medieval period. Near longbows are between shoulder and head height and serve as an intermediate between medium bows and the true longbow. The *Mary Rose* bows represent the “fully-developed longbow”, bows that are 5’8” or taller. However, this categorisation is not agreed amongst historians.

The idea of the existence of a prerequisite to the longbow was first discussed by late nineteenth century scholars, such as Charles Oman and J.E. Morris. These authors identified a change in military tactics within the English army from the archers playing a minor role to a major role during the reign of Edward I. They explained this change by suggesting that prior to this period the bows available were much smaller and weaker, and therefore less effective in battle. They believed that the longbow proper wasn’t used by the

English until Edward I discovered the longbow in use in South Wales, recognised its potential and incorporated it into his army. Initially, this was generally accepted by historians, with only the work of Bradbury (1985) offering any challenge to the idea.

Bradbury argues that there is not enough of a difference between the supposed shortbow, or what he calls the ordinary wooden bow, and the longbow to justify the separation of the two. Instead, he suggests that there is likely an increase in bow length over time, but this is due to increase practice with the weapon, which allows the higher draw weights caused by lengthening the limbs, not an invention of a brand-new weapon. Additionally, while there is some tactical change and increase in the use of archery during the reign of Edward I, the change is not as drastic as other authors have indicated. The increased chronicling of the use of archery is part of an increase chronicling of weaponry in general, and there is evidence that indicates archery was important in the English army prior to 1300AD (Bradbury, 1985). Additionally, the discovery of longbows dating back to prehistoric times, offer evidence that the longbow was not an English invention nor was it developed in the Medieval period.

Despite this, many historians continued to advocate for the shortbow and the development of the longbow as being a key part of a revolution in infantry tactics. Rogers in particular has continued the argument for the existence of the shortbow and a revolution in English tactics that surrounds the development of the longbow. In “The military revolutions of the Hundred Years War” (Rogers, 1993), he describes two revolutions that occurred in Europe during the Hundred Years War: the infantry revolution and the artillery revolution. The infantry revolution is characterised by a change the army being primarily made up of mounted knights to foot soldiers. For the English army, the development of the longbow from the 4ft elm welsh bow was a key part of this revolution, as the 6ft longbow stores 25% more energy than a 4ft bow, making it more powerful. Even after Strickland’s (2005) thorough criticism of the theory, Rogers has continued to argue for the existence of the shortbow, publishing “The development of the longbow in late medieval England and “technological determinism”, where he proposes the definitions outlined above, specifically to address Strickland’s contention.

In general, this discussion has taken the word longbow too literally in attempting to define length categories for this type of bow. The introduction of a multitude of terms by Rogers does nothing but complicate the topic, and his attempt to give his categories numerical values is unsuitable. These measurements are based on the average height of a man being 5’8”. However, it seems to have been forgotten that when using an average, people both taller and shorter than this height are present in the population. In fact, the average height of the skeletons aboard *Mary Rose* is 5’6”, with the shortest man measuring 1529mm and the tallest 1803mm, approximately 5’ and 5’10” respectively (Mitchell, personal communication, 2020). This clearly brings into question Rogers’ categories as a “fully-developed longbow” measuring to head height for the shortest man would fall into Rogers’ medium bow category numerically. Meanwhile a bow of 5’8” would appear as a near longbow against the tallest individual, not a true longbow as the measurement suggests.

The ‘shortbows’ from Waterford, Ireland, which Rogers refer to, are essentially the same as those from *Mary Rose* in their other design aspects; they are made of yew, heartwood and sapwood are present, some of the fragments feature double knocks and two seem to feature marks as the *Mary Rose* longbows do (Haplin, 1997). Even within the *Mary Rose* collection there is a large variation in shape and size, as discussed in section 1.3. Therefore, even the *Mary Rose* longbows cannot be said to give an idea of the “typical” longbow length that could be used as a basis for categorisation. As stated by Bradbury (1985), “one man’s longbow is another man’s shortbow”. There were certainly shorter bows as there were shorter men, as well as women and children using bows during the period.

The aim of this work is to understand the functionality of the weapon and how it changes as a result of variations in length, overall shape, and internal wood structure. Thus, definitions that mandate a certain length or width are unsuitable. Additionally, they are not necessary to understand the place of the longbow in British society or it’s usage in battle. The term longbow does not appear in literature until much later than the supposed rise of the weapon, and even in this instance this is only used to contrast to the crossbow, while shortbow is not used at all. Even Rogers admits that these are modern classifications. Trying to retrospectively impose categorisations onto longbows has done nothing to aid in the understanding of the weapon itself. A theoretical approach that focuses on understanding the artefacts we have and using that information to think about the culture and society which they were part of will be more useful to gain an insight into this weapon and the use of archery than continuing the debate of how long a longbow is.

1.2 Other Definitions

Other terms used in this thesis which require definition are brace height, draw length and draw weight.

Brace height: the distance between the belly of the bow and the string when the bow is strung.

Draw length: the distance between the belly of the bow and the string when the bow is drawn, including the brace height. For example, in a bow with a draw length of 28 inches and an initial brace height of 6 inches, the string is drawn back an extra 22 inches.

Draw weight: the force needed to bring the bow to full draw. This is traditionally discussed in pound-force but will be measured initially in newtons for this project, and then converted for comparison to other work.

1.3 Mary Rose Collection

Mary Rose was the flagship of King Henry VIII's navy from her completion in April 1512 to the fateful day of her sinking, 19th July 1545. During this time, she was involved in several battles against the French and Scottish and underwent repairs and a rebuild in 1527 and 1536, respectively. Unusually for kings at the time, Henry VIII followed a policy of maintaining his navy in times of peace, and she was placed under the care of ship keepers when not in use (Lavery, 2015). The cause of her sinking in 1545 has been the subject of debate ever since. Contemporary texts show two different accounts based on the nationality of the author; the French of course claimed to have sunk her, while associates of her captain blamed an incompetent and unrulily crew (Moorhouse, 2005). Today, the most likely explanation is believed to be that the rebuild of 1536 overloaded her with cannons, which, along with the weight of a fully armoured crew, lowered her gunports too close to the water, putting her in a very risky position (Rule, 1982). Whether it was due to the wind, a sudden rush of crew to one side or an error while turning, water flooded in through her gunports and brought her down.

Shortly after, Henry VIII hired a group of Venetians, the salvage specialists of the time, to attempt to salvage *Mary Rose*. However, during their attempts, the main mast was pulled from the mast step and so she was abandoned, aside from some recovery of ordnance (Rule, 1982; Moorhouse, 2005). The ship was then largely forgotten about until the Deane Brothers discovered her in 1836, while working on Royal George. Over the next four years the brothers recovered many items from wreck, including a cannon bearing the insignia of Henry VIII and the date 1543, which allowed the wreck to be identified, and four longbows, which are housed in the Tower of London. Due to the limits of the diving equipment available at the time, excavation into the sediment was not possible and she was abandoned again (Rule, 1982). Project Solent Ships, led by Alexander Mckee, was responsible for her second and final discovery, which lead to her full excavation and raising of the hull on the 11th of October 1982 (Marsden, 2003).

During the excavation of the ship, thousands of unique artefacts were recovered, which opened up a whole new understanding of life aboard a Tudor warship. *Mary Rose* lay on her side on the seafloor and, while the portside of the ship eroded, a quick inflow of silts covered the starboard side, preserving it and all of the artefacts within it. The particular composition of the Solent silt is thought to be responsible for the preservation of wood and other organic materials on the ship, while many metal objects have completely disappeared (Allison & Briggs, 1991). Among this remarkable assemblage is a large collection of archery material, including the largest collection of yew longbows recovered, a huge number of arrows, arrow spacers, longbow chests and wrist guards. This presents a unique opportunity to learn about the use of archery at sea, but also about the infamous weapon in general.

In the following sections, an outline of the archery material found aboard *Mary Rose* will be given, a more in-depth description of these artefacts can be found in Weapons of Warre (Hildred, 2011).

1.3.1 Longbows

Of the 250 longbows recorded on the Anthony Roll 1545 as present on *Mary Rose* the day she sank (Hardy, 2006), 172 have been recovered, a majority of which are complete and appear almost band new (Hardy, 2011). The only thing missing are the horn nocks, which left behind staining on either end of each longbow, indicating where they were once present (Hardy, 2006). The longbows were found on all the surviving decks of the ship, with the largest number coming from the upper and orlop decks, where large chests of longbows were found (Figure 1-4). The castle deck was significantly more degraded than the other decks meaning that the floor does not survive, due to this it is possible some of the longbows on the upper deck were originally on the castle deck but have moved over time.

The length of the longbows ranges from 1746 mm (approximately 5’8”) to 2113 mm (approximately 6’11”), with an average of 1959 mm (approximately 6’5”). At the centre the average width and depth is 35.7 mm and 33.1 mm respectively, with and average depth to width ratio of 1:1.08. Within the collection, variations on the classic D-shape cross-section have been identified. These have been called slab-sided, flat D, round D, and deep D (Figure 1-5). Additionally, the longbows have been classified as either course, medium or fine grained, meaning they have less than 40, 41-60, or 61+ annual growth ring per inch, respectively. From weight measurements and an estimation of the volume of the longbows (Figure 1-6) an estimation of the density of the longbows was calculated, which ranged between 0.7356 and 0.4434 g per cm^3, with an average of 0.5876. There was no correlation between the grain category and the density estimate.

A small group of the longbows have been said to be handled as they have a more rounded section where the longbows could be gripped. These are also some of the larger longbows in the collection, with the highest estimated draw weight. One suggestion is that this section was used to attach a binding which would protect the longbow from burning when shooting fire arrows. Based on the work of Stretton (2017d), this theory holds, as fire arrows are heavier and therefore need a larger and stronger longbow to fire them.

Close examination of the longbows showed that many of them have incised or pricked marks around the centre of the longbow, in most cases on the upper limb just above the centre. These marks come in an array of forms; 2 to 8 chevrons, crosses, circles, flowers, and more complex marks. The most numerous types of mark are the chevrons, which appear to have been simply made with the tip of a blade. The purpose of these marks is unknown. There is too much similarity between the different marks for these to be ownership marks, as are seen on many of the other artefacts on the ship. However, if they are makers marks or indications of something, such as the arrow pass or which limb is the upper limb, as has been suggested, why are some of the longbows missing these important marks?

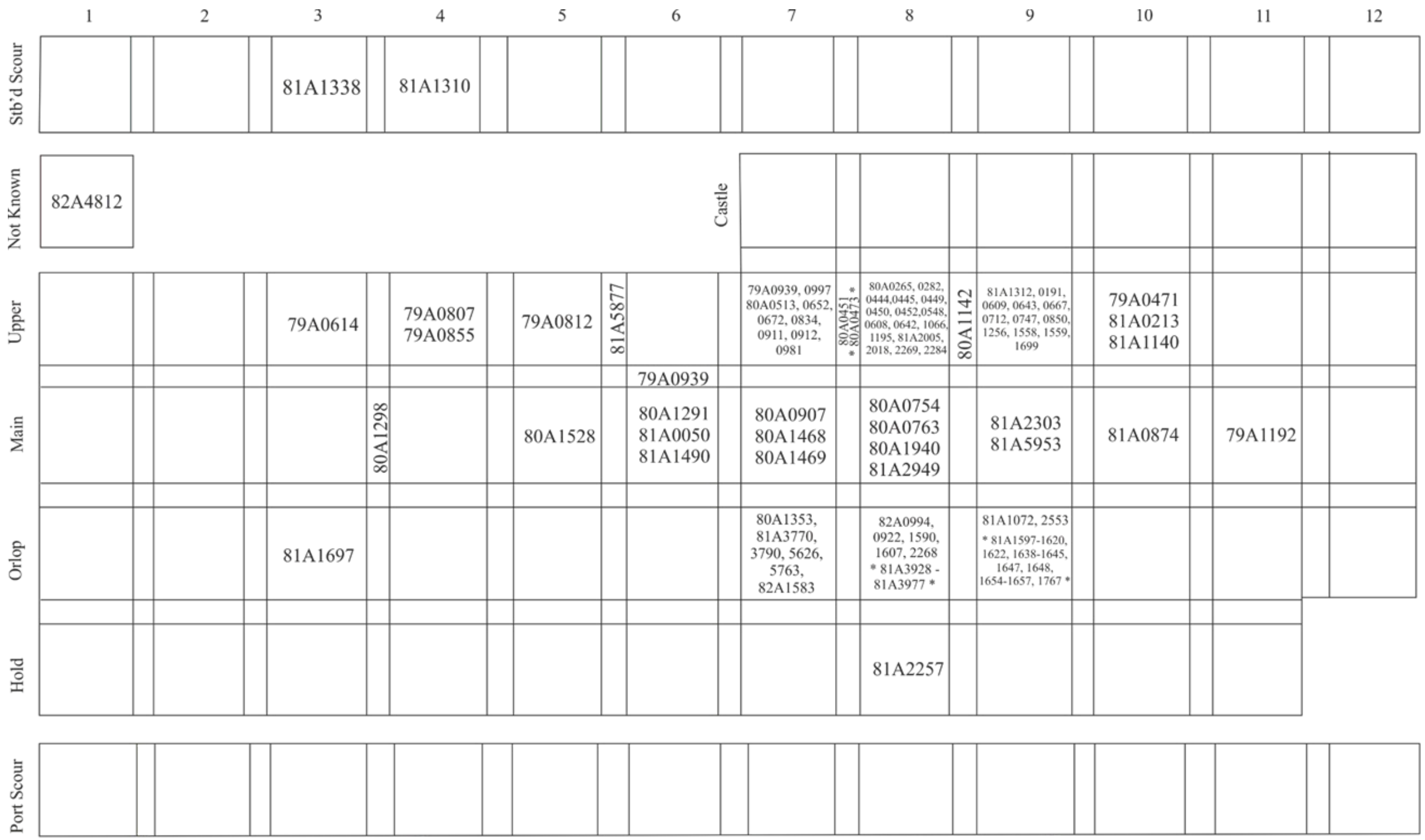


Figure 1-4 Diagram of the find locations of Mary Rose longbows, relative to the decks of the ship. Adapted from Weapons of Warre figure 8.2 (Hildred, 2011b, p. 584). ** Indicates longbows found in a chest

There also appears to be no connection between the physical properties of the longbows, including length, cross-section, grain width and handle, with their mark. This was noted in Weapons of Warre based on observation and has also investigated statistically (discussed further in chapter 2.1.4).

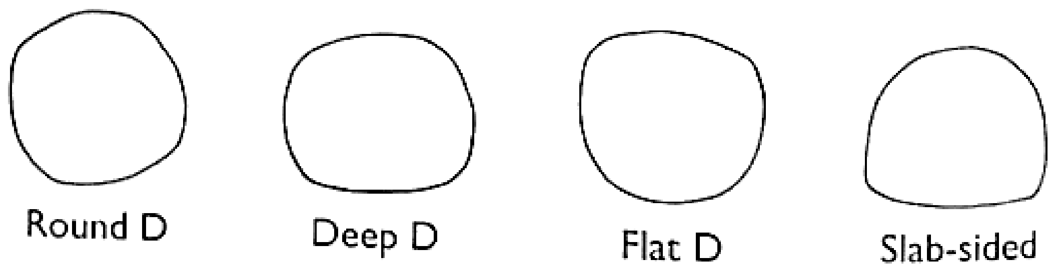


Figure 1-5 Diagram showing the four different cross-section shapes. From Weapons of Warre, figure 8.7 (Hardy, 2011, p. 592).

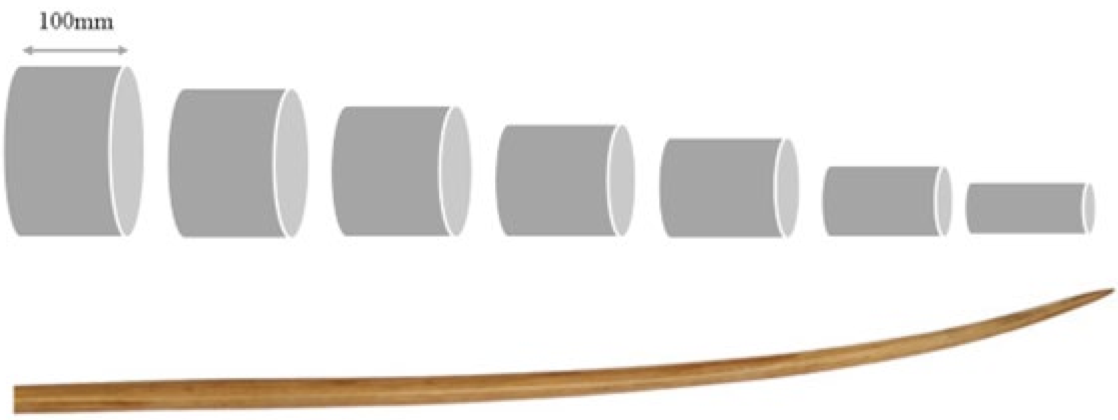


Figure 1-6 Diagram showing how the estimation of volume was calculated. Each of the bows were approximated as a series of 100mm cylinders with diameter equal to their width measurement as recorded in Weapons of Warre. The total volume was the sum of all the cylinders.

1.3.2 Arrows

The *Mary Rose* collection also includes 7834 arrow fragments, believed to represent around 3738 arrows, of these 2303 are considered complete. However, no arrow heads or complete fletching have been recovered so no arrow can be considered truly complete. The arrows are in a poorer state than the longbows, and many have undergone a lot of post-excavation and post-conservation damage, including twisting, fracturing and shrinkage. Arrows were found across all of the ship, but similarly to the longbows, a majority were recovered from chests, found on the Upper deck, Orlop deck and Hold. Some were found loose while others were tied with leather binding or within arrow spacers – small leather disks with circular holes cut into them.

The length of the complete arrows varies from 667 mm to 880 mm, with a clear bimodal distribution at 740 mm and 790 mm. When the median nock length of the arrows, 6 mm, and the median tip length, 21 mm, these modes become estimated draw lengths of 712 (approximately 28 inches) and 762 mm (approximately 30 inches). There are more 30" arrows than 28", in a proportion of 4.5:1.

The Anthony Roll lists 9600 arrows being present aboard *Mary Rose*, however, unlike the longbows, the wood for the arrows is unspecified. An analysis of the wood species aboard the ship found that nine different woods were used for the arrows (Table 1-1), with the most prevalent being poplar. This variety of woods is notable because the species used would affect the weight and spine of the arrow, which are both considered to be directly related to the draw weight of the longbow it can be successfully shot from Watson (2011a) found a significant difference between the weights of the arrows linked to the wood species they were made from, with the biggest difference being between poplar and birch shafts, at 33.5 g and 52.4 g respectively.

Five different arrow shapes, also called profiles, have been identified within the collection (Figure 1-7); barrelled, bobtailed, breasted, parallel, and saddled (Watson, 2011c). Barrelled shafts taper towards the ends, which is known to reduce the vibration of the arrow, giving greater stability, which is needed when shooting a long distance. Bobtailed are also considered to be good for distance shooting, with a taper from the shoulder to the nock (Watson, 2011c, pp. 682-683). Soar (2010) has also suggested that this type would be best for heavier arrowheads. Breasted shafts taper in the opposite direction, from nock to shoulder, and are noted by Ascham (1545) to be best at point blank range. Parallel are more or less the same diameter along the shaft, making them a more general-purpose type. Saddled shafts have a reduced diameter towards the middle but have not been noted to have any specific usage yet. Some authors have even suggested that this is not a purposeful shape but rather a result of moisture distribution at the time of making (Watson, 2011c). However, they do make up a similar percentage of the arrows studied from *Mary Rose* to the breasted shafts, which seems strange for an accidental creation (Table 1-2).

Species	Number	% of Sample
Poplar	501	77
Birch	90	14
Alder	38	6
Willow	7	1
Elder	3	0.50
Hornbeam	2	0.30
Birch/Poplar	2	0.30
Hawthorn	1	0.15
Ash	1	0.15
Walnut	1	0.15

Table 1-1 The different wood species found in a sample study of Mary Rose arrows. From Weapons of Warre, table 8.35 (Watson, 2011c, p. 674)

Species	Barrelled	Bobtailed	Breasted	Parallel	Saddled	Total
alder	7	6	1	3	1	18
birch	7	33	1	20	2	63
elder	0	1	0	0	0	1
hornbeam	0	1	0	0	0	1
poplar	19	34	1	28	2	84
willow	0	3	0	2	0	5
Total	33	78	3	53	5	172

Table 1-2 The different arrow shaft profiles and the relative distribution of wood species. From table 8.52, Weapons of Warre, p.684

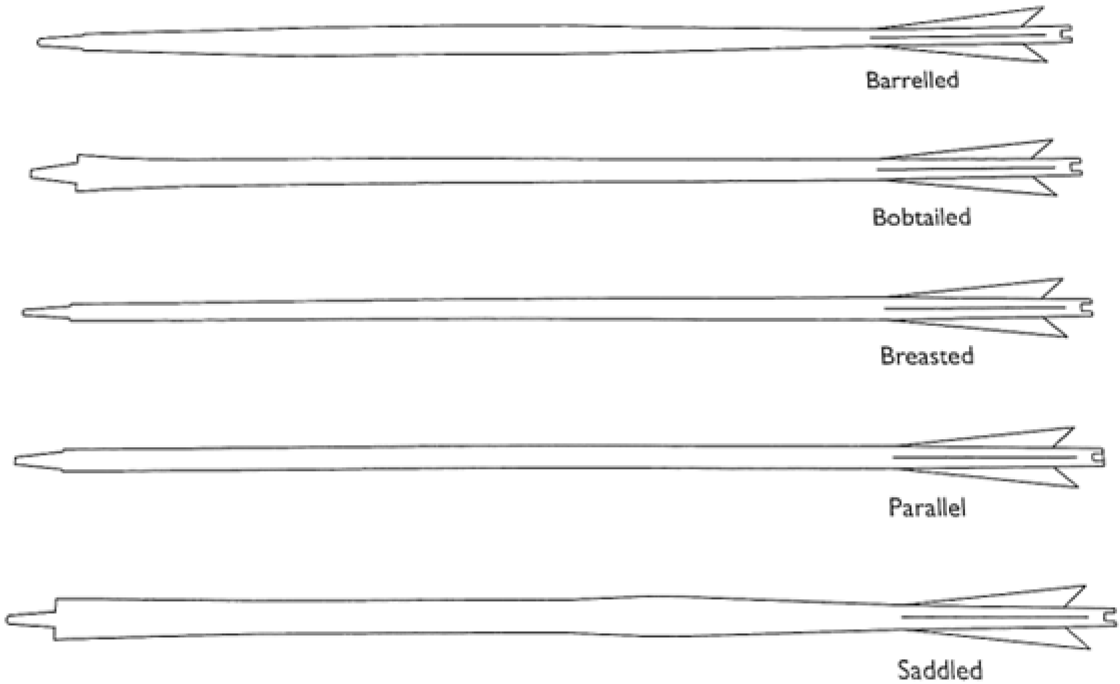


Figure 1-7 Arrow shaft profiles, figure 8.81 from Weapons of Warre, (Watson, 2011c, p. 683).

The variation within the arrows could possibly link to different uses of the arrows, particularly in the cases of the different profiles, in turn reflecting to different groups of archers aboard the ship. Yet, the selection of arrows in each chest seems to be random, no chests contain specific arrows of a similar size, weight, and profile, which would make it difficult to find the right arrow for a particular purpose, particularly in the rush of a battle. It may be that different profiles are purely a stylistic choice by various fletchers, rather than having a different function.

Although no arrowheads survive from *Mary Rose*, other sites in England, as well as contemporary sources, can give us an idea of what arrowheads may have been present. The size of the holes in the arrow spacers are also an indicator of the size of the head because they would need to be able to slip smoothly through without catching on the leather (Hildred, et al., 2011). Using this information, two arrowhead types have been suggested; a small barbed broadhead, designed to penetrate and tear flesh, and a small bodkin head, designed for piecing armour. In the Jessop (1966) classification system for arrowheads, these are type M4, and type M6, M8-M10, respectively (Figure 1-8) (Hildred, et al., 2011).

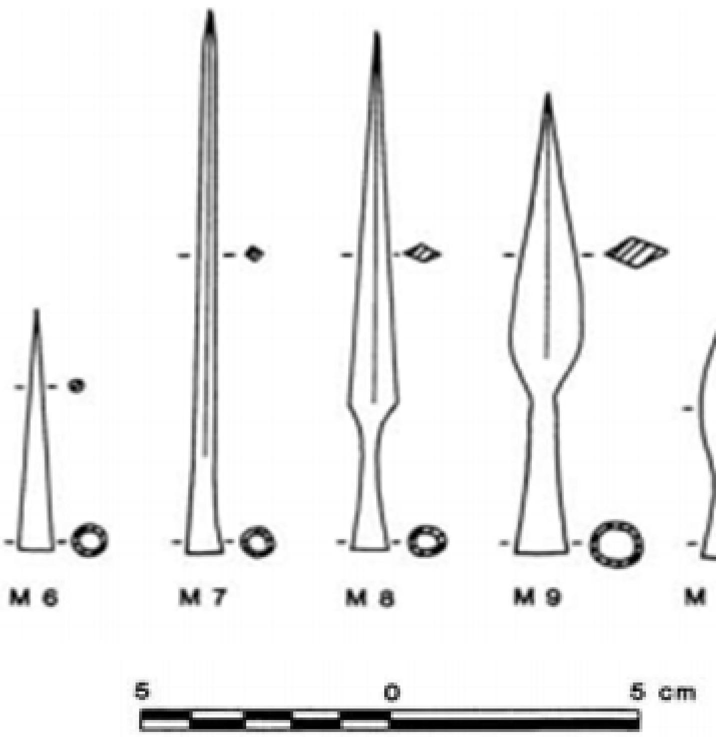


Figure 1-8 Arrowhead types M6 to M10 from Jessop's (1996) new arrowhead typology.

In addition to this, there may have been fire arrows onboard the ship. Fire arrows are known from contemporary sources to have been used aboard ships, and thought to be very effective in this role, especially as gunpowder began to be carried. Several designs of fire arrowhead have been identified, as well as methods of waterproofing them, which would be very useful for storage and use on a ship (Figure 1-9 and Figure 1-10). Generally, fire arrows can be categorised into two groups: a cage type and a bag type (Loades, 2019). The cage-type fire arrow involved, as the name suggests, a sort of cage built into the arrowhead, filled with an incendiary device. Bag-type arrowheads were long and thin so a bag of flammable substance could be secured over the top. Stretton (2017a-g; 2018) has carried out extensive research into these types and found that while the cage type would have been easier to prepare on board ship, but they were more likely to extinguish in flight. The ready-made bag type was more reliable and could be coated to make them waterproof, while still burning well when lit. Although aimed at testing fire arrows against typical house materials, Stretton's tests show the general effectiveness of fire arrows in setting both damp material and thick wood ablaze, as well as achieving a range of up to 180 metres (Stretton, 2017c and d). These tests were carried out using a similar arrow shaft to that of a normal arrow, therefore, without the heads, fire arrows would be indistinguishable from the rest of the collection. That being said, there are some strange finds from *Mary Rose*, which could be shafts for fire arrows. The nine wooden arrow-like objects have ambiguous features, which make certain identification difficult. The notched taper at the end, for example, is typical of a crossbow bolt, and they were originally identified as this during excavation. However, they are longer than was usual for a crossbow and the identification has since been changed to handgun bolts (Hildred, 2011e). While they are shorter than a typical longbow arrow, were they fitted with an extra-long bodkin fire arrowhead, as tested by Stretton, they could have been shot from a longbow.

Figure 1-9 Four types of fire arrowhead design tested by Mary Stretton: chisel head, extra-long bodkin, basket and Alnwick (top to bottom). Photo: Mark Stretton, http://markstretton.blogspot.com/2017/09/fire-arrows-how-medieval-fire-arrows.html?view=sidebar [Accessed 13/07/2021].

Figure 1-10 Four fire arrowhead designs from above loaded with flammable substances ready for test firing. Photos: Mark Stretton, http://markstretton.blogspot.com/2017/09/fire-arrows-how-medieval-fire-arrows.html?view=sidebar [Accessed 13/07/2021]

1.3.3 Other Archery Materials

The assemblage from *Mary Rose* also includes a lot of other archery equipment, including arrow spacers (mentioned above), a possible arrow bag, a length of potential bowstring and wristguards.

Arrow spacers are a leather disk designed to sit inside an arrow bag, keeping arrows secure and prevent damage to the flight. Seventeen arrow spacers were recovered from *Mary Rose*, with nine of them being complete. The diameter of the spacers varies between 105 mm to 160 mm, but all have 24 holes cut into them, which are between 12 and 15 mm in diameter. All of the spacers were found outside of chests, predominantly on the upper deck, with three from the Main deck and five from the Orlop deck. One arrow spacer in M2 was found along with a rectangular piece of leather, which is believed to be the remains of an arrow bag (Hildred, 2011e).

An excavation of the spoil mounds carried out in 2003 recovered a piece of possible bowstring, 200mm long and 3mm in diameter (maximum) (Hildred & Waller, 2011). The material of the string is yet to be identified but closely resembles a nineteenth century hemp bowstring. Other natural materials which may have been used for bowstring include nettle, silk, and linen (Hildred & Waller, 2011). The tensile strength of the bowstring is an important element in the power and efficiency of the bow. Common practice among modern longbow archers is to have a bowstring that has a tensile strength at least three times that of the draw weight of the longbow, four or five times would ensure the safety of the longbow, while seven times would ensure longevity of the string. However, in most longbow experiments, a modern bowstring is used so our understanding of the performance of medieval bowstring is even more limited than that of the longbow. Estimations on the diameter of the string can be made based on the arrow nocks, as the string would need to be small enough to fit into this slot. From a small study of 184 arrows, it was found that there was a range of sizes between 2 and 5 mm, with most between 3 and 4 mm. However, as the arrows have suffered from considerable post excavation and post conservation effects, it is difficult to assess whether these are accurate measurements (Hildred & Waller, 2011).

Wristguards, also known as bracers, are used by archers to protect the arm in case of an imperfect shot where the bowstring might graze the arm, and to keep loose clothing out of the line of the bowstring during the shot. Twenty-four wristguards were found on *Mary Rose*, including one made of ivory and another of horn. The other twenty-two are leather. A majority of them are decorated by blind stamping onto damp leather, although the design varies between them all. Even those that feature similar symbols, for example two feature fleurs de lys, have variations in the stamp used and are arranged in different patterns on the leather (Soar, 2011). Soar discusses how the decoration may reflect archer's affiliation with certain groups, including their livery companies, mustering authorities, local guilds, or parish churches. However, the variation between the decorations suggests that all archers are not from a single group. Some of the wristguards of particularly high-quality, including those made of ivory and horn, have been identified as high-status objects. These may indicate a hierarchy among the archers on board, with those wearing the seven undecorated wristguards, or those who are completely without, at the lowest level. Four of the wristguards were found inside personal chests suggesting that archery was not the primary function of the person to whom they belonged, at least not on the ship.

1.3.4 Skeletal Remains of Archers

Excavations of *Mary Rose* also uncovered 179 skeletons, including 92 that are considered to be fairly complete skeletons (FCS). Many FCS were associated with the archery stores; 29 individuals were identified in the area U7 to U9, where the upper deck longbow and arrow chests were, and 10 were found in O7 and O8, were the orlop chests were (Hildred & Stirland, 2011).

Examination of the remains showed some unusual morphological features, which may be associated with the use of the longbow. For example, a significant proportion of skeletons were found to have the morphological anomaly os acromiale. This is where the scapulae (shoulder blades) do not fuse with the epiphyses (the end of the bone which is unfused in childhood to allow growth). While this does occur in the modern population, it is at a much lower rate; 3-6% compared to 12.5% of *Mary Rose* skeletons, suggesting there is an unnatural cause (Hildred & Stirland, 2011). The most likely explanation is a common pattern of activity, which used the shoulders, such as archery. A large amount of training and practice with the longbow before the bones fuse, between the ages of 18 and 19 in males, could cause os acromiale. Therefore, these skeletons may indicate men who were specialist archers, who had trained even more than was required by law ((Hildred & Stirland, 2011). In addition, there are several individuals whose bones show very developed muscle and ligament attachments in the arms and the clavicles, as well as stresses on the spine, including twisting of the vertebral articulations, which may be associated with the repeated use of the longbow (Hildred & Stirland, 2011).

1.3.4.1 Origins of the Crew

There is generally an assumption that the crew of *Mary Rose*, flagship of the English navy, were white and of English or Welsh descent, especially when considering the archers, since the English were famed at this time for their deadly use of the longbow (as discussed above). However, there is a building body of evidence to suggest that England, and by extension the crew of *Mary Rose*, was much more diverse than this. Trade links with Europe and the Mediterranean were well established by the reign of Henry VIII, which facilitated the movement of people as well as goods, and although trade didn't expand beyond this until Elizabeth I's reign, there is evidence of at least 360 individuals of African descent living in England between 1500 and 1640. This is only named individuals, there is of course the possibility of many more (Scorrer, et al., 2021).

Artefacts from *Mary Rose*, such as various ceramic types, the decorated casket panel of Italian origin, and the Spanish adzes in the carpenter's cabin, suggest that a diverse crew was present. However, it is also possible that these artefacts were brought to England via trade routes rather than a reflection of the crew's origins (Scorrer, et al., 2021). Scorrer, et al., (2021)'s research uses a multi-isotope analysis to gain an insight into this more directly. Isotopes in dentine can be used to give analyse the origin and childhood diet of an individual as they do not remodel throughout life. The ratio of 87Sr/86Sr relates to the geology of the area where the food digested was grown, while 18O/16O ratios relate to the local water values. Together these can be used to estimate the region where a person grew-up. The skeletons selected for this study were the eight characters were created by the *Mary Rose* Trust to tell the story of *Mary Rose* when the new museum was designed: the Carpenter (FCS-81), the Royal Archer (FCS-75), the Gentlemen (FCS-85), the Cook (FCS-12), the Officer (FCS-84), the Purser (FCS-88), and the Young Mariner (FCS-09). These characters are based on the artifacts that the FCS were found alongside.

Results of the isotopic analysis showed that three out of the eight individuals grew up in a significantly warmer climate than England: the carpenter, the archer royal, and the gentleman. The origin of the associated artefacts was then used to make draw more specific origins about the crew. Spanish adzes (mentioned above) as well as Spanish coins found in the carpenter's cabin suggest that FCS-81 was of Iberian origin, while the Italian casket panel was found in the chest thought to belong to the Gentleman, indicating FCS-85 grew up in Italy. The Royal Archer was found with a leather wristguard bearing an image of a pomegranate, a symbol associated with the Moors, who had brought the fruit from Africa to Europe, suggesting he may have also grown up in Spain. However, the isotope values from this individual are also consistent with a North African origin.

While only a small sample of individuals was analysed in this research, the results are still significant in showing the multicultural origin of the crew. Considering a crew, who did not necessarily grow up in England, and thus were not subject to the longbow training regime required by law is important to this study because regular practice is commonly used for justification as to why the longbow draw weights could be so heigh, when they sound impossible today.

1.3.4.2 Stature Estimation

The skeletal remains from *Mary Rose* have recently been revisited by Dr. Emily Mitchell, who kindly provided her data and calculations on their height for comparison to the longbows (As discussed in 1.1.3). Comparison of the skeletons to the estimated draw lengths of the longbows was also considered, as how far an archer could draw a longbow is related to the length of his arms. However, as the longbow is drawn to the ear, the additional distance across an individual's chest that it would be drawn could not be meaningfully estimated.

1.3.5 A Note on Artifact Numbers

Artifacts recovered from the *Mary Rose* are numbered first by year found and then artifact found in that year. For example, the longbow 80A0907, which will be specifically referenced in this thesis, was recovered in the year 1980 and was the 907th artifact recovered that year.

The replica longbows manufactured for this project follow a similar naming convention that is also an amalgamation with the naming of previous *Mary Rose* replicas. The year of their creation (2021) followed by MRA (*Mary Rose* Approximation) and numbered 1 through 5.

1.4 Research Problem

At first glance, the *Mary Rose* longbows appear to be very similar to each other. However, as described above, there is actually a large amount of variation within the collection, which has given rise to many theories about the longbows and how they were used at sea. Generally, these can be categorised into two opposing groups; theories that suggest the variation is explained by different groups within the archers on board, and theories that the longbows were standardised in their draw weight and the variation is the result of the wood's properties.

Many people have suggested that there are groups of longbows aboard the ship that had different roles and argued that the variation within the dimensions and locations of the longbows represents this. For example, it has been suggested that the larger, handled longbows were for the shooting of fire arrows. Stretton's (2017a-g; 2018) experiments with fire arrows showed that attaching the charge makes these arrows on the heavier side, and thus a longbow with a larger draw weight would be necessary to achieve a good range with these arrows. Additionally, the handled section of the longbow could be for attaching leather binding, which would protect the longbow from any scorching when the fire arrow was drawn. Other suggestions for the different roles aboard the ship include other specialist heads, such as bags of lime dust and pigs' bladders filled with oil, range finders for gunners, sharpshooters picking off enemy marksmen on the opposing ship, and wind indicators (Hardy, 2006).

Additionally, there is a matter of the meaning behind the marks. Many other artefacts on *Mary Rose* were found to have been marked with ownership marks. However, this has been ruled out for the longbows as most of the marks are repeated multiple times in the collection. They are perhaps makers marks, which trace the longbow back to the bowyer, but not all longbows bear a mark. It could be that only master bowyers place a mark on their longbows. Yet, with Henry's keenness for archery and having the best wood imported for staves, it does not seem to fit that anyone less than a master would supply longbows for his ships. Others have suggested that they may indicate something to the archer; where to hold the longbow, which way is up, where to nock the arrow etc. This, however, still does not explain why some would have them and others do not.

As well as the physical variation of the longbows, there is also the matter of context and location where the longbows were found. As outlined above the ship was segmented during the excavation, while these locations would not have existed while this ship was in use, archers in different areas of the ship could have performed different roles, similar to how soldiers in a land battle were laid out strategically. Additionally, it is important to remember that the castle was not as well preserved as the other decks. Historical evidence shows us that fore and aft castles were introduced to accommodate archers; thus, it is highly likely that some of the longbows recovered from the upper deck sections 7 to 10 actually belonged to archers on top of the castle.

Furthermore, the longbows were found in two contexts: loose or in chests, with two on the orlop deck and two on the upper deck. The storing of the longbows in groups chests is particularly confusing as it is generally thought that longbows are very personal weapons, with the length of the longbow and the length of the draw are made to complement the height and arm length of the man that draws it. However, with the longbows being stored in mixed chests on the boat this raises questions about distribution. Should the men be required to suddenly use these longbows, how would one quickly find their own weapon, if it was jumbled in a chest with 50 others? It is possible that the longbows which were found loose are the longbows that were actually in use, or intended to be in use, on the ship. While those in chests were being transported for the possibility of land battle. Therefore, there may be a difference between longbows found loose, which are personal weapons, while chest longbows are standardised versions, which most people would be able to pick up and use, even if it wasn’t the best match to them personally.

The opposing argument to that of groups within the collection is similar to this; that the longbows are all a standardised weapon, not in appearance but in terms of draw weight. Wood is not homologous, even within the same species, and variations in the wood create variations in the mechanical properties. Therefore, in order for all longbows to have the same draw weight, slightly different shapes would be required. Due to the time period and nature of the manufacturing process being by hand the longbows likely do not have the exact same draw weight, but if the bowyers were aiming for a particular draw weight, we will see a normal distribution with the peak around the target draw weight. If the longbows are all standardised to draw weight, this means that any man onboard the ship could pick up the weapon when necessary. While might not be a perfect match, all men were mandated to train in archery from a young age so it is likely they would be able to use a less than ideal longbow, while maintaining a good degree of efficiency. Records which list specific numbers of longbows, arrows and bowstrings for each ship suggest that this was a standardised version of the weapon that was provided by the state. However, it is possible that personal weapons were brought onboard by the men in addition to those provided by the state.

This research aimed to address the question "were the longbows a standardised weapon anyone could use or were there specialist archers aboard the ship?"; not only addressing one of the major outstanding questions about the longbows as outlined in this chapter, but also beginning to reunite the longbows with their maritime context, and thinking about how this weapon was used tactically at sea. To do this, replica longbows which represent some of the key variations in the *Mary Rose* collection were created. Collecting data on the physical dimensions as well as their performance allowed the connection between the two to be analysed. This relationship was then projected onto the *Mary Rose* longbows, through gathering the same data about the physical dimensions from a selection of longbows from the collection, allowing their performance to be estimated. With this information it was possible to begin to think about how the longbows were used tactically aboard the ship.

Chapter 2

Working With Longbows: A Review of Previous Research

Two areas of research are of particular interest to this project; previous studies of archery and the longbow, and X-ray Computed Tomography (CT) scanning of wood specimens, which will be employed in this project.

2.1 Archery

The study of archery is of interest to many groups for different reasons. Archaeologists and historians wish to understand the history of archery as a means for hunting, a weapon in combat, and a sport. Mathematicians and physicists are interested in transfers of energy in the bow and modelling the flight of the arrow using equations. Sport scientists study the strain on the body and improving physical performance, while engineers look for ways to improve the modern bow-and-arrow for better performance in competitions and while hunting. In order to fully understand the working of the longbow, a combination of techniques from all these fields is required. This in turn will increase our understanding of its place in history.

Most previous studies on the longbow have focused on experiments with replicas to measure the performance of the longbow in terms of speed of the arrow and the impact on the target, particularly a target wearing replica armour. Mathematical modelling and mechanics of the bow have also been applied to the longbow, but much less frequently.

Initial work on the longbows from *Mary Rose* combined both experimentation and mathematical modelling, using the first to check the accuracy of the second, after it was discovered that the longbows themselves could not have their draw weight measured. There have also been skeletal studies into the strain on medieval human remains, for example Stirland (1993) and Rhodes and Knüsel (2005). However, these will not be discussed here as the focus of this thesis is the function of the longbow itself, not its relationship with the archer.

2.1.1 Previous work on Mary Rose Longbows

After the longbows were raised, Robert Hardy and his secretary, Mrs Garcin, began the long process of removing the salt and drying the longbows. A few of the more degraded longbows were preserved with PEG (polyethylene glycol), along with the ship and some of the other wooden artefacts, but most of the longbows appeared to be in good enough condition that they could simply be dried out. Once the longbows were dried, they were waxed with a vegetable oil and polished with beeswax (Hardy, 2006). This is also mentioned in Ascham's (1545) Toxophillus, as something that should be done regularly to keep the wood in a good condition for shooting.

Once this process had been carried out, the testing began. Generally, the longbows recovered from *Mary Rose* appear to be in perfect condition, with the exception of some which were nearer the surface of the sediment. Measurements of the modulus of elasticity, taken from broken longbows, suggested that this was also the case internally. However, once the testing began it became clear it was not the case. Only one of the longbows sampled reached full draw (30in) but with a smaller than expected draw weight of only 60lbs. The others cracked and one broke before reaching the full draw length, revealing that the longbows were internally degraded (Hardy, et al., 2011). Therefore, because the draw weight could not be measured directly, it was necessary to use a model to gain an estimate. Two different models were applied; one based on measurements taken from the longbows and one based on the arrows that were recovered.

The first method was developed by Kooi (Kooi & Sparenberg, 1980; Kooi,1991; Kooi,1993; Kooi & Bergman, 1997) and involved using a range of measurements taken from the longbows to predict the draw weight. A replica longbow made by Roy King, was also modelled and this was used to verify the accuracy of the model. The draw weights produced were very large and unexpected; up to 185lbs for the largest longbows (Hardy, et al., 2011), which immediately sparked controversy as, prior to this, longbows were believed to have a draw weight of around 70lbs. Archery enthusiasts such as Mark Stretton, have shown that it is possible for a man to draw a longbow of this poundage without practicing from a young age as was mandated in the Medieval and Tudor periods. However, some scholars still dispute this, citing, among other things, the diet and general health of medieval people impacting their ability to perform at this level. It is true that the model employed by Kooi is not perfect. The calculation utilizes a modulus of elasticity that was measured from broken longbows and adjusted using an approximation based on the density of the longbows and a measurement from the replica (Hardy, et al., 2011). This poses several problems and involves multiple assumptions. The modulus measured from the longbows has already been shown to be misleading, and including the measurement from the replica longbow assumes that the modulus of elasticity between American Yew, which was used for the replica, and European Yew that the *Mary Rose* longbows are crafted from is identical. In addition, this model could not be used to gain the level of detail required to address the problem described in 1.4. The modulus of elasticity changes between pieces of wood, so approximating all of the longbows draw weights based on the single estimated value calculated in the study would lead to further inaccuracies. Thus, it was decided that a model which only incorporates elements that can be directly measured from the longbows was needed. This would have fewer potential inaccuracies, with completely non-destructive techniques, and therefore be more useful for estimating the individual draw weights of the longbows.

The other model for the draw weight was based on data from the arrow shafts. The arrow must buckle when shot in order to snake around the bow and fire straight - known as the archer's paradox. For this to work properly heavier arrows require heavier draw weight longbows and vice versa (Hardy, et al., 2011). Therefore, it is possible to model what draw weights would be required for different arrows based on the deflection caused on the arrow by placing a 2lb weight in the centre (Watson, 2011a). This showed that to fire the *Mary Rose* arrows that were studied, longbows between 40 and 190lbs would be needed (Watson, 2011b). This large range adds very little to the discussion of the longbows. The upper limit is in good agreement with the results of Kooi's model. However, the lower limit encompasses practically all longbows and therefore indicates little more than that the arrows work. Moreover, this did not associate the arrows with any particular longbows, which would be needed for an in-depth study of function.

2.1.2 Physics of Archery and Mathematical Modelling

Applying an understanding of physics to archery began in the 1930's and 40's. Klopsteg's (1943) paper 'Physics of Bows and Arrows' was one of the first to discuss the bow in terms of the energy stored in the limbs and transferred to the arrow upon release. While Higgins (1933) published one of the first articles on the aerodynamics of the arrow, including a mathematical model for mapping the flight path. The methods presented in these papers can now be computerised for ease and time efficiency, but both discuss key elements of the bow and arrow which have not been explored for historical archery. For example, the effect of the angle of shooting, the area of the fletching (Higgins, 1933) and the efficiency of the bow (Klopsteg, 1943). Another area of interest is Klopsteg's discussion of optimal bow design. He suggests the traditional D shape of the longbow is actually detrimental to is performance as the fibres under compression are shorter due to the rounding and further from the neutral axis than the fibres under tension. To maximise the bows potential, it should be the opposite case, where the fibres under tension are in fact further from the neural axis than the fibres under compression. However, later, Blyth (2006) shows that this is not the case; he describes how the longbow is the best design for a self-bow not only because of the cross-sectional shape but also the length and tapering of the tips. Due to the asymmetry in tensile and compressive failure stress in wood, the D shape actually maximises the cross-section by causing both sides to fail under the same loading. Even without understanding this scientifically it is clear that bowyers had a practical understanding of this as Ascham (1545) also discusses that the D shape is the best for longbow design. This makes the variation in cross-section found within the *Mary Rose* curious; if this design is truly optimal, why would this variation occur, and what is the effect of it on longbow performance?

As discussed in the previous section, Kooi has published multiple articles on the mathematical modelling of traditional bows (Kooi and Sparenberg, 1980; Kooi, 1991, 1993; Kooi and Bergman, 1997). In addition to the flaws outlined above, which specifically apply to its application to the *Mary Rose* longbows, his models show that 100% efficiency as possible, meaning all energy that is stored in the deformation of the limbs is transferred to the arrow upon release of the string. This is a common result of simple bow models caused by the assumptions made in the calculations. Denny (2003) also presents a model for the internal dynamics of the bow, developing the work of Hickman, which shows the same problem. One of these assumptions is that the string is inextensible and has no mass. In reality, this is of course not the case. While modern bowstring may be optimised to approach on this assumption, there is no data on the elasticity or mass of potential traditional bowstring materials, such as hemp or nettle. Even experiments with replica medieval longbows use a modern string, so it is not possible to factor the bowstring into the calculation of efficiency. For this reason, it was decided to incorporate experimentation with traditional bowstring materials into this work, which would allow for a much more realistic assessment of the efficiency of the longbow.

With the exception of Kooi, the application of physics to archery does not consider historical bows. The 'traditional' bows that are considered in the earlier papers are more akin to Victorian target longbows than the war bows of the medieval period. A modern understanding of how we can apply the laws of physics to archery, for example in Meyer (Meyer, 2015), have not been applied to historical archery. Doing so would provide a lot of information on the mechanics, elasticity and aerodynamics of past archery equipment, which links to many of the questions asked by archaeologists and historians, including why they the longbow was so successful and how was it used in battle. This project further works on this union of scientific modelling approaches, using materials engineering, with experimental archaeology and historical interpretation to increase our understanding of the *Mary Rose* longbows.

2.1.3 Experimental Archery

Experimental archery has been used more popularly for the study of medieval longbows. Through the use of replica longbows and arrows it is possible to observe the flight of the arrow and the impact of its landing, as well as how changes to the bow and arrow affect these. Most popularly these experiments aim to evaluate the effectiveness of arrows against medieval armour in order to prove or disprove the reputation of the longbow. Experimental archery has also been used in some studies as a means to compare the longbow to other hand-held catapults. However, these will not be discussed here as this work does not include the comparison of the longbow to other weapons.

Jones (1992)is credited as the first to experiment with the penetration of medieval arrows into contemporary armour. In his simple experiment, he shot arrows at different thicknesses of metal, 1 to 3mm, to see whether they could penetrate. However, this has since been criticised for several reasons. Firstly, the yew longbow used drew at around 70 lbs, which is now thought to not actually represent the draw weights of the time and is more comparable to a Victorian target bow than a medieval longbow (Bourke & Whetham, 2007). Additionally, the arrows he used are thought to have faded out of use by the 14th century alongside armour development, as they were designed for mail armour. Therefore, the lack of penetration of iron plates caused by these arrows is not surprising (Bourke & Whetham, 2007) . In addition to this, the metal sheets at which he shot were not supported by anything. Although his reason for excluding this – that flesh offers little resistance to penetration (Jones, 1992) – is not incorrect, Jones does not consider that being supported by flesh alters the behaviour of the structure. As well as this, it is not only the metal armour which must be considered when assessing penetration and fatality, but the layers of clothing worn beneath, which would offer resistance to the penetration of the arrow. Overall, Jones showed that it was possible to pierce armour with arrows but drawing conclusions about the deadliness of this is not possible from his tests.

In an attempt to address these issues, Bourke & Whetham (2007) repeated the experiment with a heavier longbow, a selection of 3 arrowheads, and backed the metal sheets with Plastalina – a flesh-simulating clay used to test modern police armour. This was also accompanied by a laboratory version of the tests, using an air cannon to fire the arrows. Firing arrows in this way removes any inconsistency in energy transferred to the arrow caused by having a human operating the longbow but at the same time the spin of the arrow and the archer's paradox are not accurately represented. However, both tests gave similar penetration results, which may suggest these factors are not so important in determining the penetration of the arrow. This version of Jones' (1992) test still received criticism (DeVries, 2007). Mainly, DeVries raises issue with the draw weight used as he does not agree with the heavy draw weights calculated for *Mary Rose* longbows as well as some other opinions of the authors, which are unimportant to the review of methodology. However, DeVries does correctly point out the fact there were many layers of clothing underneath armour in battle, offering resistance to arrows (DeVries, 2007), which these experiments continue to ignore. If we are to use this kind of testing to assess how deadly the weapon was then complete simulation of the attire worn by soldiers is needed. In addition, modern string is used and justified by the authors because of its comparable thickness to that believed to be used on *Mary Rose* (DeVries, 2007). However, thickness is not the only factor in how the string performs so replica string should be tested along with replica longbows, which is, as mentioned in the previous section, noticeably missing from all the literature.

Crowley (2005) incorporated some of these variables into her work; three different woods, fletching lengths and shaft shapes were represented, as well as four arrowheads. The results are presented as a trajectory model, using the drag calculated from the experiments. This showed that the arrows could have been shot around 300m and possessed over 80J of energy on impact, which is considered to be the level at which it is deadly to an unarmed person (Crowley, 2005). However, all the variables were condensed into only five arrows. This means that there are too many differences between the arrows to be able to ascertain the effect of each element on the flight (Crowley, 2005).

The most extensive testing of the longbows was carried out by Mark Stretton. Initially published in The Glade, his work is now more accessible on his blog and published in Soar's Secrets of the English longbow (Stretton, 2010). In his first set of tests, Stretton compares six types of medieval arrowhead: the short type 10 bodkin, the long type 7 bodkin, lozenge shaped bodkin, leaf shaped, crescent and swallowtail broadhead. He collects data about their flight (Stretton, 2016a) and their effectiveness against different targets; unprotected flesh (Stretton, 2016b), mail armour and brigandine armour (Stretton, 2016c) and plate armour (Stretton, 2016d). He also investigates the impact of the arrow against a moving target (Stretton, 2016j; Stretton, 2016k; Stretton, 2016l; Stretton, 2016m; Stretton, 2016n) and the effect of changing the distance from the target (Stretton, 2016h) and shooting downhill (Stretton, 2016o). In a later set of tests, he considers the fire arrow; how they could have been made (Stretton, 2017c) and loaded (Stretton, 2017d), how far they could be shot (Stretton, 2017e)and what they could set on fire (Stretton, 2017f; Stretton, 2017g; Stretton, 2018). Many of these experiments serve more as a starting point for investigating these topics as there are several things that could be improved upon or taken further. For example, the use of a proper flesh simulator, such as Plastalina, and, once again, including the underclothes worn beneath armour. Wet fletching is considered (Stretton, 2017a), but in a battle at sea or in the rain the fletching is not the only part of the archery equipment that would be wet – what impact does this have on the system as a whole? However, these experiments offer a good foundation of understanding, particularly in terms of fire arrows, which are seldom experimented with elsewhere. This is useful for studying the *Mary Rose* longbows as the use of fire arrows aboard the ship has been suggested as an explanation for some of the variation, and for some odd arrow-like finds (as discussed above).

2.1.4 Preliminary Work

For my undergraduate dissertation, I also carried out research into the *Mary Rose* longbows. Using statistical methods, I investigated whether different groups in the longbows could be identified by analysing and comparing the dimensions of longbows from different contexts and locations, longbows with different marks, longbows with different grain counts, and longbows with different cross-section shapes. Unfortunately, the results of this analysis were inconclusive; some tests suggested there was not a standard draw weight, but others failed to find clear grouping.

Two main issues with this study were apparent; firstly, this method of using the longbows' dimensions as indicators of function in terms of draw weight and range is very simplified. While the dimensions are certainly related with these qualities, analysing them in this manner oversimplifies the relationship between the measured characteristic and the draw weight. There is also an assumption that the dimensions are all directly related to an equal degree, which is undoubtedly not the case. This may explain why there are some interesting results but no clear conclusions. Additionally, the data for density and grain were a significant problem. In response to the data for grain being qualitative; described as coarse, medium or fine, an estimation for density was calculated. However, there seemed to be no relationship between the calculated density and the grain categories as one might expect, which calls into question the accuracy of the estimate. On the other hand, yew displays less difference between faster and slower grown wood, than other types (Professor Nigel Nayling, personal communication, 2018) meaning that the grain and density measurements actually represent two different pieces of data. I speculated that grain might have been more important, as it can be visually seen rather than needing to be measured, so this is most likely what the bowyers of the time will have worked from. However, it is not clear which one or if both these measurements are related to the draw weight, or how they are related. Unhelpfully, both tended to suggest different conclusions in the statistical analysis.

Therefore, there needs to be a more definite establishment of density and a quantitative description of grain on order to study how they relate to the draw weight of the longbows. Due to these issues and the unclear nature of the results they produced, I proposed an alternative method to address the question, modelling the longbows for their draw weight and range then statistically analysing those results for groups.

Within the statistical analysis, the different cross-section groups stood out as a potential indicator of different roles aboard the ship. All of the groups had different average lengths and average densities, which suggests they also have different draw weights, and therefore, potentially different roles. However, before investigating this further, establishing whether these groups were an accurate way to describe the variation in the cross-section of the longbows was necessary as the longbows had only been categorised in this manner by visual inspection. To do this a sample of the longbows were laser scanned to make three-dimensional models. From this an accurate outline of the cross-section could be extracted at the centre and every 100mm along each of the limbs. Then geometric morphometrics was used to analyse this data and how accurate the different groups were. The results showed that the flat D and deep D groups were the most significantly different and had the highest class-correctness of 63.64% and 70.59% respectively. The other two groups were less clear, the slab-sided longbows in particular being difficult to differentiate from the Flat D longbows. For this reason, the flat D and deep D groups only will be considered in the replicas to investigate whether different cross-section shapes have different draw weights.

2.1.5 Archery Research Summary

Despite the importance of the *Mary Rose* collection to our understanding of the famous 'English' longbow and the many questions it has raised, there has been limited investigation into the longbows. So far it has been limited to gathering quantifiable data and some initial modelling based on a select number of longbows. There have been no attempts to use more recent technological advances, such as micro-CT scanning, to improve our understanding and address the questions outlined in section 1.4. Meanwhile, studies about medieval longbows in general address whether this weapon was as deadly as contemporary records report.

Statistical analysis of the *Mary Rose* longbows' measurements did not provide clear results on the relationship between the variations within the collection and their potential groupings. Instead, estimations of the performance of the longbows in terms of their draw weight and range are needed. However, the original models of the *Mary Rose* longbows could not provide this data as they did not produce individual results for all of the longbows. Additionally, the results of this modelling are considered to be controversial by both scholars and the historical archery community, as well as having limitations in the methodology. If the longbows could be modelled in a way that relied solely on measurements that could be taken non-destructively from both historical artefacts and their replicas, it would be possible to produce results with less estimation and assumptions.

Along with the issues of the modelling methods themselves, little time has been dedicated within the literature to considering whether there are significant differences in the performance of European Yew, which the *Mary Rose* longbows are made from, and the performance of Pacific Yew, which in the present day is more accessible to manufacture replica longbows from. When translating the test results of a Pacific Yew replica to the *Mary Rose* longbows through modelling, any differences do need to be accounted for in order to improve accuracy.

Physics and mathematical based studies of the bow-and-arrow mainly focus on improving performance of the modern bow for sport and hunting, which is not applicable for understanding historical archery. However, they do reveal an element to the system which has been ignored in experimental archaeology studies – the bowstring. In some simplistic bow models, it is possible to achieve 100% efficiency, assuming the mass of the bowstring is 0. While this may be close to accurate for modern bowstring, that may also be optimised to reduce mass, this is not comparable to historical examples. However, no data exists on the properties of natural bowstrings or how they affect the performance of the longbow; both in experimental studies and for hobbyists, longbows are strung with modern strings. This is a key missing piece to the puzzle of understanding medieval longbows and their performance.

2.2 X-ray Computed Tomography for Wood Visualization

X-ray Computed Tomography (CT) is well known in the wood-based industries and in wood science. It has been shown to reveal structural defects in trees, poles, and lumber, such as rot and knots, as well as the density, moisture content, distribution of moisture and the effect of pollution. For wood-based industry this information is useful in selecting and cutting the highest quality timber possible and for the controlled drying of lumber. Foresters and wood scientist can also use CT scanning to look at wood growth and biology in different species non-destructively, and construction companies may use it to maintain older buildings and ensure the structural integrity of new construction. The use of the technique for dendrochronology, climatology, wood identification and in the study of wood-based cultural heritage has also been growing in recent years, with many studies showing good results. A review of the use of CT scanning for analysing wood properties, particularly of those looking for knots and other defects, and measuring density, as well as those using historical wood samples, was carried out to assess the viability of CT scanning for this project.

2.2.1 Scan Resolution for Tree Ring Visualisation

Density is perhaps the most measured feature of wood as it is related to the quality, the amount of biomass available, tree growth and climate, and is a good predictor of the mechanical properties of the wood (Jacquin, et al., 2017). Density can be obtained from CT scans because it is directly related to the Hounsfield number, which is the x-ray absorption coefficient of each voxel normalised to the standard x-ray absorption of water (Wei, et al., 2011). Even without calculation, differences in density can be easily seen on a CT scan as areas of higher density have higher x-ray absorption and therefore show up as lighter than areas with lower density. This can also be useful for studying other elements of the wood (discussed further below). While some studies are satisfied with achieving the mean density of the sample, many have focused on measuring inter-ring density values, inadvertently also giving information on the resolution required to visualise individual tree rings clearly.

The usefulness of medical CT scanners for this kind of research is limited (Davis & Wells, 1992). Freyburger, et al. (2009)and Steffenrem et al., (2014) showed how medical CT scanners could be used to obtain an average density for wood samples. However, both studies reported ‘smoothing’ of the inter-ring differences and invisibility of the smallest rings (less than 1mm) due to the low resolution. Generally, medical CT scanners are considered useful when only mean density is required, or when the wood to be studied is a very fast grown species with wide growth rings (Jacquin, et al., 2017).

With micro-CT scanning, a much higher level of detail can be achieved. Grabner, et al. (2009) showed that a resolution of 8 μm per pixel was achievable, which was able to distinguish between rings as small as 0.12mm. However, not all ring widths are this small, therefore on another specimen 140 μm was enough to image all of them. Bill, et al. (2012) reported that typically 50- 75 μm was a high enough resolution for dendrochronological analysis, in which all tree rings must be detectable. Moreover, it is possible to use these scanners to obtain inter-ring density values (De Ridder et al., 2010; De Mill, et al., 2016). However, other authors such as Okochi et al., (2007) have struggled to obtain such results. While looking at tree ring width was possible, they concluded that their images were not good enough to generate intra-ring density values.

Previous research therefore clearly shows that the resolution required for visualising the tree rings in a wood sample is highly species specific. However, there appears to be no data on whether it is possible to generate this data for either European or Pacific Yew. A dendrochronological study of European Yew in Poland (using samples studies under a microscope rather than CT) produced results with an average ring width of 0.84mm (Cedro, 2023), giving some idea of the resolution needed to visualise all the rings using CT.

2.2.2 Identifying Features

Differences in density within the wood also make it possible to distinguish certain features of wood. Onoe, et al., (1984) showed it was possible to use CT images to distinguish between the heartwood and the softwood in some species, as they differ in density and moisture content. By programming thresholds of density values, known as the Bayesian Maximum Likelihood Classifier, it is possible to separate the two out for analysis. As longbows are made up of both heartwood and sapwood, which both have different properties, this would be a useful measurement to make to assess the proportion of each present in the longbows and whether this is linked to their performance. However, Wei, et al., (2011) notes that these thresholds are not always able to differentiate between dead knots and heartwood, and between sound knots and softwood, due to overlapping values between the two. This can create some problems and make the accuracy poor.

Another method using the feed-forward back-propagation artificial neural network (BP-ANN), a type of artificial intelligence used for complex classification tasks, has been shown to have much higher accuracies for classifying heartwood and sapwood of 95%. However, this is only in a single species of wood, so its wider application is not well established (Wei, et al., 2011). The same image processing techniques can also identify knots, based on their differing density to their surroundings and their elliptical shape, with similar accuracies (Wei, et al., 2011). For this application the BP-ANN has be applied to many species and has had above 90% accuracy for all (Wei, et al., 2011), although this did not include yew.

2.2.3 CT Scanning of Heritage Artifacts

In cultural heritage, CT scanning of wooden objects has revealed important information about artefacts such as their manufacturing processes, defects that needed to be considered in conservation, dating and wood identification (Casali, 2006). For example, when applied to two paintings on wooden tablets, damage by woodworm and a crack in the wood that were hidden inside the tablets were revealed. These are very important to consider for the future conservation of the paintings as they may compromise the stability of the wood (Morigi, et al., 2007). Stoel & Borman (2008) used CT scanning to investigate whether density of the wood played a role in the quality of violins, comparing classical Cremonese violins to modern ones. Though no differences were found, the CT imaging method was successful and produced good density maps of the violins. Sirr & Waddle (1999) have similarly used the technique on violins to identify the extent of damage, which was either underestimated or invisible from the surface, as well as evaluating the authenticity of the object. Dating is the most common use of CT on wooden artefacts. Implementing dendrochronology, this requires a relatively high resolution in order to visualise all of the rings present. This was used, for example, for the Viking ship burials from Oslo, and for late-medieval artefacts in the "After the Black Death: Painting and Polychrome Sculpture in Norway" project (Daly & Streeton, 2017). CT scanning has also been used successfully as a non-destructive tool for wood species identification (For example in Bird, et al., 2008; Grabner, et al., 2009 and Fioravanti, et al., 2017). More recently, Rankin, et al. (2021), used micro-focus CT to identify the wood species of two wooden objects; a tuning peg and a smoking pipe stopper, from the wreck of the London (1665 CE). The study also revealed information about their manufacturing processes and internal condition.

Wood from archaeological sites can present unique challenges as it is affected by a number of different degradation processes, as well as the conditions in which it was buried. Waterlogged wood in particular can cause a problem for CT scanning as the water does not contrast well with the wood. However, successful projects have been carried out (Bill et al., 2012; Mori et al., 2019). Dreossi, et al. (2009), were able to successfully characterise archaeological waterlogged oak, and quantify the degradation of the wood through comparison of the x-ray attenuation to the material density. Conversely, previously waterlogged artefacts that have been conserved pose another potential issue to visualising the internal wood structure. Conservation of waterlogged wood generally includes the replacement of water with another substance which will maintain the internal stability without water. In the case of objects from *Mary Rose*, and indeed the ship herself, this is using polyethylene glycol (PEG). The two wooden objects from the London studied by Rankin, et al. (2021) were also preserved in this way. In addition to the information about the wood, this study also showed that PEG impregnation does not affect the ability to visualise microscopic anatomical features using CT.

2.2.4 CT for Wood Visualization Summary

There are many studies that show the successful use of CT scanning to gain information on the internal structure of wood, including quantifying knots and the proportion of heartwood and sapwood present. The technique has also been shown to be successful for both modern and archaeological examples, indicating that this technique was well suited to the needs of this project. However, these studies also show that the machine requirements and the results yielded can be highly species dependant. The wood involved in this project is European and Pacific yew, which has not previously been studied in detail so it was not clear from the previous literature what results CT would yield for this wood. It has been shown that the rings of this wood can be quite small, so there will be a need for high resolution in order to visualise them all.

As the longbows did not undergo any preservation treatment, this was not a concern for these scans. Though, the previous work on the *Mary Rose* longbows proved that the wood is internally more degraded than it appears externally, which may affect the quality of the scan. There is also a possibility of mineral inclusions, from the sea and items which were corroding around the longbows, which may show up on the scans and affect the results.

Chapter 3

Of Dimensions and Draw Weight: The Measurement and Lab Testing of Replica Longbows

Five replica longbows, made to be as similar to specific *Mary Rose* examples as possible, were crafted for this project by Joe Gibbs (Hillbilly Bows). The replicas used for experimentation and hobby discussed in the literature review are generally more generic "medieval" longbows. Using what is believed to be traditional techniques, staves are shaped into longbows driven by the wood itself and the desired draw weight in the style of those used historically. As this project aimed to investigate the link between the physical properties of the bow and its performance an almost backwards approach was needed; crafting longbows to specifications of physical dimensions and then testing for the draw weight in the laboratory. Replicating specific *Mary Rose* longbows would also aid in relating the results back to the original artefacts, allowing an exploration of use aboard the ship, rather than just contributing more generically to longbow research. However, at the same time, it is important to note that the manufacture of a longbow is to some extent still governed by the stave. It is impossible to create identical replicas of this type of bow owing to the nature of the material. Thus, some difference between the original artefacts and the replicas was expected. This difference, quantified through comparison of measurements, is discussed in the results of this chapter.

The *Mary Rose* longbows chosen for replication represent as much of the variation within the collection as possible, while doing so in a way that made their effects still testable. Too much variation between the longbows would make it impossible to assess the source of the variation, whereas too little would not allow us to explore the research problem outlined in chapter one fully. The choice of these longbows was based on a variety of factors, including the preliminary work conducted to analyse the cross-sectional shapes, as discussed in the literature review. This reasoning and the specific longbows chosen to meet the criteria is discussed further in the materials and methods section.

In addition to replica longbows, this project has included the testing of replica bowstring. As has been discussed, the bowstring is an important part of the overall bow-and-arrow system, but it has seldom been explored in the context of medieval longbows. The replicas used in previous experiments have used modern Dacron bowstring as it is believed to be more reliable and long-lasting, with little consideration given to the possible effect of this on performance. However, it is near impossible to make any adjustments for this as no solid data exists on the tensile strength, performance, or durability of natural bowstring material. The material of the *Mary Rose* bowstring fragment has not been identified and there is not a clear record of what material was used. Contemporary sources, such as the Anthony Roll, which tells us a lot of the information we know about the armament of the ship, simply lists "bowstrings" and their quantity (six gross in the case of *Mary Rose*). Not material. For this project, linen and hemp have been tested as potential materials from which the bowstring may have been made. These materials were also explored using X-ray Computed Tomography, which is discussed later in chapter five.

Measurement and lab testing of the replica longbows was a necessary first step of this project as these factors had to be known for the design of the shooting machine used for field testing the replica longbows, discussed in the following chapter. These results also provided the first look at what might be the most important factors in determining the performance of the longbow from the physical dimensions. Additionally, while data was collected on the draw weight, it was also possible to measure the displacement of the upper limb, both during testing and to compare the deformation before and after testing. Elements which have not previously been quantified.

3.1 Materials and Methods

3.1.1 Selection of *Mary Rose* Longbows for Replicas

Four *Mary Rose* longbows were chosen to model the replica longbows on: artifact numbers 80A0907, 80A1298, 81A1602 and 81A1614. Some information on the dimensions of these longbows and the corresponding replica numbers are shown in the table below (Table 3-1). These longbows were chosen to allow the effect of length, cross-section shape and variations in the wood itself on the bow performance to be evaluated.

Mary Rose Artifact	Context	Cross-section shape	Longest Length (mm)	Marks	Upper Limb Double Notch	Replica Longbow
80A1298	Loose, Main Deck	Flat-D	1810	3 Chevron	No	21MRA1, 21MRA5
81A1614	Chest, Orlop Deck	Deep-D	1953	Absent	Yes	21MRA2
80A0907	Loose, Main deck	Flat-D	1960	8 Chevron	No	21MRA3
81A1602	Chest, Orlop deck	Deep-D	2040	2 Chevron	No	21MRA4

Table 3-1 Information about the Mary Rose longbows chosen for replication, with corresponding replica numbers.

80A1298 is one of the shortest longbows in the collection while 81A1602 is one of the longest. The other two longbows, 81A1614 and 80A0907, are approximately average length for the collection (collection mean = 1959 mm, SD = 56). Within this, two of the longbows (81A1614 and 81A1602) have a deep-D cross-sectional shape, while the other two are flat-D. Of the four cross-sectional groups outlined in Weapons of Warre (Hildred, 2011), previous geometric morphometric analysis found these two to be the most distinct groups. Thus, they are the most likely to show any performative difference cause by cross-sectional variation. Comparison of within pairs allow the evaluation of the effect of length. Meanwhile, the replicas of 81A1614 and 80A0907 allowed comparison between the two cross-sectional shapes. Two replicas were created of 80A1298 (21MRA1 and 21MRA5) to allow for the comparison of performance based solely on wood variation. As the rest of the dimensions were the same, any difference in function is attributed to differences in the pieces of wood from which the longbows were made.

3.1.2 Measurement and Testing Methods

The replica longbows were hand measured using a tape measure and digital callipers to gather the same data as the original recording of the *Mary Rose* longbows; a linear length (length from tip to tip holding the tap taut) and longest length (length from tip to tip following the curve of the longbow) measurement, and a width and depth measurement every 100 mm along the limbs from the centre. This made the same information from both the replicas and the original artifacts was available for comparison and calculating the accuracy of the replicas. Additionally, some measurements of the size of the horn nocks were taken. These are not present on the *Mary Rose* longbows due to lack of preservation of the material.

The draw weight of the longbows was measured using the Instron 5569 (Instron, United States), fitted with a 2 kN load cell. This machine has a load measurement accuracy of ± 0.4 % of the reading down to 1/100 of the load cell capacity (in this case 20 N) and ± 0.5 % of the reading down to 1/250 of the load cell capacity (in this case 8 N). Custom grips were designed and produced using 3D printing to secure the longbows to the base of the machine over an area roughly equal to that which would be covered by the hand and hold the string to the moving load cell over an area roughly equal to three fingers (Figure 3-1). The movement of the machine would therefore emulate an archer drawing the longbow as closely as possible. This set up was also used to string the longbow by placing the stringer in the top grip and manually controlling the movement of the machine upwards, until it was possible to pull the bowstring into the notch in the nock.

The machine was programmed to move upwards at its maximum speed of 500 mm/min and then return to zero at the same speed once it had reached a specified draw length (Figure 3-2). This reduced possible damage to the longbow that would have been caused by drawing it slower or holding it in the drawn position. Before programming the machine to draw the longbows to their complete draw length, they were first warmed up by carrying out multiple draws at smaller lengths and incrementally increasing the length until the full draw length was reached. The full draw length for 21MRA2, 21MRA3, and 21MRA4 is 30 inches (762 mm), while 21MRA1 and 21MRA5 have a draw length of 28 inches (711 mm) because the longbows are shorter in overall length. This is also in line with the lengths of arrows found on *Mary Rose*, which indicated two different draw lengths, as discussed in chapter 1.3.2. All the longbows had a brace height of 6 inches (152 mm) so to find the draw weight at full draw, the machine was programmed to pull the string back 22 inches (560 mm) for the shorter longbows and 24 inches (610 mm) for the other three.

Figure 3-1 Set up for testing the longbows using the custom designed grips to secure the longbow to the base of the machine and the string to the load cell. Photo: Author.

A Manta camera fitted with a 50 mm Nikkor lens was set up to capture images of the upper limb while the longbows were being drawn as well as before and after the experiment. Every 100 mm, where the longbow had been measured for width and depth, a marker for point tracking was placed (Figure 3-3). Using this the maximum upper limb displacement when strung and when the longbow was its maximum draw length could be measured. In addition, it was possible to compare the longbow unstrung before and after the experiments to investigate lasting deformation of the limbs. To measure this, images from the camera were compiled into a video and point tracking was carried out in Kinovea, v. 8.15.

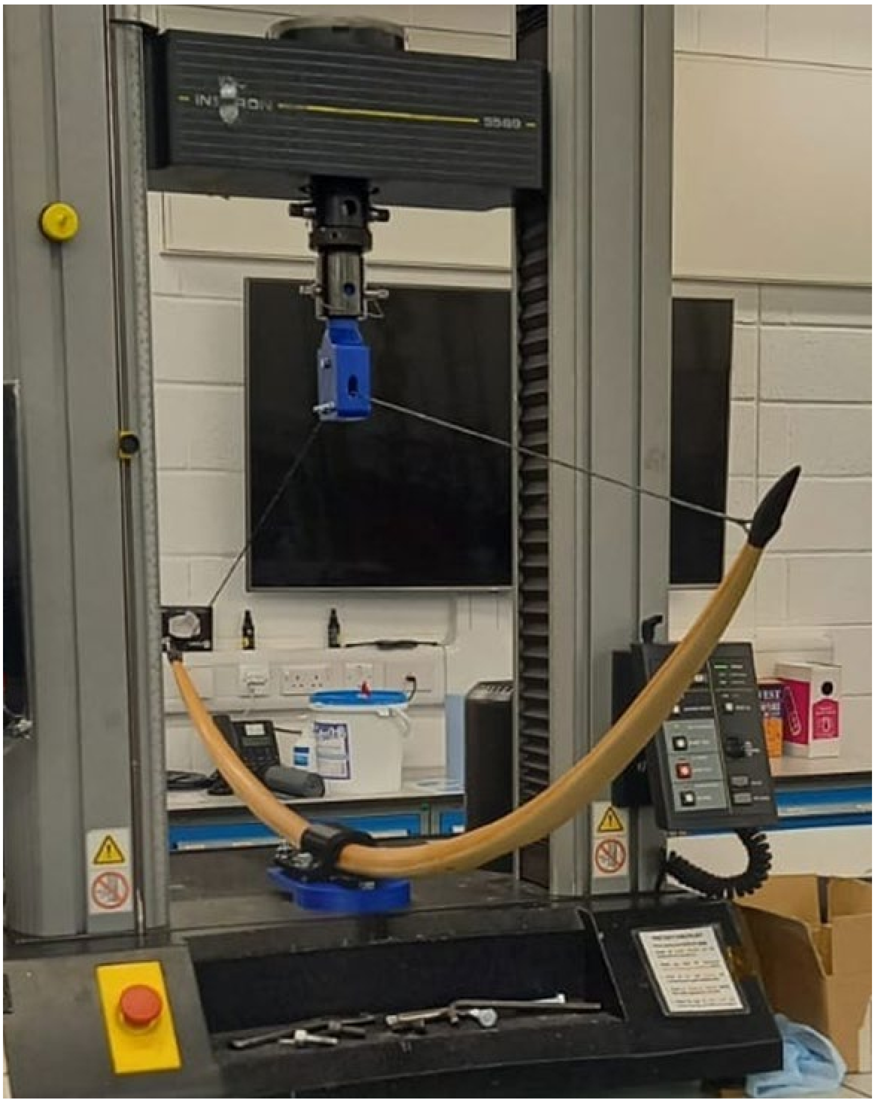


Figure 3-2 Testing of 21MRA5 in action. Photo: Author

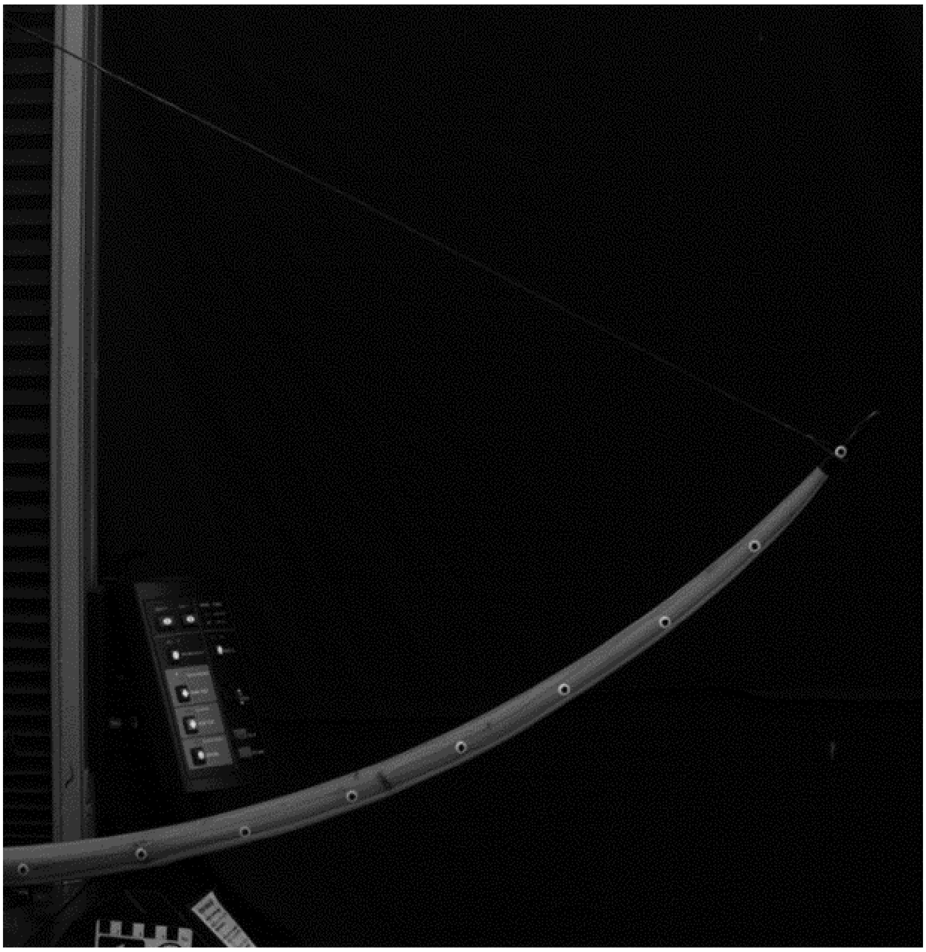


Figure 3-3 Example of the photographs captured by the camera to be used for point tracking. Longbow shown is 21MRA5 at full draw. Photo: Author

Each longbow was tested multiple times, on different days that were spaced out over several months to explore the lasting deformation of the wood as it was used and whether there was any influence of the set up on the results. 21MRA2, 21MRA3, and 21MRA5 were tested first as there were issues with the string length for 21MRA4, which meant it could not be tested until this was resolved. Due to this delay, it was deemed unnecessary to conduct longer term testing 21MRA4 as the trends can be reasonably expected to be the same as for the other three. Instead, only the tests necessary for a comparable draw weight measurement were carried out for this longbow. 21MRA1 was not tested at all. Stringing of 21MRA1 revealed that the longbow had warped at some point between its creation and testing (Figure 3-4). Attempts to test this longbow regardless were unsuccessful, resulting in the string coming off the end of the longbow as the machine returned to zero.

Figure 3-4 Warping of 21MRA1. Held in this position the longbow should be curved underneath the sting, as in Figure 3.2, so the limbs here are twisting to the right. Photo: Author

After these tests 21MRA5 was submerged in water in order to investigate the effect on the performance of the longbow. It is highly likely that the English army would have found their longbows dampened by rain or, in a maritime context, sea spray. However, beyond Stretton's investigation (2017a) of wet fletching, there has been no experimentation into whether this had an effect on the performance of the longbow. To examine this, the longbow was soaked in water and weighed daily until it is fully saturated, indicated by the weight of the longbow no longer increasing. At this point, the longbow was due to be tested wet, and then regularly over the course of drying out. However, when the longbow was taken for testing, this revealed that the longbow had warped so this testing was unable to be completed (Figure 3-5).

Figure 3-5 Warping of 21MRA5 after submersion in water. In this position the limbs should be curved directly up with the string between them, as in Figure 3.2, so the limbs are warped to the left. Photo: Author.

3.1.3 Natural Bowstrings

Linen and hemp were chosen as materials for testing as these are two of the most popularly suggested possible materials for the *Mary Rose* bowstring fragment and due to availability of material. Nettle was also suggested; however, it was not possible to source any nettle bowstring for this project.

Ten samples of the two natural bowstring materials were tested in the same machine as the replica longbows, Instron 5569, using cor-de-chasse grips (Figure 3-6). The method followed was as close to BS5053:1985 as possible. However, for the hemp string it was not possible to have an effective length of 500 mm due to the length that was available (each piece of string was supplied in 1m long sections). Instead, an effective length of 300 mm was used, and the speed of the machine was reduced to 300 mm/min in accordance with the guidelines. For the linen bowstring, an effective length of 500 mm was possible, and the speed used was 500 mm/min.

Figure 3-6 Sample of hemp bowstring secured at the top and bottom in cor-de-chasse grips ready for testing. Photo: Author

3.2 Results

3.2.1 Replica Longbows

3.2.1.1 Accuracy of the Replicas

In general, the accuracy of the replicas when compared to the original artefacts is very high. The length measurements of the replicas are longer by about 40 to 70 mm. This equates to approximately 2 - 3 %, which accommodates for the addition of the horn nocks at either end. On the original artifacts these have been lost and so the longbows measure as shorter. Therefore, this increase was expected and an accurate representation of the lengths of the longbows when they were in use.

The width and depth measurements showed more variation from the original measurements, with some areas being as much as 28 % larger. That said, the cross-sectional dimensions of the longbow are small, around 30 to 40 mm at the centre tapering off to between 10 and 20 mm at the tips, so small differences do equate to a larger percentage error. The largest percentage increase is in fact only 5 mm difference between the original artefact and the replica.

The main inaccuracy of the replicas can be seen towards the tips. The original longbows taper down to a smaller diameter than has been achieved for the replicas. Some variation was expected due to the nature of the material and the measurements remain within the range represented by the collection of *Mary Rose* longbows as a whole. Therefore, even where the replicas are not exact copies of specified longbows, they are still representative of the longbows found aboard *Mary Rose*.

3.2.1.2 Draw Weight Measurement

The first five measurements made during the first three days of testing for each of the replicas tested are summarised in Figure 3-7. Due to the longer-term testing of 21MRA2, 21MRA3 and 21MRA5 results have been visualised in this way for ease of comparison. The full data for all tests has been used for calculations of averages and statistical comparison. 21MRA4 had the highest force measurement with an average 679.7 N (SD = 13.6 N), while 21MRA5 had the lowest at 382.5 N (SD = 3.8 N). 21MRA2 and 21MRA3 were between the two with average forces of 566.2 N (SD = 7 N) and 512.4 N (SD = 9.8 N), respectively. The conversion of these forces to draw weight in pounds is shown below in Table 3-2. This is the standard measurement to use to refer to the draw weight of bows.

The initial results of drawing the longbows showed a small drop in force needed to draw the longbow over the tests. 21MRA5 began with a maximum force of 389.6 N on the first draw of day one but after the fifth draw this had dropped to 385 N. 21MRA2 showed a similar result with a maximum force of 587.3 N in the first test of day one dropping to 570 N by the fifth. However, it was also observed that between the first and second day of testing (separated by approximately 3 weeks) there was an increase in the force required. For 21MRA2 this was almost the same as the first test at 538.6 N and for 21MRA5 it was slightly higher at 391.9 N. This then dropped again over the tests on that day to 568.3 N and 384.8

N respectively. It was at this point that it was decided longer term testing was needed to establish whether this pattern continued and whether it was influenced in any way by the machine.

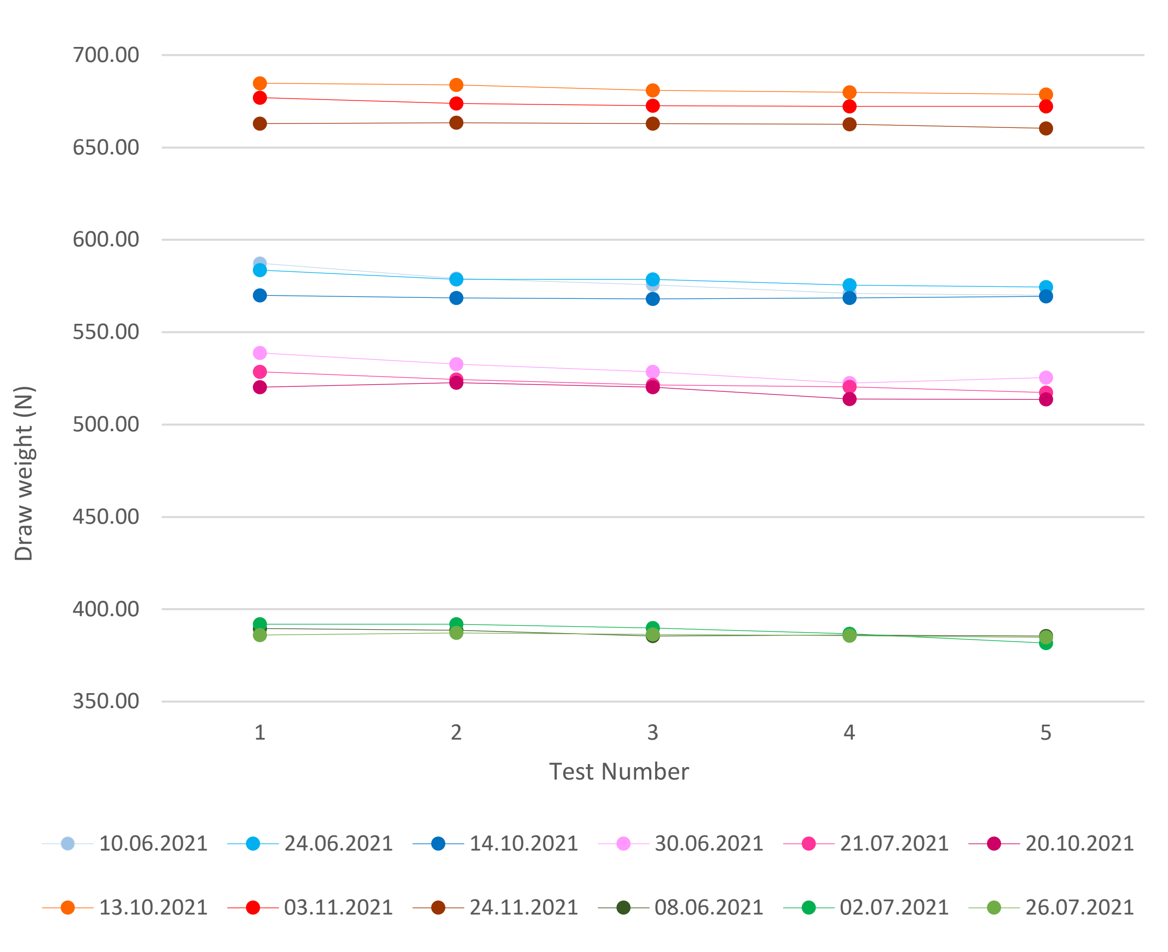


Figure 3-7 First 5 tests from each of the first 3 days of testing for 21MRA2 (blue), 21MRA3 (pink), 21MRA4 (blue) and 21MRA5(green).

A higher number of repeat tests were carried out for 21MRA2, 21MRA3 and 21MRA5 for this purpose. The results of this can be seen in Figure 3-8, Figure 3-9 and Figure 3-10. During these tests, the effect of removing the longbows from the machine between tests was also experimented with. For some tests the replica was removed between each draw, while for others it was drawn a few times without removal, then removed. These are indicated on the figures below. Over the course of this testing the maximum force decreased by 8.7 N for 21MRA5, 40.8 N for 21MRA3, and 30.2 N for 21MRA2. However, this decrease is relatively small, only equating to 2 to 8% of the initial maximum force from the first test.

Replica	Force in N	Draw Weight in lbs
21MRA2	566.2	127.4
21MRA3	512.4	115.1
21MRA4	679.7	151.1
21MRA5	382.5	86

Table 3-2 Average draw force measured in newtons and the conversion to draw weight measured in pounds for each of the replica longbows tested.

There appeared to be no overall difference in the trend caused by removing the longbow from the machine during testing. In some instances, particularly towards the end of testing for 21MRA5, an increase in force appears to be linked to the removal of the longbow from the machine, but this is not a consistent pattern over the longbows. There are peaks and throughs throughout all of the data collected regardless of consistent removal or not. Overall, the trend that the force decreases over the test remains true.

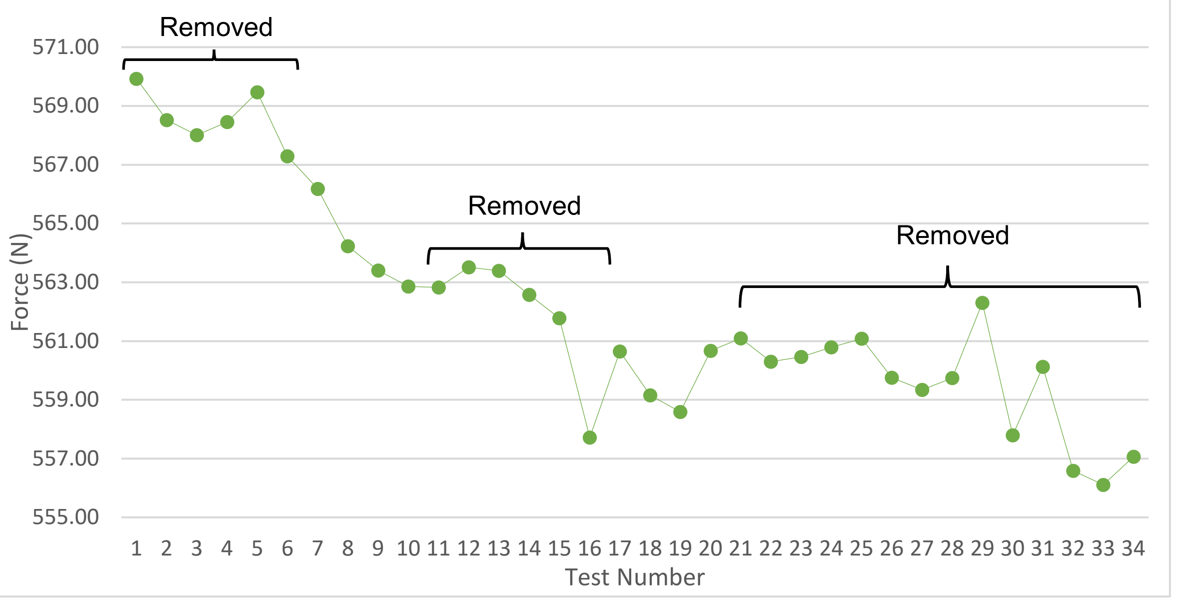


Figure 3-8 Long-term testing of 21MRA2 including the removal of the longbow from the machine between tests, as indicated on the graph.

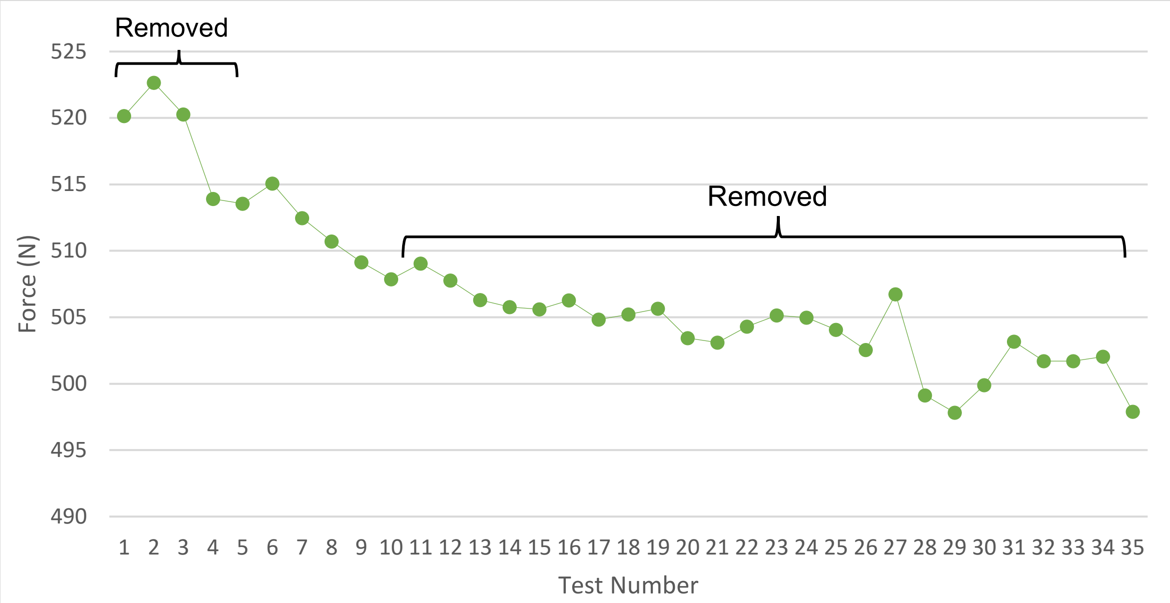


Figure 3-9 Long-term testing of 21MRA3 including the removal of the longbow from the machine between tests, as indicated on the graph.

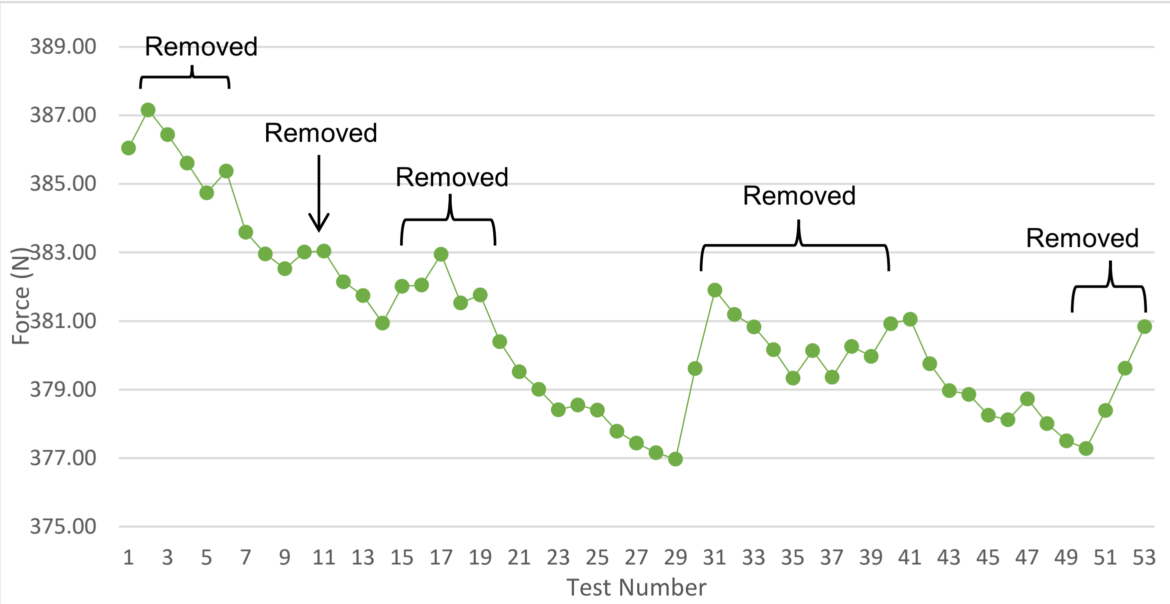


Figure 3-10 Long-term testing of 21MRA5 including the removal of the longbow from the machine between tests, as indicated on the graph

Between the last test of the second day and the first test of the third day, when the longer-term experimentation was carried out, the force increase was not as significant with 21MRA2 only increasing by 1.6 N from 568.3 N to 569.9 N, and 21MRA5 increasing by 2.4

N from 384.8 N to 387.2 N. A similar pattern was seen in the testing for 21MRA3. These results are summarised in Table 3-3. 21MRA2 was tested over a greater number of days to explore how this pattern would develop over more testing days. The results of this are shown in Figure 3-11. There continued to be a pattern of the longbow recovering some of the force needed to draw it in between testing days, but never back to the initial value. On the fourth test day, five more individual tests were carried out, which showed a similar pattern of decreasing measurement over the individual tests. On the fifth and sixth day of testing the longbow was only tested one time after warming up. While the fifth day of testing also showed a decrease, the draw weight measured on the sixth day was higher than the fifth as well as some of the tests on the fourth day. However, this increase was in line with the variation that had been observed in the initial three days.

	Day 1 Start (N)	Day 1 End (N)	Day 2 Start (N)	Day 2 End (N)	Day 3 Start (N)	Day 3 End (N)	Difference (N)	Difference (%)
21MRA2	587.3	570	583.6	568.3	569.9	556.1	31.2	5.3
21MRA3	538.7	513.2	528.5	515.3	522.7	497.8	40.91	7.6
21MRA5	389.6	385.5	391.9	384.8	387.2	377	12.6	3.2

Table 3-3 Summary of the forces measured from 21MRA2, 21MRA3 and 21MRA5 on the first three days of testing, with the overall difference (between day 1 start and day 3 end) shown in both difference in measured values and in percentage.

As the testing of 21MRA4 occurred after the long-term test results were obtained, it was decided conducting this testing of 21MRA4 was not necessary. This replica was only tested over 3 days, including 25 individual tests. The results observed for this longbow have the same pattern as has been described for the other three longbows, with the first result being 684.8 N and subsequent tests having lower recorded measurements (Figure 3-12). Thus, the results of long-term testing can reasonably be expected to be the same as the other longbows as well.

Single factor analysis of variance (ANOVA) had a P-value of 2.11×10^{-243} showing that the difference in force between the longbows was statistically significant. F-tests and t-tests were also conducted to establish if this applied to each individual pair of longbows. All F-tests showed there were unequal variances between all pairs ($p < 0.05$, for full p-values see Appendix A.1) so t-tests for unequal variances were used in each case. The results of these t-tests confirmed there was a statistical difference in the force needed to draw the replicas between all individual longbows ($p < 0.001$, for full p-values see Appendix A.1).

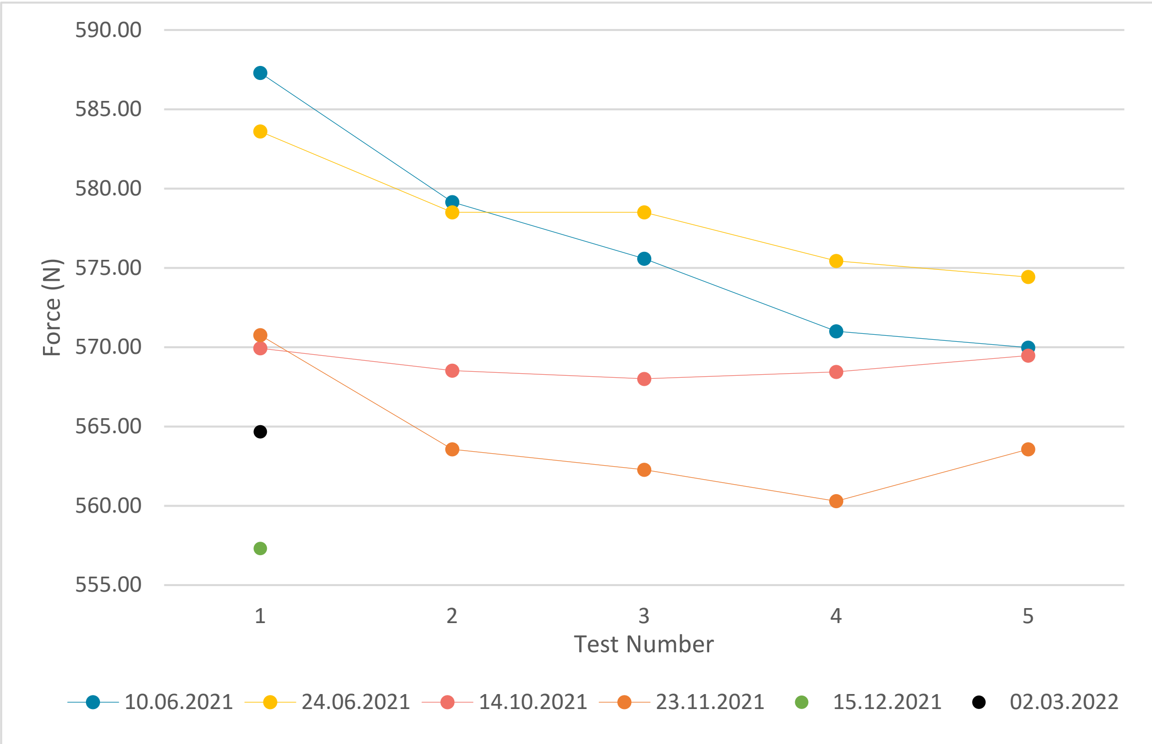


Figure 3-11 Results from all six days of testing 21MRA2, including first five tests from each of the first three days of testing discussed above and the full results from the three additional testing days.

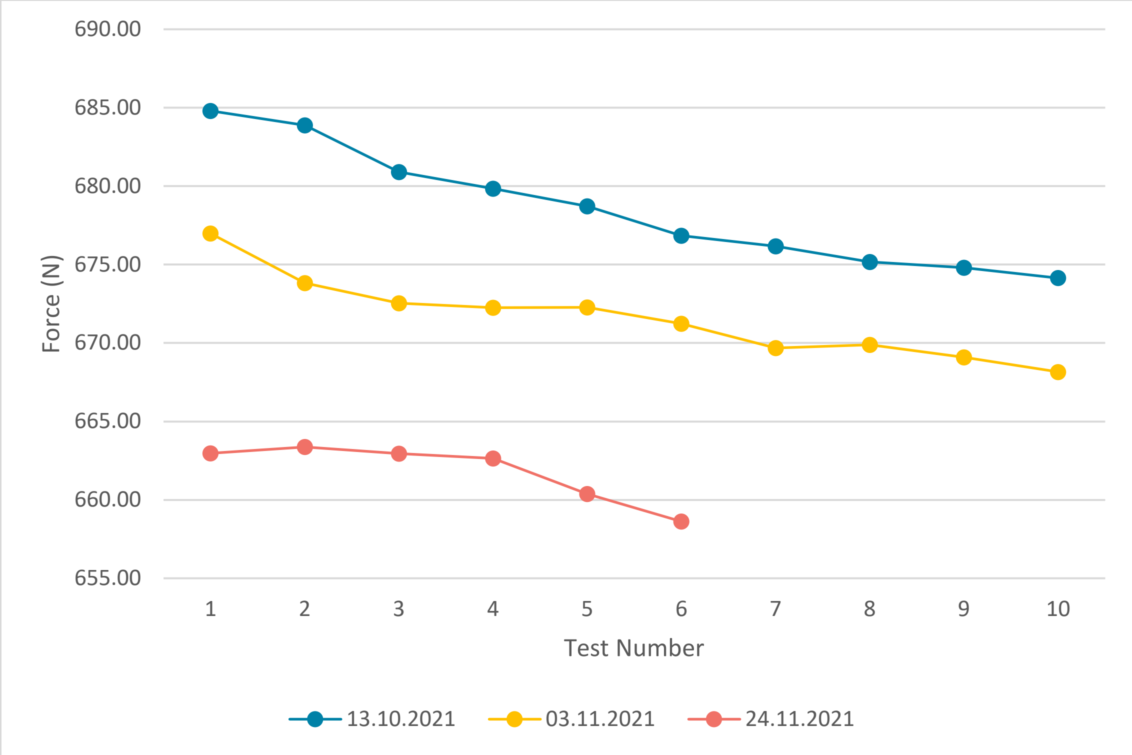


Figure 3-12 Draw force measurements from the three days of testing 21MRA4.

3.2.1.3 Limb Displacement

Displacement measurements were taken on the upper limb for all longbows during the first five tests on each of the first three days of testing. The average displacement at the maximum draw length is shown in Table 3-4. As expected, the tip of the longbow is displaced more than points closer to the centre. There was some variation in the displacement results over the tests, but the standard deviation for all points on all four longbows is low. For 21MRA3, 21MRA4 and 21MRA5 it was below 1 cm for all points and below 2 cm for 21MRA2. Although the standard deviation appears to increase as you move along the length of the limb from centre to tip, if it is taken proportional to the limb movement at each point, it is actually decreasing along the limb. This variation is more likely explained by the accuracy of the measurement, both by the camera and in the software used, which is more pronounced in areas where the movement is smaller, then by meaningful changes in the limb deformation between the tests.

Position	21MRA2 (mm)	21MRA3 (mm)	21MRA4 (mm)	21MRA5 (mm)
100mm	0.1	0.3	0.6	0.1
200mm	0.5	0.5	0.6	0.2
300mm	0.3	0.6	0.7	0.2
400mm	0.3	0.8	0.8	0.3
500mm	0.3	1.1	0.9	0.4
600mm	0.4	1.5	1.1	0.5
700mm	0.7	1.8	1.3	0.8
800mm	1.4	2.2	1.5	0.9
900mm	1.8	2.8	1.7	-
Tip	2.1	3.2	1.9	1.1

Table 3-4 Measurement of the distance between where the longbow sat unstrung before testing and where it sat unstrung. For 21MRA3 and 21MRA5 value given is an average of first three test days. 21MRA2 is data from day 2 of testing only, as the longbow had to be adjusted in the machine between the start and end of the testing meaning the results measured do not represent actual deformation of the longbow. For the same reason results from day 3 of testing 21MRA4 has been excluded so this value is an average of the first 2 days of testing.

	21MRA2 (mm) M	21MRA2 (mm) SD	21MRA3 (mm) M	21MRA3 (mm) SD	21MRA4 (mm) M	21MRA4 (mm) SD	21MRA5 (mm) M	21MRA5 (mm) M
100mm	3.7	1.2	1.2	0.8	3.2	0.4	4.6	1.9
200mm	19.1	4.0	15.0	3.1	14.1	1.3	22.3	3.6
300mm	49.4	10.7	25.6	2.2	31.3	2.1	44.0	3.7
400mm	73.7	11.1	53.6	3.8	51.9	1.5	65.5	4.8
500mm	97.5	11.1	80.0	3.8	79.2	1.7	89.3	2.3
600mm	123.3	12.8	102.5	3.2	109.4	1.8	112.5	3.5
700mm	154.9	10.2	136.9	5.4	141.0	3.8	147.4	3.7
800mm	191.0	12.9	168.0	7.5	174.7	7.6	178.6	6.1
900mm	227.7	13.9	202.7	6.4	212.0	3.4	-	-
Tip	269.0	15.8	238.6	9.8	256.5	4.1	212.2	8.7

Table 3-5 Mean and standard deviation of the displacement of the upper limb at full draw, measured at 100mm intervals.

Comparison between the starting unstrung position of the limb to the end unstrung position indicated there is some lasting deformation of the limb but the magnitude is very small (Table 3-5). In most cases there was less than 4mm difference between the start and the end, with the most deformation at the tip and decreasing towards the centre. There are some tests, for example the first day of testing 21MRA2, where difference between the start and end position is the same for all points. However, in these cases the longbow had to be repositioned, so these results are not accurate. The comparison between the start and the end for longbows that were removed from the machine during the day; 21MRA2, 21MRA3 and 21MRA5 on day three of their testing, have also not been considered as the replacement of the longbow back into the machine is not perfectly the same every time.

3.2.2 Natural Bowstrings

The results from the ten samples of linen (Table 3-6) and hemp (Table 3-7) are shown below. The average maximum force for linen was 855 N, with a standard deviation of 198.6 N. The results indicate some correlation between the diameter of the bowstring and the maximum force, with the highest results 1233 N and 1035 N being associated with the larger diameter pieces of 4.4 mm and 4.6 mm respectively (Figure 3-13). However, R^2 value for this relationship (0.7855) gives an overestimation of how dependant these variables are. The other eight test pieces, which range between 3.2 and 3.6 mm in diameter, have no correlation (R^2 = 0.0628). The measurements after testing showed that there was an average strain of 0.04, with two samples having no elongation, so a strain value of 0, and one a strain value of 0.1. The average tensile strength was 84 N/cm² with a standard deviation of 11.8 N/cm².

For hemp, the average maximum force was lower at 574.6 N. There was less variation in the maximum force when compared to linen, with a standard deviation of 61.4 N. The tensile strength of hemp was therefore lower with an average of 65.9 N/cm² and standard deviation of 9.4 N/cm². Additionally, there was no correlation between the sample diameter and the maximum force, with an R^2 value of only 0.0094 (Figure 3-14). However, the range of sample diameters was also less. If samples 2 and 6 are eliminated from the linen group, the R^2 value for the relationship between diameter and force drops significantly to only 0.0628. The elongation of the hemp samples was the same on average, with a mean strain value of 0.04. Only one sample had no elongation, and two samples had a strain value of 0.07.

Linen	Maximum Force (N)	Diameter (mm)	Tensile Strength (N/cm²)	Elongation (mm)	Strain
1	786.7	3.4	87.2	15	0.03
2	1233.1	4.4	83	25	0.05
3	812.8	3.2	103.6	0	0.00
4	750.8	3.4	81.3	37	0.07
5	689.7	3.2	86.3	22	0.04
6	1191.6	4.6	71.1	25	0.05
7	681	3.5	70.8	25	0.05
8	752.3	3.5	79.1	10	0.02
9	750.1	3.6	74.5	0	0.00
10	901.8	3.3	103.5	60	0.1
Average	855	3.6	84	21.9	0.04
SD	198.6	0.5	11.8	17.8	0.04

Table 3-6 Results from the testing of Linen bowstring, including the maximum force before breakage, diameter of each piece, tensile strength calculated, elongation of the sample measured, and the strain calculated. Each piece began with an effective length of 500 mm.

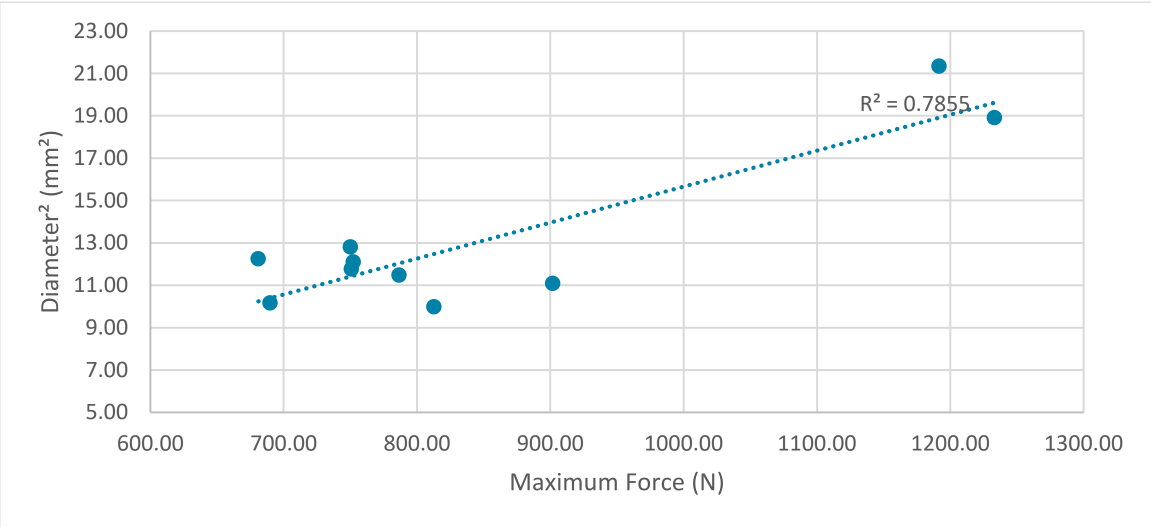


Figure 3-13 Relationship between the squared diameter of each Linen bowstring sample and the maximum force recorded before breakage.

Hemp	Maximum Force (N)	Diameter (mm)	Tensile Strength (N/cm²)	Elongation (mm)	Strain
1	614	3.4	66.4	4	0.01
2	620.1	3.3	72.5	20	0.07
3	431.3	3.5	45.9	0	0.00
4	551.6	3.4	62.2	10	0.03
5	520.2	2.9	78.8	14	0.05
6	629.8	3.4	69.8	11	0.04
7	627.3	3.3	72	20	0.07
8	592.1	3.5	62.6	13	0.04
9	574.5	3.6	57.1	12	0.04
10	585.3	3.2	71.4	14	0.05
Average	574.6	3.4	65.9	11.8	0.04
SD	61.4	0.2	9.4	6.2	0.02

Table 3-7 Results from the testing of Hemp bowstring, including the maximum force before breakage, diameter of each piece, tensile strength calculated, elongation of the sample measured, and the strain calculated. Each piece began with an effective length of 300 mm.

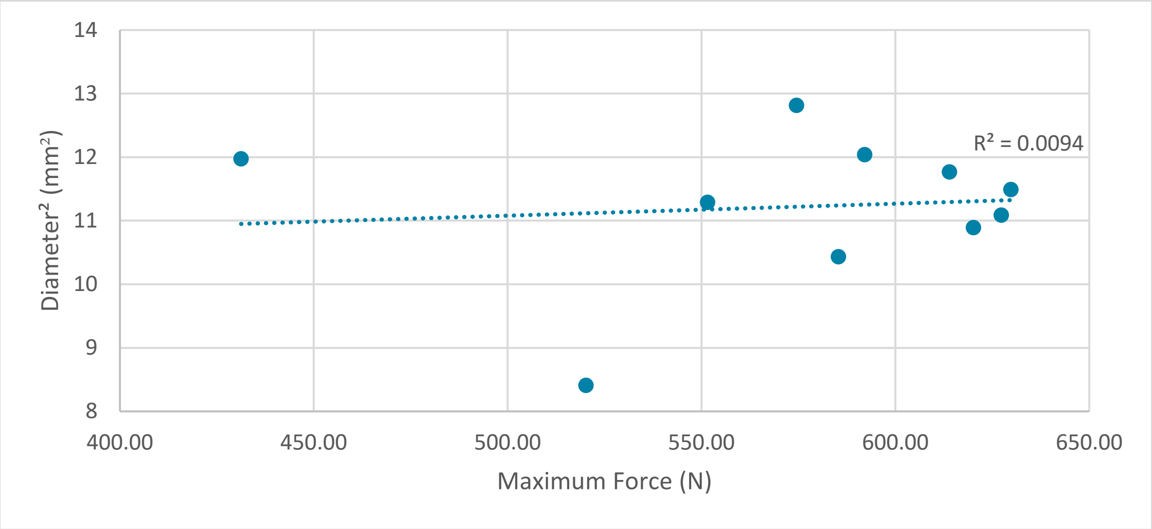


Figure 3-14 Relationship between the squared diameter of each Hemp bowstring sample and the maximum force recorded before breakage.

3.3 Discussion

The draw weights measured from the replica longbows have a range of 85 lbs to 151 lbs, which is higher than the original assumption of the longbows' average draw weight (70 lbs) but on the lower end of Kooi's controversial modelling of the longbows. His model, when adjusted in line with the results from a replica longbow, predicted a range of 98 lbs to 185 lbs, with most expected to be around 150 - 160 lbs (Hardy, et al., 2011). To line up with this, we would expect our average length replicas (21MRA2 and 21MRA3) to be around this expected mode, with the other two (21MRA4 and 21MRA5) towards the upper and lower ends, respectively.

This original study used three replica longbows, also made using American Yew, to improve and validate the model. These had a range of 102 to 135 lbs, which is consistent with the findings of this study. However, these are more generic longbows, made "to the overall design features of the *Mary Rose* bows" (Hardy, et al., 2011) opposed to approximations of specific longbows used in this study so it is not possible to compare them individually to our results.

In comparison, these results align well with the proposed draw weights of Watson's arrow-based modelling system, which gave an estimation of 40 to 190 lbs with most between 50 and 130 lbs (Watson, 2011b). This comparison does assume the results from the replicas are directly comparable to the *Mary Rose* longbows, to what degree this is true will be discussed further in later chapters when the internal structure of both replicas and *Mary Rose* longbows is compared.

A small decrease in draw weight over the testing period was noted for all replica longbows; by 5 % or lower over the first three days of testing, with the exception of 21MRA3 which had a 7.5 % decrease. Test showed that this was a true deterioration of the wood and not related to the testing set-up. Although some recovery of the draw weight was observed between days of testing, when the longbows were left unstrung, this was never back to the original measured value, indicating some of the change was elastic deformation and some was plastic deformation. This decrease has not been noted numerically in other studies as beyond giving the initial value, draw weight is generally not discussed or tested for. However, archers who were involved in this project reported that they had experienced loss of power of their longbows over usage and this was well known and expected within the historical archer community. The results do not show a strong relationship between draw weight and the amount of reduction in power. While 21MRA5 saw the smallest drop in draw weight over the first 25 tests (1.2 %), the rest of the replicas do not follow this pattern, with 21MRA3 having a higher reduction in draw weight of 4.7 %, compared to both 21MRA4 (3.8 %) and 21MRA2 (3.2 %), which had a higher initial draw weight than 21MRA3.

To what degree this affects the performance of the longbow was not mentioned, but it is unlikely to be significant at these low percentages. This will be discussed further in connection to the field testing results in the following chapter.

3.3.1 Relationship Between Draw Weight and Dimensions

The results from testing the replicas indicate that there is a connection between the dimensions of the longbow and draw weight. Table 3-8 shows the key dimensions of the longbows and the average draw weight measured from the tests. The average length longbows, 21MRA2 and 21MRA3, had a higher draw weight than 21MRA5, which is shorter, and 21MRA4, the longest longbow had the highest draw weight of all the replicas tested. This suggests that the length of the longbow is related to the draw weight as would be expected. Additionally, the slightly higher draw weight measured for 21MRA2 compared to 21MRA3 may be a result of the different cross-sections. 21MRA2 is a Deep D longbow, while 21MRA3 is a Flat D longbow. However, these differences between the longbows may also be caused by differences between the wood itself.

The warping of 21MRA1 makes the effect of the wood itself difficult to quantify as there is no data to compare to 21MRA5. As copies of the same original artefact, 80A1298, these replicas should have allowed us to see what difference in draw weight could be attributed to the wood itself. The later warping of 21MRA5 also means that neither of the shortest longbows could be tested in the field, so range and efficiency data for this longbow is unavailable. However, the results of CT scanning the longbows discussed in chapter five can go some way to help account for this.

The reason for the warping of 21MRA1 and 21MRA5 is not clear. There was also a third copy of this longbow which warped during manufacture, which perhaps suggests it is related to the specific dimensions of 80A1298 that were being replicated. There is no evidence of warping on the original artifact, even given its 500 year-long submersion, but it is difficult to tell without stringing the longbow. That being said, there is no mention in the literature of this as an issue, and there appears to be no contemporary concern that this warping may occur. It therefore becomes more likely to be an issue with the wood. Although the replica longbows were crafted to be as close to the specific examples listed as possible, there are still elements of the manufacturing process that must be determined by the stave. Thus, it is likely that similar staves would have been chosen for these three longbows, which may have originated from the same tree or trees growing in very similar conditions. During growth this tree or trees likely had some sort of one sided-ness, such as shade on one side causing more branches with more leaves to grow on one side, the additional weight causing a natural bend in the tree. With these branches removed the wood appeared straight but when the staves were reduced in mass to form the longbows this allowed the natural curve of the wood to reappear. As the staves originated in North America, there is no way to know this for certain, but the lack of other evidence suggests this is the most likely. Additionally, we know that it was a concern for the Tudors to ensure the best staves were used for their longbows from the imports of yew wood from Europe (Hardy, 2006). Here the warmer climates allow Yew to grow taller and straighter, with less knots, than in England.

If these findings are assumed to be representative of the original *Mary Rose* longbows, not in exact numbers but in general patterning, there is no indication of meaning to the marks or pattern in the find location from the four longbows selected for replication. Three of these had markings in the form of chevrons (80A1298, 80A0907, and 81A1602) but of different numbers (3, 8 and 2, respectively). However, these numbers do not correlate to either increasing or decreasing draw weight. Neither the two orlop deck, chest longbows, or the two main deck loose longbows have any features in common with each other.

Replica Number	*Mary Rose* Artifact	Cross-section	Longest Length (mm)	Weight (g)	Mean Draw Weight (lbs)
21MRA1	80A1298	Flat D	1912	889	-
21MRA2	81A1614	Deep D	1993	881	127.34
21MRA3	80A0907	Flat D	2030	860	115.1
21MRA4	81A1602	Deep D	2087	1178	151.1
21MRA5	80A1298	Flat D	1911	895	86

Table 3-8 Summary of key measurements from replica bows discussed in this chapter.

3.3.2 Natural Bowstring

The results of the bowstring tests show that hemp is weaker than linen, with the higher end of its range being below the lower end of the range for linen. In all of the tests, hemp would have been strong enough to withstand the force needed to draw the smallest longbow and some pieces on the higher end of the range would have been able to draw 21MRA2 and 21MRA3. However, none of the test pieces would withstand the force needed to draw the largest longbow. Linen, on the other hand, had a majority of test pieces strong enough for the largest longbow, with only two pieces having a breaking force below 750 N. Therefore, of the two materials tested, linen seems more likely than hemp, but this is still not ideal.

Two of the linen test pieces with a larger diameter, had breaking forces of 1233 N and 1035 N. These are roughly around 3 times the draw weight of the smallest longbow but otherwise none of the test pieces satisfied the minimum common best practice discussed in 1.3.3. This would negatively impact the durability of the strings, which may be reflected in the high ratio of strings to longbows recorded in the Anthony Roll for *Mary Rose*. According to these figures, each longbow has three strings (Hildred, 2011, table 8.1). Measurements of the nocks on the arrows were between 2mm and 5mm, and with the strong positive correlation between the diameter and the strength of the linen string, it is possible there were larger diameter strings with higher strengths for the larger longbows. However, this would add an additional layer to complexity aboard the ship. Finding the right longbow, finding right string to match it, and then the right arrows to shoot using that longbow would be an impractical set up for defending the ship from attack. It is more likely that the best practice was not the same as it is today, and the durability problem was dealt with by increasing the number of strings per longbow. Of course, it is also possible that there are other materials or combinations of materials that were not explored by this testing that may have a better strength. Fibres from nettle and the incorporation of horsehair has been suggested, for example (Alex Hildred, Personal Communication, 2022).

Chapter 4

Ready, Aim, Loose: Field Testing at Fort Purbrook, Portsmouth

Experimental shooting has been popular in the study of historical archery, primarily for the purposes of investigating the penetration of the arrow into armour, as discussed in chapter two. These studies have had varying degrees of success in addressing the matter of how deadly the longbow truly was, but often have gaps in the materials or methods used. There is limited study outside of this, primarily carried out by Mark Stretton, who also investigated fire arrows and the effect of wet fletching. The purpose of the field testing in this study was almost the opposite to that of pervious works; focusing on the performance of the longbow itself through what initial arrow speed was produced instead of the end result when the arrow lands.

In addition to this, all previous studies use human archers to fire the longbows being tested. Whilst this of course how the longbow is used, over an experimental period this either means multiple people are needed or a single archer will need more time over which they will experience fatigue, which introduces inaccuracies and human error into the data. As a manually operated weapon, these would have been factors in the use of a longbow historically, however, in order to assess the properties of the longbow itself, rather than the archer as a unit, this research used a machine to remove the human aspect and produce repeatable results. The effect of the archer on the bow-and-arrow system is an aspect that can easily be factored in by repeating the shooting experiments using an archer and comparing the results.

Experiments with the *Mary Rose* replicas were coupled with testing of different arrow types, in partnership with fletcher Joff Williams. For some time Joff has been interested in investigating the five ‘essential’ characteristics that determine the behaviour of a set of arrows; mass, spine, drag, profile, and balance point, and what the actual practical effect of changes in these characteristics is. Along with some fellow traditional archers, a series of tests were carried out to investigate this. The specific hypotheses and short summary of the findings is shown in Table 4-1.

Hypothesises 6a – as draw weight increases, release velocity decreases with the inertia in the longbow limbs and the heavier arrow – and 6b – as longbow draw weight increases force and energy increases with increased arrow weight – are directly related to the aims of this project to improve understanding of the relationship between the physical dimensions of the longbow and its performance. While the other hypothesises 1 through 4, relate to some of the questions about the wider *Mary Rose* archery equipment. As discussed in chapter 1, there is a large variation in wood types and arrow styles withing the *Mary Rose* collection. In order to get the best performance from the bow-and arrow system the two should be matched. This means that the spine of the arrow is matched to the draw weight of the longbow, allowing the arrow to bend around the longbow when shot – known as the archer’s paradox. It is this principle that allowed the modelling of longbow draw weights based on the arrows, carried out by Watson (2011a). However, it is known that arrows of different variations were stored together in barrels, similar to the mixed storage of longbows in chests. Therefore, in order to find the arrows for their longbow a soldier would have to search through these, a long process one would certainly not want to do in the midst of battle. This raises the question of how key it was to have the perfect arrow as is understood in today’s terms and whether there were any noticeable differences between the arrows made of different woods and in different shapes.

Joff’s work goes some way to answering these questions, but, as above with other experimental works, these were done with human archers so have a certain amount of human error also factoring into the results. Interestingly, Joff also noted that difference in natural draw length was a variation between archers and over time there was a tendency to revert back to this where the arrow would allow, instead of pulling the 30 inches standard for the test. By removing human error through the use of a machine, conclusions can be more confidently based on variations in the arrow as there are less variations in the test results. This was particularly needed in the case of hypothesis 6a, where the results obtained by Joff were inconclusive.

Hypothesis 1	As the surface area of an arrow increases, the range decreases.	True with a moderate degree of confidence.
Hypothesis 2	As the fulcrum of an arrow moves further towards the pile, the range decreases.	True with a moderate degree of confidence.
Hypothesis 3	As the profile of the arrow is altered to a better aerodynamic shape (profile > bobtail > barrel), the range increases.	True with a high degree of confidence.
Hypothesis 4	As the weight of an arrow increases, the range decreases.	True with a high degree of confidence.
Hypothesis 5	The arrow will follow a parabolic flight.	False – arrow follows an elliptical path.
Hypothesis 6a	As draw weight increases, release velocity decreases with the inertia in the longbow limbs and the heavier arrow.	Inconclusive.
Hypothesis 6b	As longbow draw weight increases force and energy increases with increased arrow weight.	True.

Table 4-1 Hypothesises tested by Joff and the conclusions made. Table from a written document of his work provided as part of our personal communications throughout this stage of the project.

4.1 Materials and Methods

All testing was carried out at the Peter Ashley Activity centre based in Fort Purbrook, Portsmouth, England. The fort is also home to the Purbrook Bowmen meaning the site was already prepared with the necessary equipment and risk assessments for archery, as well as the fort itself featuring a 100-yard (91.44 m) range in the dry moat.

4.1.1 Shooting Machine

The shooting machine was custom designed and built by Bartosz Wawrzyniak, as a third-year engineering project at the University of Southampton. The design was bounded by a set of parameters, determined mainly by the replicas as well as requirements of the construction and safe usage. These were the replica longbow's length and cross-section size, draw length and draw weight, and the shooting angle. The machine required safety while operating, smooth motion of the draw, and simple manufacturing (due to time constraints of the project). It had to be stable enough to withstand the forces of the draw and the loosing of the arrow, but lightweight enough to be easily transported to and around the fort.

In the design phase, the machine was split into five subsystems: longbow holder, main structure, trigger, puller, and aiming system. Each of these were designed initially through sketches before being 3D modelled in Solidworks, to fulfil the parameters outlined. In order to give the machine stability, a four-legged rectangular main structure (1.25 m x 1.5 m x 0.5 m) was chosen. The size gave the machine enough height and length to allow the mounting of the longbow at the front and the full draw of the longbow within the structure, as well as space for the puller and trigger systems mounted at the rear of the machine.

The trigger system was based initially on archery release aids used in modern archery. One of these aids was mounted onto a bar with rollers at either end, allowing the bar to pulled back manually along the length of the main structure using a hand winch. The replicas were mounted at the other end of the structure in two Global Truss Half Couplers, buffered with a layer of rubber to protect the longbow. These half couplers had a total grip length of 70 mm, equivalent to the grip used to hold the replicas during the laboratory tests (Figure 4-1a).

Following the construction of the machine, some tests were carried out without fully firing a longbow in order to ensure that the machine was able to handle the large draw weight of the replicas safely. These tests revealed that the archery aid trigger was not sufficient for the draw weight as it failed at a very small draw length signalling this element had to be redesigned. In collaboration with Daniel Hawley from the Purbrook Bowmen, a metal grip that emulated a three finger hold on the bowstring was designed and installed onto the sliding bar. The grip was held in place by a trigger attached to a string; pulling on the string moved the trigger allowing the finger-like grip to rotate, releasing the bowstring and arrow. This redesigned grip also had the benefit of more accurately representing an archers shot, with the bowstring rolling off the grip slightly to the left emulating the bowstring rolling off the archers' fingers (Figure 4-1b). At the same time as the new trigger system was installed, stoppers were added to prevent the sliding bar from colliding with the puller system after the release of the arrow, as well as the addition of more rollers to add greater stability to the sliding holding the trigger. The final machine is shown in Figure 4-1c.

Figure 4-1 a (top left) CAD model of longbow holder subsystem. 4-1b (bottom left) improved trigger design attached to machine. 4-1c (right) complete assembled machine.

4.1.2 Longbows and Arrows

Due to warping of two of the replicas, only 21MRA2, 21MRA3 and 21MRA4 were able to be used for the field testing. All three replicas had a set of four arrows manufactured by Joff Williams to match the draw weights of the longbows as well as possible (Table 4-2). For these tests, the initial speed and the dispersion of the arrows were the primary data collected. The initial speed was measured using a Competition Electronics Pro-Chrono Digital chronograph (accuracy +/- 1 % of measured velocity) which was placed just in front of the machine. Dispersion was measured by covering the target in sheets of paper. After the experiments a grid superimposed onto the sheet of holes and the distance from origin to the centre of each recorded. The dispersion was then normalised around the origin for each replica longbow to allow comparison. In addition to this, a highspeed camera (Motion Pro X3) was used to capture footage of the shots from directly behind. This served as a back-up method of tracking the shots for dispersion measurement, as well as allowing the flow of the machine during shooting and the path of the arrow to be observed. The penetration of the arrows was also recorded for all tests by measuring the length of the arrow which had gone inside the target after it was removed. However, was not a dependant variable for the tests so controls were not put in place to ensure the best possible result. The targets used had already been shot at many times, meaning certain areas (around the centre) were more damaged and therefore easier to penetrate. Thus, the results did not yield any useful information and are not discussed here.

Replica / Arrow Set	21MRA2 / XP374	21MRA3 / XP375	21MRA4 / XP373
Grain -Arrow 1	934	1017	1080
Grain -Arrow 2	921	1020	1096
Grain -Arrow 3	932	1011	1099
Grain -Arrow 4	891	1023	1099
Average	919.5	1017.8	1093.5

Table 4-2 Details of the arrow sets provided by Joff Williams for each of the three replica longbows tested.

For the arrow tests, three different categories of variation were explored; profile (overall shape of the arrow shaft), mass (measured for arrows in terms of grains) and drag (size of the fletching). For each of three categories there were three different groups of arrows, which represented the most popular arrow variations within that category (Table 4-3). All of these arrows were shot from the same 70 lb longbow at a distance of 40 yards (36.6 m) from the shooting machine to the target. From these tests, the strike height was recorded for each of the arrows in every group. This is related to the decrease in speed over the flight of the arrow, therefore indicating the difference to the flight of the arrow made by the variations in each category. The strike height was recorded by measuring the distance from the ground to the bottom of the arrow before they were removed.

Replica linen bowstring was planned to be used for field testing on the replica longbows to study the impact on the initial speed and flight of the arrow when compared to modern bowstring. However, no successful shots were completed using this as just the bracing of the longbow caused the string to break.

Profile	Mass (grains)	Drag (fletching size, inches)
Parallel	465	4.44
Barrelled	535	5.64
Bobtailed	615	9.00

Table 4-3 Categories and groups of arrows included in testing. In each category the rest of the arrow was kept the same between the groups.

4.2 Results

4.2.1 Replica Longbows

The average initial speed measured from each of the three replica longbows, 21MRA2, 21MRA3 and 21MRA4, are shown in Figure 4-2 alongside the corresponding ± 1% error in the chronograph measurement. 21MRA4 had the highest average speed of 56.5 m/s (SD = 0.8 m/s), while 21MRA2 and 21MRA3 had a nearly identical average speed (M = 52.2 m/s and SD = 0.3 m/s, M = 52 m/s and SD = 0.1 m/s, respectively). As there is only a small difference between the two the percentage error means the average speed of these replicas overlap substantially. Using a t-test, it was shown that statistically there was no difference between the two (p value = 0.095). However, both were shown to be significantly different to 21MRA4 ($p < 0.005$).

The distribution of the arrows shot from each of the three replicas, normalised around the origin for each group, is shown in Figure 4-3. Arrows shot from 21MRA3 had the largest dispersion with an average distance from the centre of 29.53 cm (SD = 20 cm) while arrows shot from 21MRA2 had the smallest (M = 19.1 cm, SD = 9 cm). However, using a single factor ANOVA it was shown that there was no significant difference between the dispersion of arrows shot from any of the three replica longbows (p value = 0.27).

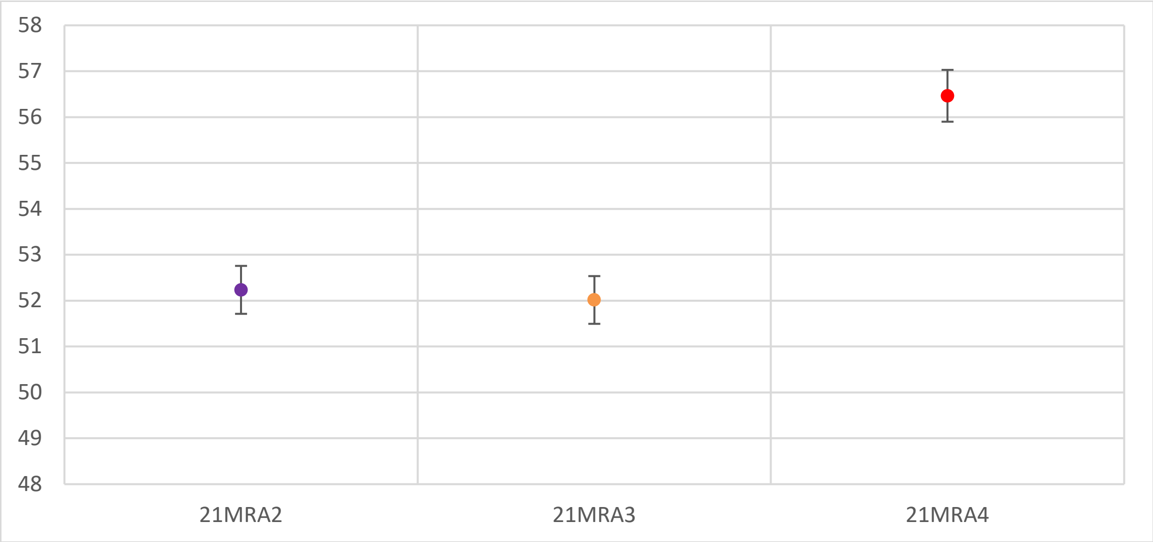


Figure 4-2 Average initial speed of arrows shot from the three replica longbows tested at Fort Purbrook (21MRA2, 21MRA3 and 21MRA4) with error bars of ± 1% indicating the accuracy of the chronograph used.

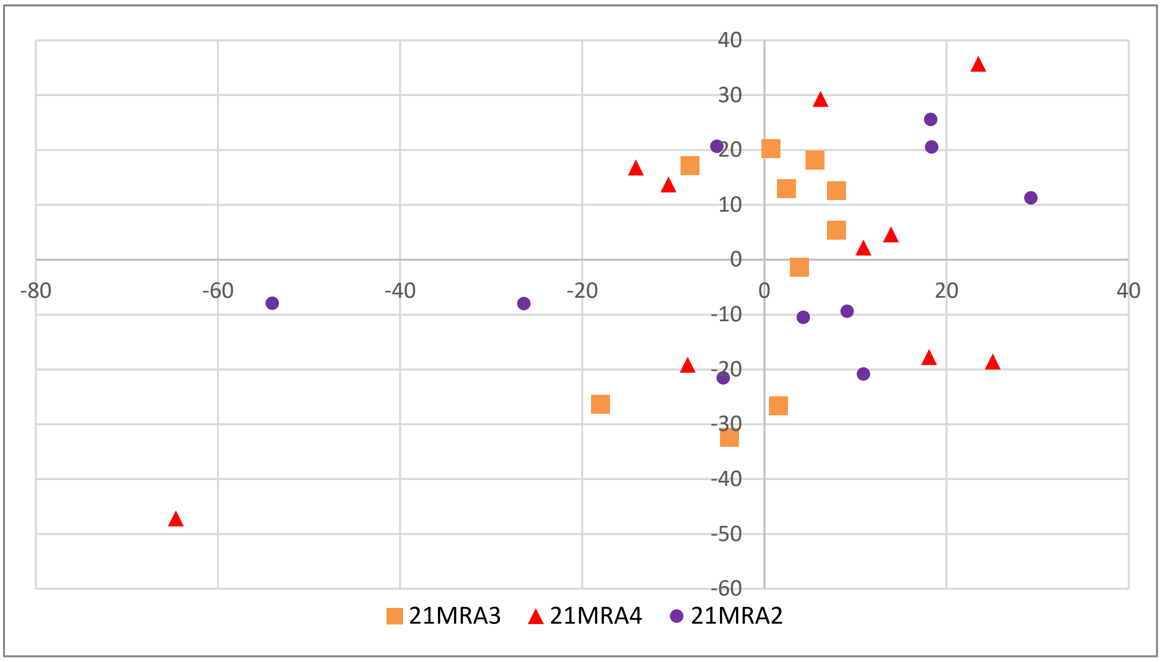


Figure 4-3 Dispersion of arrows shot from 21MRA2, 21MRA3 and 21MRA4, normalised around the origin.

4.2.2 Arrow Variations

Table 4-4 shows the average strike height recorded for each of the three groups within the profile, mass and drag categories.

Within the profile category, the strike height of the Barrelled arrows was nearly identical to that of the Bobtailed arrows (M = 141 cm and M = 142 cm respectively), while that of the Parallel arrows was 30 cm lower on average (M = 110 cm). However, the overlap of the measured values between the three categories is significant, with all three having a large standard deviation (Figure 4-4).

There is a similar pattern within the drag category; all sets of arrows appear to have a different mean ranging from 130 cm to 112 cm. However, the overlap of the recorded measurements is significant (Figure 4-5), with the results for both the arrows from the 5.64 in^2 group and the arrows from the 9 in^2 group within the range for the 4.44 in^2 group. Unlike the profile category, one of the groups (5.64 in^2) is more consistent than the others.

	Average Strike Height (cm)	**Standard Deviation (cm)**
Barrelled	141	30.7
Bobtailed	142	27.8
Parallel	110	27.6
615 **(grains)**	79	35.7
535 **(grains)**	137	7.4
465 **(grains)**	159	14.3
4.44 **(inches)**	120	29.5
5.64 **(inches)**	130	11.2
9.00 **(inches)**	112	22.2

Table 4-4 Summary of the strike height results for each of the categories tested (profile – containing Barrelled, Bobtailed and parallel, mass – containing arrows of 615 grn, 535 grns and 465 grns and drag – containing arrows with fletching length 4.4. in, 5.64 in and 9 in).

The results from the mass category do not follow this pattern, with each group having its own range of values with minimal overlap between (Figure 4-6). The 465-grain group had the highest average strike height of 159 cm, while the 615-grain group had the lowest (M =

79 cm). This group also had the largest range of values (SD = 35.6 cm), with 535 grain group being the most consistent (SD = 7.4 cm).

As expected from visualising the data above, single factor ANOVA showed that there was no significant difference between strike heights of the three profile groups (p value = 0.5), or between the strike heights of the three drag groups (p value = 0.7). However, there was a difference between the three mass groups (p value = 0.03). This was investigated further using t-tests, determined by corresponding f-tests (p values shown in Appendix A.2), which showed there was only a significant difference between the strike height of the 465-grain group and the 615-grain group (p = 0.04).

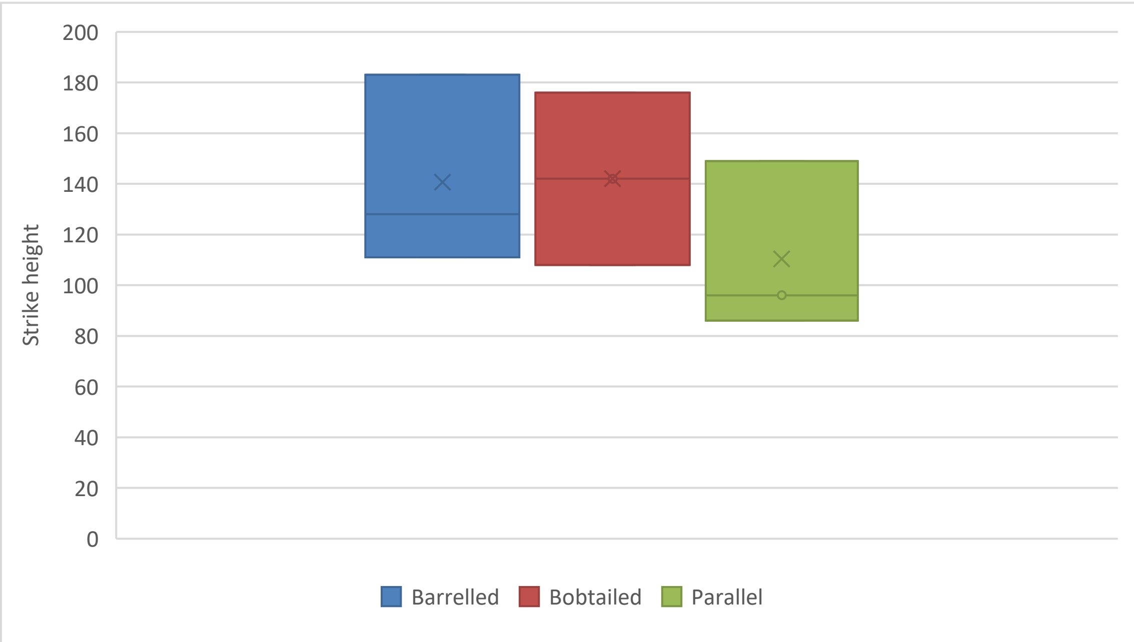


Figure 4-4 Strike height results of the three groups (Barrelled, Bobtailed and Parallel) within the Profile category.

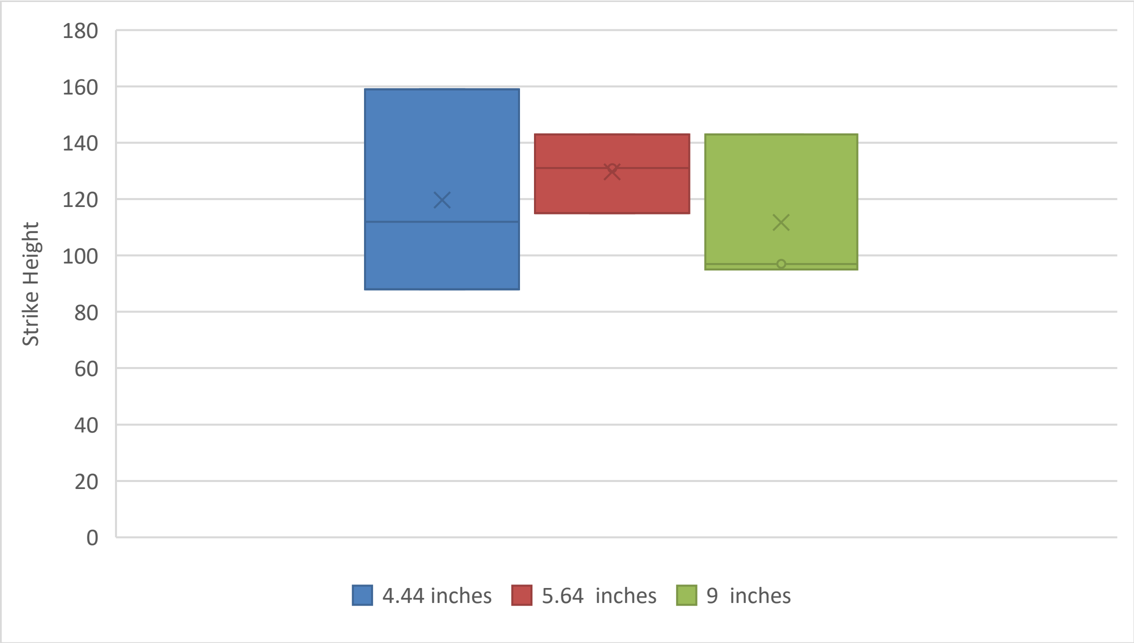


Figure 4-5 Strike height results of the three groups (4.44 inches, 5.64 inches and 9 inches) within the Drag category

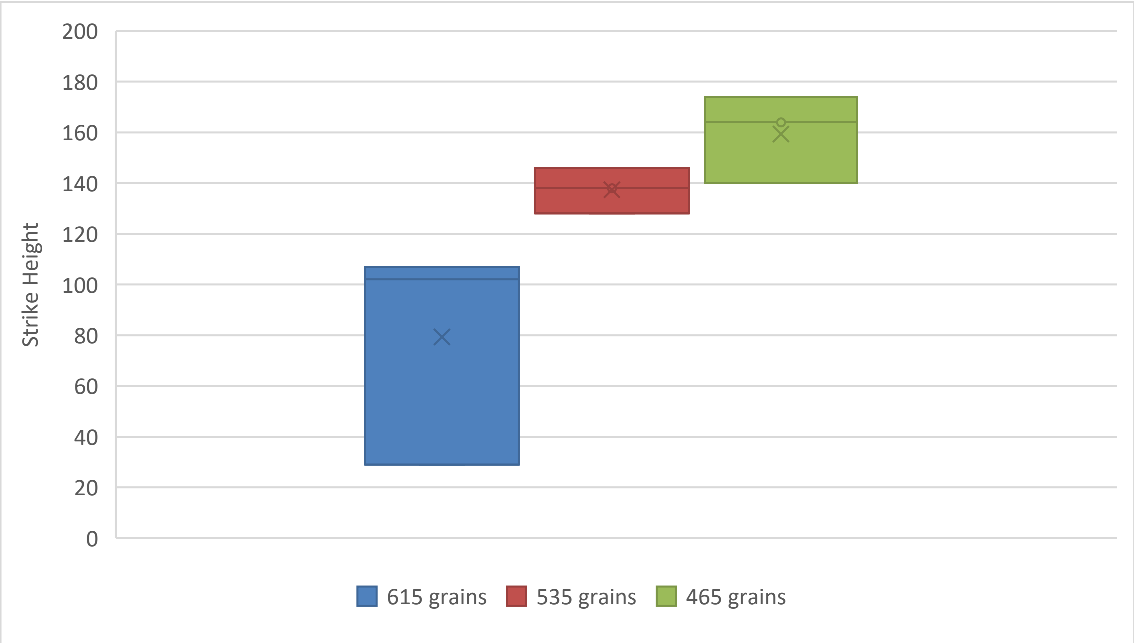


Figure 4-6 Strike height results of the three groups (615 grains, 535 grains, 465 grains) within the Mass category.

4.3 Discussion

4.3.1 Initial Speed of Arrows Shot from Replica Longbows

The main physical measurements taken in the previous chapter are shown alongside the average initial speed and average dispersion measured in this chapter in Table 4-5. Although there are differences between the dimensions of 21MRA2 and 21MRA3 in terms of their cross-sectional shape and longest length, as well as in their draw weight, this did not translate to a difference in the initial average speed. Only 21MRA4 had a significantly different initial speed, which suggests the relationship between draw weight and arrow speed is not linear, and though a statistically significant difference in draw weight was found this is not a functional difference. Tests carried out by Richardson (1998), showed a small decrease in average velocity between a 90 lbs and a 78 lbs replica *Mary Rose* longbow (43.47 m/s and 41.65 m/s respectively), when shooting the same arrowhead type. A 72 lbs longbow was also used but with a different arrowhead type, so it is unclear whether the decrease in that case (37.30 m/s) is associated with the longbow draw weight or additional drag of the arrow itself. There is at least some affect of the arrowhead shown in these tests as a Type 16 arrowhead and a bodkin arrowhead shot from the same 90 lbs longbow had a difference in average velocity of 1 m/s.

Replica Number	Cross-section	Longest Length (mm)	Weight (g)	Draw Weight (lbs)	Initial Speed (m/s)	Dispersion (cm)
21MRA2	Deep D	1993	881	127.4	52.2	19.1
21MRA3	Flat D	2030	860	115.1	52.	29.5
21MRA4	Deep D	2087	1178	151.1	56.5	26.4

Table 4-5 Measurements taken from the replica longbows in chapter 3 and the average initial speed and dispersion measured as described in this chapter.

These results suggest that draw weight alone cannot indicate the performance of the longbow. More research is needed to establish the relationship between the draw weight and arrow speed is needed in order to use the first to predict the latter and fully understand historic longbow use.

As the difference in draw weight between 21MRA5 and 21MRA3 was greater than that between 21MRA4 and 21MRA2, and similar to the difference between 21MRA4 and 21MRA3, 21MRA5 would likely have a smaller initial speed than measured for 21MRA2 and 21MRA3. There were some tests of other draw weight longbows carried out to further explore the relationship to the initial speed. However, issues with the chronograph meant that these measurements were not usable. This was likely due to the changeable weather on the first day of testing. Chronographs are easily affected by bright sunlight so the best conditions for use outside are overcast, which were the conditions on the second day of testing.

4.3.2 Significance of Arrow Variation

Three hypotheses on arrow variation were tested during this project; as the surface area of an arrow increases, the range decreases; as the profile of the arrow is altered to a better aerodynamic shape, the range increases and as the weight of an arrow increases, the range decreases. Previous investigation by Joff indicated that these were all true to some extent. However, the field testing with the shooting machine was unsuccessful in confirming this in most cases. The only category of arrows tested where there was a statistically significant difference between groups was mass, where the lightest arrow had the highest strike height while the heaviest had the lowest. Thus, indicating the third hypothesis was correct; as the weight of an arrow increases, the range decreases.

For the other categories, profile and drag, there were no significantly significant results between the groups of arrows, directly contradicting the previous results. However, the previous results were gained over the entire flight of the arrow, and more repeat tests were carried out. Due to time limitations, in this testing only three shots were carried out for each group within the different categories, which is far lower than the ideal number of tests for statistical analysis. Additionally, testing was limited to over a 40-yard range meaning that instead of measuring the maximum distance of the flight of each arrow, as had been done for Joff's measurements with human archers, we measured the strike height on a target. Similar to maximum flight distance, the difference in strike height shows the extent to which differences in the arrow affect its speed over the flight; an arrow which is losing speed quicker will strike at a lower height than one which is more aerodynamic. However, the more distance between the longbow and the target, the more these differences would be pronounced. Therefore, testing over the maximum possible flight is ideal and if not possible, testing over multiple distances between the longbow machine and the target. Due to time and space constraints, it was not possible to carry out either of these scenarios. To further the investigation into this topic and confirm the results gathered by Joff with the use of a shooting machine to remove human error, it would be necessary to increase the number of repeated shots of these arrow types and to test them over their full range.

These results, in comparison to those collected by Joff, do indicate that the impact of the changes in the arrow mass, profile and draw is more pronounced over a longer distance. To determine the degree to which this occurs, testing not only over maximum range, but also regular intervals would be needed. However, even without this testing, it is an important consideration to make when evaluating the use of the bow-and-arrow system in medieval combat; how often would a medieval archer be relying on maximum range to reach their target? In fact, there is furthermore a question of whether a medieval archer had a ‘target’ per se if they were shooting as part of ‘a cloud of arrows’ towards the enemy. As part of this, would the differences in arrow performance be noticeable? If over shorter distances, variation in the arrows do not have a significant difference in performance, than the variation observed in the *Mary Rose* collection is potentially of little importance. It is probable that an important factor in supplying the king’s ships with arrows was the sheer quantity meaning any suitable wood, which could be formed into any arrow shape was acceptable. Perhaps individual fletchers had preferred ‘styles’ when it came to shape and fletching size and that is what they contributed to the arsenal.

Chapter 5

Beneath the Surface: X-ray Computed Tomography of *Mary Rose* Longbows and Their Replicas.

As discussed in chapter 2, x-ray computed tomography (CT) has been shown to be successful in studies of wood from both modern and historical contexts, including waterlogged archaeological material. With the right resolution for the wood species, micro-CT has been shown to be able to distinguish between rings as small as 0.12 mm wide for the purposes of measuring inter-ring density. While other studies have shown it is also possible to quantify the amount of heartwood and sapwood present, as well as measure knots and other defects in the wood.

However, no studies were found which focused on European (*Taxus baccata*) or Pacific Yew (*Taxus brevifolia*), which are the species of wood the longbows studied in this project are made from. Therefore, it was not clear before beginning this work what the machine set up required was, or what the results would be. Moreover, as previously discussed, the appearance of the *Mary Rose* longbows as 'like new' is very misleading. The initial work carried out by Hardy (2006) clearly showed that the wood is more degraded internally than it appears externally. Therefore, it was not clear to what extent this would affect the results from the *Mary Rose* longbows specifically.

Despite these uncertainties, CT scanning was successfully carried out, first on the replica longbows to test the settings required and judge the success of the method, then on a selection of *Mary Rose* longbows. The results of these scans were then used to compare the internal structure of the replica longbows to their counterparts from *Mary Rose*, as well as assess the connection between differences in the internal wood structure of the replica longbows to their performance, as described in chapters 3 and 4.

Evaluating the internal structure of the replicas and the original artifacts was important for two reasons. Firstly, as European yew is protected by the European Community (Habitats Directive 92/43/EEC), it was not possible to have the replica longbows made from the exact same subspecies as used for the *Mary Rose* longbows. Instead, they had to be made with American yew. Therefore, it is important to assess the differences between these subspecies and how they might affect the performance of the replicas in comparison to the *Mary Rose* longbows, as it was ultimately the aim of this research to further understand the *Mary Rose* longbows through the replicas. Moreover, wood is not homogenous, even within the same species, so it would be necessary to image and compare the two before relating the results of the replicas to the *Mary Rose* longbows, even if the two were both made from European yew. Additionally, the internal structure of the longbows has been shown to be degraded by their breakage during initial testing as outlined above. However, despite this, the extent to which internal degradation has occurred has not been investigated. Visualising this is therefore important not only for understanding the longbows and their usage but also for seeing the current preservation and developing the conservation needed to maintain their existence for future generations.

The use of CT for fibre identification was also investigated within this project. One fragment of potential bowstring was recovered during the excavations of *Mary Rose* (Figure 5-1), but the material has not been identified. Several materials, such as hemp, linen, and nettle, have been suggested as possibilities based on observation and historical evidence. However, none of these have been confirmed. In dendrology, the identification of wood species via CT has been well established so it follows that it may be possible to apply this to other plant material. The bowstring is an important but often overlooked area of the bow-and-arrow system, with other studies of the longbow using modern bowstring materials without any consideration to whether this may affect the results.

Figure 5-1 Fragment of possible bowstring recovered from Mary Rose. Photo taken from Weapons of Warre (Hildred, 2011, p. 633)

5.1 Materials and Methods

5.1.1 Objects Imaged

A total of eleven complete longbows, one fragment of longbow and three bowstring sections were imaged using CT for this project. This included all five replica longbows and six complete longbows from *Mary Rose.* The fragment of longbow (80A0513) was imaged between the scanning of the replica longbows and the *Mary Rose* longbows to further investigate the settings required and initially evaluate the internal condition of the historic wood.

The complete *Mary Rose* longbows scanned included those that the replicas were modelled on (artifact numbers 80A0907, 80A1298, 81A1614 and 81A1602) as well as 81A3960 and

81A3965. This allowed for the internal structure of the replicas to be compared to the *Mary Rose* longbows to which they match in dimensions. In addition, 80A0907 and 80A1298 are longbows that were recovered loose on the Main deck of the ship, while the others were recovered from within sealed chests on the Orlop deck. This allowed us to examine if there are differences between the loose longbows and the chest longbows, both in terms of their internal wood structure and in terms of their preservation. 81A3965 is a very knotted example of a longbow and was found in the same chest as 81A3960. Scanning of this longbow also allowed us to investigate differences between longbows with more and less knots in the wood.

The two bowstring samples with known material, hemp and linen, and a section of the *Mary Rose* bowstring were scanned for experimentation with using this method for fibre identification.

5.1.2 Scanner Settings

All CT scanning was carried out at the µ-VIS X-ray Imaging Centre at the University of Southampton, using the Nikon Hutch 225/450 for the shorter replica longbows (21MRA1, 21MRA2, 21MRA3 and 21MRA5), and the *Mary Rose* longbow fragment; the Diondo 5, for the longer replica (21MRA4) and six *Mary Rose* longbows; and the Zeiss Versa 510 for the bowstring samples.

For all complete longbows, both an overview scan and a region of interest (ROI) scan were carried out (Figure 5-2). The overview scans were set up so that the full width and depth of the longbow were visible in the field of view, and as much of the length as possible was captured, while maintaining a high enough resolution to see all of the rings. The ROI scan was carried out at the centre of the longbow to achieve clearer detail on the internal structure of the wood, while keeping the entire width and depth of the longbow visible. Due to the use of two different machines, the maximum voxel size achieved while meeting these criteria, the total length scanned, the scan duration, and the voltage and current was different for both groups.

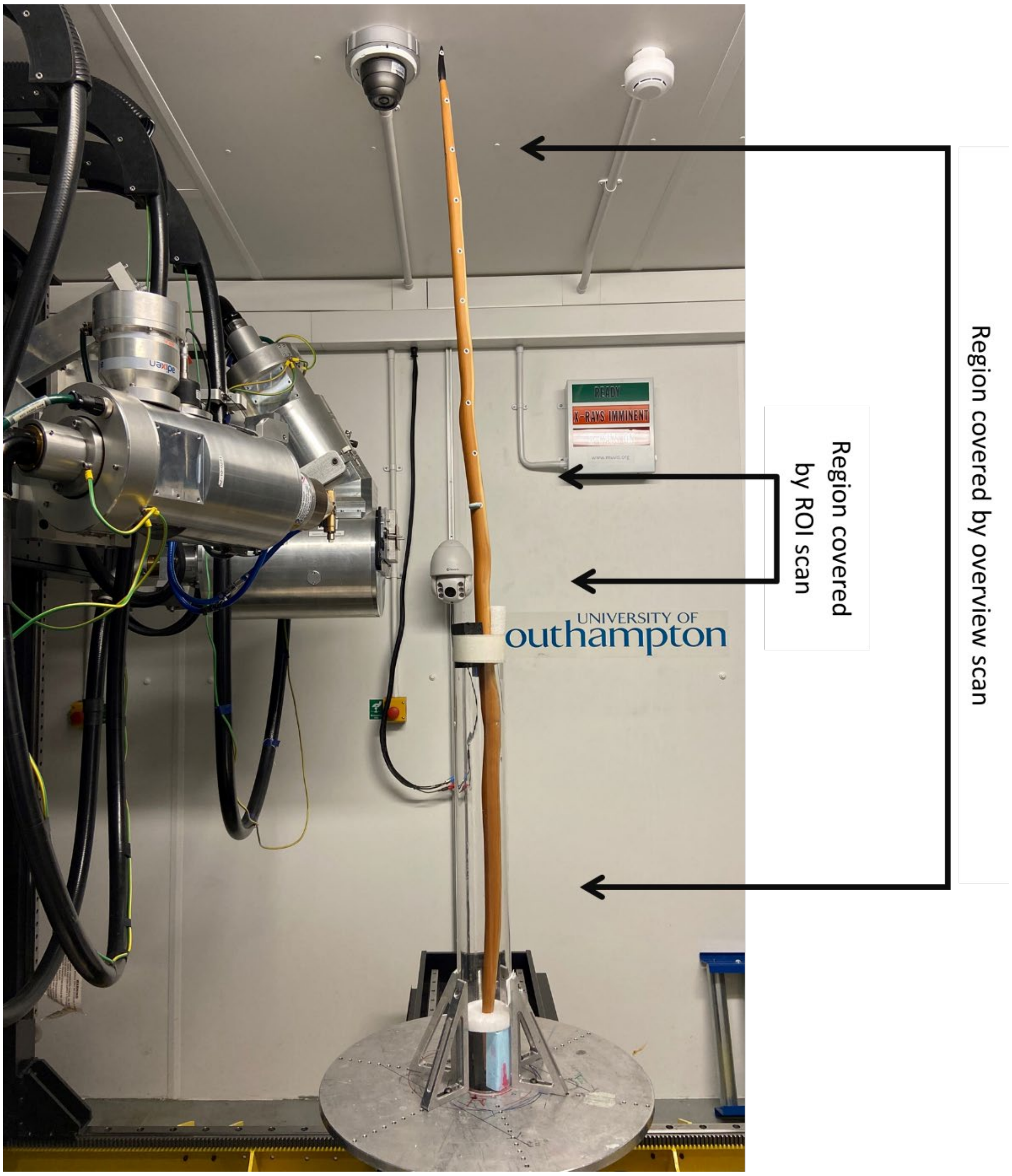


Figure 5-2 Photograph of 21MRA2 inside the Hutch ready for scanning. Labelled are the rough areas of the longbow covered by the two types of scans carried out.

The Diondo 5 was programmed to a voltage of 150 kV and current of 330 μA for both the overview and region of interest scans, with a higher exposure time and narrowed field of view for the region of interest (800 ms) giving a higher resolution of 15 μm voxel size in comparison to the 75 μm voxel size achieved in the 220 ms exposure time and full view used for the overview scan. The Diondo 5 allows for helical acquisition generating a single output covering 1.2 m of the longbow in 16306 projections over a scan time of approximately 4 hours. Although the longbows are longer than this, the travel of the machine limited how much of length could be covered. The region of interest had a total scan time of approximately 2 hours for 2431 projections covering 36 mm of the longbow.

The Nikon Hutch 225/450 was programmed to a voltage of 100 kV and current of 271 μA for the overview scans and a voltage of 110 kV and a current of 340 μA for the region of interest scans, resulting in a resolution of 75 μm and 28 μm respectively. As with the Diondo 5 scans, 1.2 m of longbow was covered. However, in this machine the scan was carried out in 10 overlapping sections per longbow, each with 1601 projections. Each section had an exposure time of 134 ms and giving a total scan time for each longbow of approximately 2 hours and 20 minutes. For the region of interest scans, the exposure time was 354 ms over 3143 projections covering 88 mm of longbow, giving a total scan time for each longbow of approximately 1 hour and 15 minutes. For the longbow fragment the voltage was set to 110 kV and the current to 200 μA resulting in a resolution of 22 μm. The fragment had a total scan time of 29 minutes, covering 14 mm of length in 631 projections.

The Zeiss Versa 510 bowstring scans were acquired using the 4x objective lens, set to include the full width and depth of each sample in the scan. The voltage and current for these scans were 80 kV and 88 μA, resulting in a 4.2 μm voxel size. Each scan had 3143 projections and an exposure time of 1 second giving a total scan time of 52 minutes per sample. A summary of all settings can be seen in Table 5-1.

Machine - Scan	Diondo 5 Overview	Diondo 5 ROI	Nikon Hutch 225/450 Overview	Nikon Hutch 225/450 ROI	Nikon Hutch 225/450 - Fragment	Zeiss Versa 510 - Bowstring
Voltage (kV)	150	150	100	110	100	80
Current (μA)	330	330	271	340	200	88
Resolution (μm)	75	15	75	28	22	4.2
Length Covered (mm)	1200	36	1200	88	14	13
Projections	16306	243	16010	3143	631	3143
Scan time (hrs)	4	2	2.3	1.25	0.48	0.87

Table 5-1 Settings for each set of scans performed as part of this study

5.1.3 Post-processing Methods

Following scanning, the overview scans from the Nikon Hutch 225/450 were concatenated into a single dataset for each longbow using Image J (version 2.0). This process removed the overlap between the scan, which also included conical artifacts that were present at each end of the individual scans. These occurred due to limited beam travelling through that section of the specimen because the machine has a cone beam of x-ray photons, meaning that the top and bottom of the sections were under sampled. This allowed for the whole scanned section to be visualised as one, as with the helical scans taken by the Diondo 5.

The overview scans were used to identify features within the wood. Four categories of features were defined; knots, features with no associated distortion, distortion only features and cracks. A description and example of each type is shown in Table 5-2. Isolating these features was done through a process of thresholding sections of the dataset in Image J.

First, each dataset was visually assessed for features to measure, and these separated into individual files. Once each feature had been identified, the contrast was adjusted to exaggerate these areas before using the threshold tool within Image J to isolate the pixels with the highest attenuation values. Exact numbers varied between features due to differences between scans and through the length of some samples. As the rings are also characterised by changes in the density (discussed further below), each scan then had to be manually edited, to fully isolate the feature, so neither full nor automated segmentation of the features was possible. Once isolated, the slice on which the size of the feature was the greatest was judged visually for the measurement of the maximum height, width, and area. After selecting the feature on this slice, it was then possible to check that this was in fact the largest part by scrolling through the stack, as a shadow of the feature on the selected slice remained visible for comparison. A similar process was followed for measuring cracks, but due to their nature only the longest length was recorded, rather than area, height, and width.

The depth of knots was measured in two ways. When looking at the data set, it was possible to see that even after a particular knot was no longer visible on the scan, there was an effect on the wood (distortion of the rings) that spanned a greater depth. Therefore, it was deemed necessary to note both the depth covered by the knot itself, and its effect on the wood either side of it. Depth was measured by counting the slices for which the feature and its distortion was visible and scaling it from pixels to millimetres. For the other types of features only one measurement of depth was recorded.

The region of interest scans were used to count the number of rings and their width for each longbow. This is a measurement of the maximum number of rings in the longbow as towards the tips, where the longbow tapers, the number of rings present is naturally reduced. The latewood of each year of growth is denser, meaning that when CT scanned each ring is bordered by lines of higher x-ray attenuation resulting in higher grey values. This was used to count the rings and measure their width using Image J to plot the grey values across a slice (Figure 5-3). Each peak on this plot was a ring and the distance between the peaks, the ring width. This process was carried out on five slices from the ROI for each longbow and the average taken in order to minimise any errors with the method.

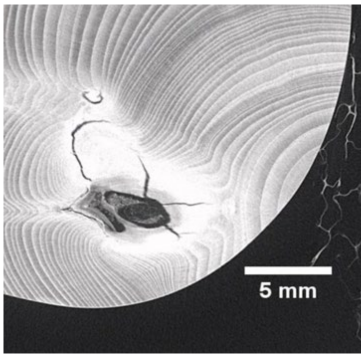
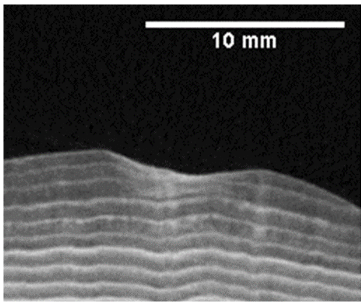
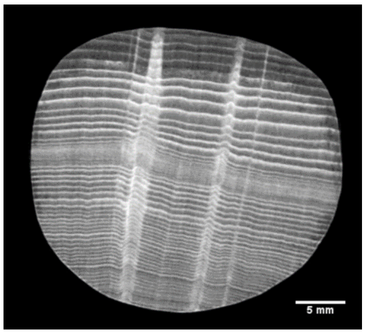
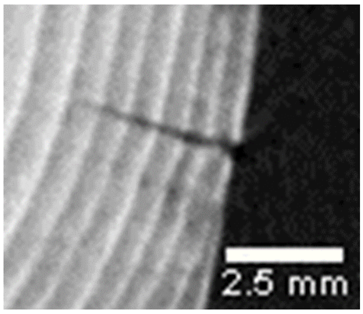
Feature Type	Description	Example Image
Knots	Appeared on the scan as an area of higher density (light grey to white in colour), often with an area of very low density (dark grey to black) contained within. The level of detail visible depended on the size of the knot. In most cased, they caused a distortion in the ring pattern before and after the knot itself was visible, which were also areas of higher density in comparison to the rest of the cross-section.	
No Distortion	Predominantly found on the edge of the cross-section, had no or very little distortion to the surrounding rings. Likely knots on the surface that had been dissected by the crafting of the longbow.	
Distortion Only	Similar pattern of lighter distortion of ring pattern to that which surrounded the knots but no knot present within area. May be linked to knots on the surface or vessels within the wood. Visible on multiple consecutive slices of scan.	
Cracks	Line voids within the cross-section, most frequently originating at the outer edge of the cross-section.	

Table 5-2 Description of features identified in the Mary Rose longbows with example images from 21MRA5, 80A3960, 81A3965, 80A1298 (top to bottom).

Not all of the rings have equally high grey values so not all the peaks were the same height, requiring some personal judgement to separate them for measuring.

Cross-sectional area of each slice where the rings were measured was also collected. This was used to calculate the comparative measurement rings per mm^2 as the variation in size of the longbow could give incorrect results that indicate large longbows have more rings, when actually the density of rings is lower there was just more area that naturally included more rings. Figure 5-4 shows a comparison between a longbow with a high density of rings and a longbow with a lower density.

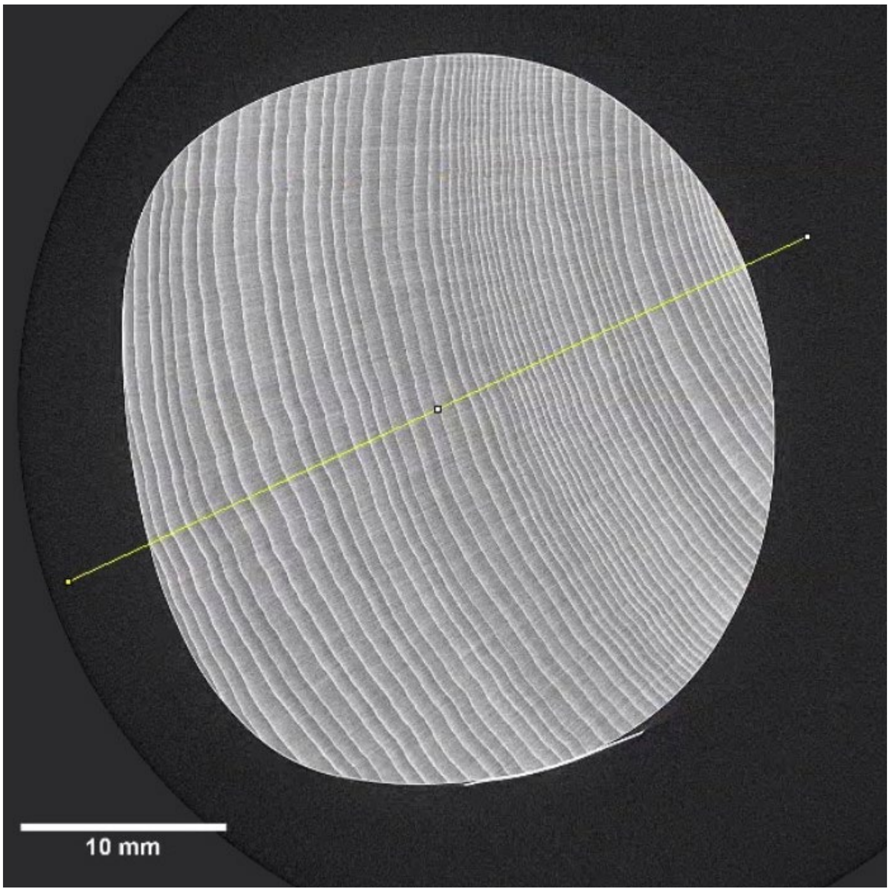


Figure 5-3 Slice from ROI scan of 21MRA2 showing the line used to plot profile for measuring ring count and ring width. This process was carried out for five slices for each longbow – both replicas and from the *Mary Rose* collection. Line angle was adjusted for each longbow to intersect perpendicular to the rings as far as possible.

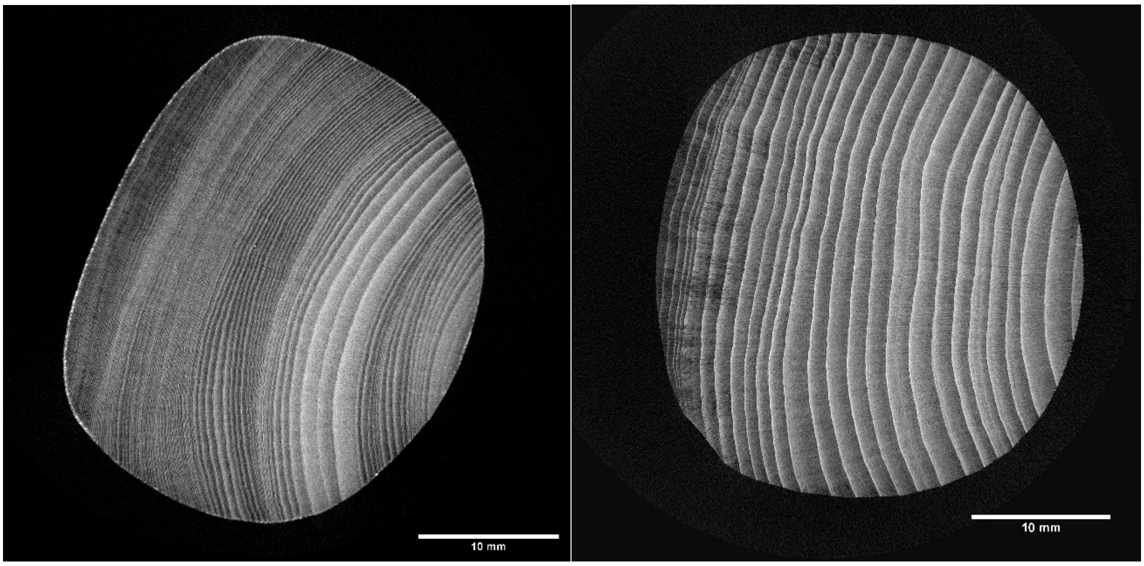


Figure 5-4 Image of centre slice from 80A0907 (left) and 81A1614 (right) showing a comparison between longbows of different ring densities. 80A0907 had the highest rings per mm2 of all longbows studied, while 81A1614 had the lowest.

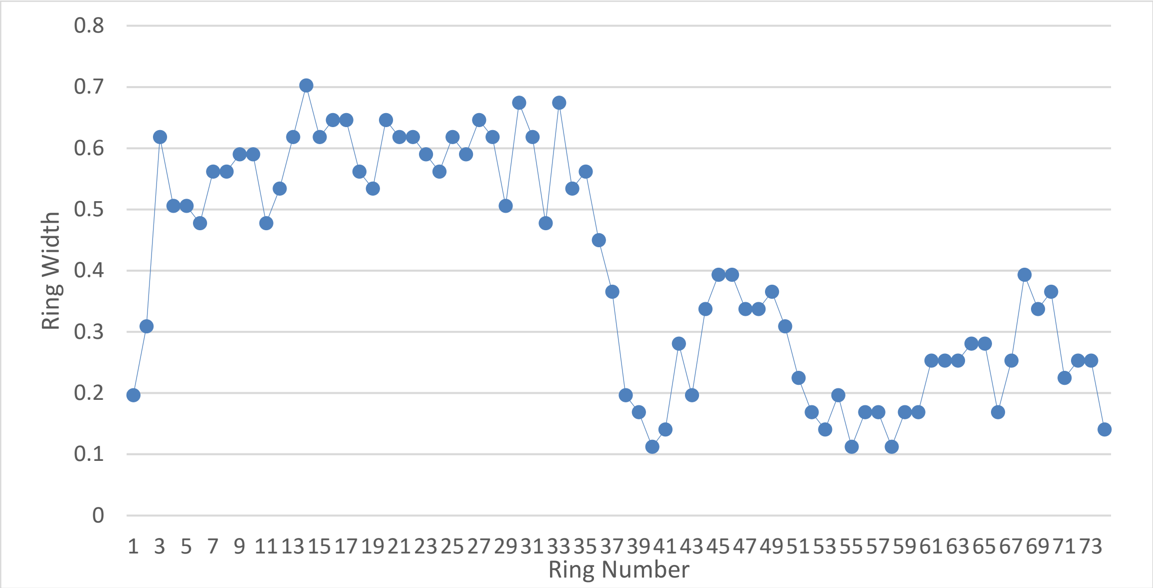
5.2 Results

Overall, the results for both the replica and *Mary Rose* longbows were high quality, showing a majority of the rings and other features clearly. None of the scans showed a difference in density between the heartwood and the sapwood, as has been shown in other wood studies. As discussed in Chapter 2, this has been found in other woods due to the differences in density and moisture content between the two. The heart and sapwood are also known to have different mechanical properties in yew and so contribute in different ways to the function of the longbow. The heartwood being stronger under compression, while the sapwood is more elastic and stronger under tension. Thus, it was expected to be visible in Yew, especially as to the naked eye there is a very clear boundary, as shown in Chapter 1. This boundary is less clear in some of the *Mary Rose* longbows due to their submersion with those that were loose generally more stained than the chest longbows, but they are all presumed to be made in this fashion with both present as this is the known method to optimise the wood for longbows.

Some of the longbows, including both replicas and *Mary Rose* examples, did show a notable change in ring width across their cross-section that may be associated with the heartwood-sapwood boundary. This was most obvious in 21MRA2, 21MRA3 and 80A1298 (Figure 5-5). However, was not a consistent finding across all to the longbows scanned, suggesting this may be a coincidence. 81A1602, for example, had a very consistent ring width across the cross-section (Figure 5-6). As a result, it was not possible to quantify the proportion of the longbows which are heart and sapwood. However, further study would aid in showing whether there is an association between the ring width size and the heartwood-sapwood boundary in Yew.

There was a slight visible difference in the contrast between the lighter edges of the rings and the rest of the wood when comparing the *Mary Rose* longbow results to the replica results (Figure 5-7). The replicas generally had a higher contrast, making the isolation of the rings using plot profile easier. This is possibly a sign of the overall degradation of the *Mary Rose* longbows, or it could potentially be a difference between the two species of wood. Areas of the *Mary Rose* longbows also had regions with a higher concentration of fine rings in comparison to the replicas, which were more difficult to differentiate from each other, particularly with the lower contrast (Figure 5-8).

The *Mary Rose* longbows contained vary dark patches, which appear to be voids within the wood that are not present in the replicas. These were most clearly seen on the fragment of longbow (80A0513) due to the higher resolution (Figure 5-9) but were present to some degree on all *Mary Rose* longbows (Figure 5-10). For two of the longbows (80A0907 and 81A1602) this was less extensive, the voids occurred in isolated patches. However, in all the other longbows they spanned at least one edge of the cross-section, as shown. Even in the longbows with isolated patches, these voids were observed in the outermost rings of the cross-section, indicating that these may be degradation of the wood due to age and underwater submersion. In 81A3965, it was additionally observed that the presence of knots and areas of distortion prevented these voids from occurring, even in areas where before and after the feature, as well as surrounding it, voids were present (Figure 5-11).



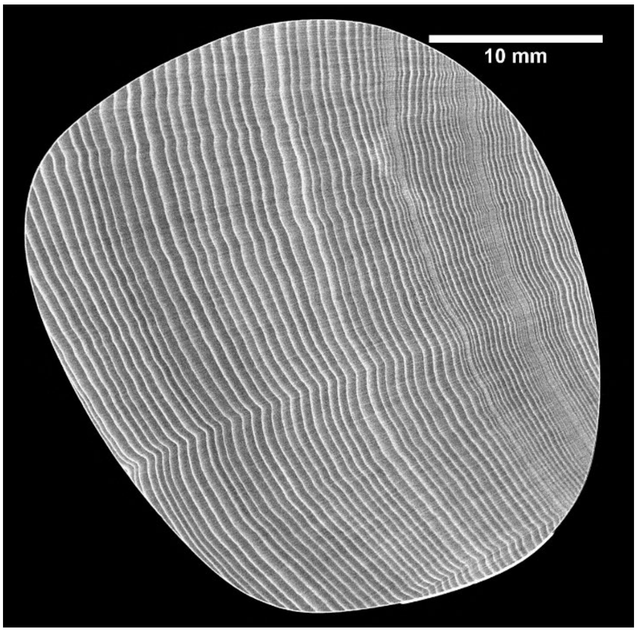
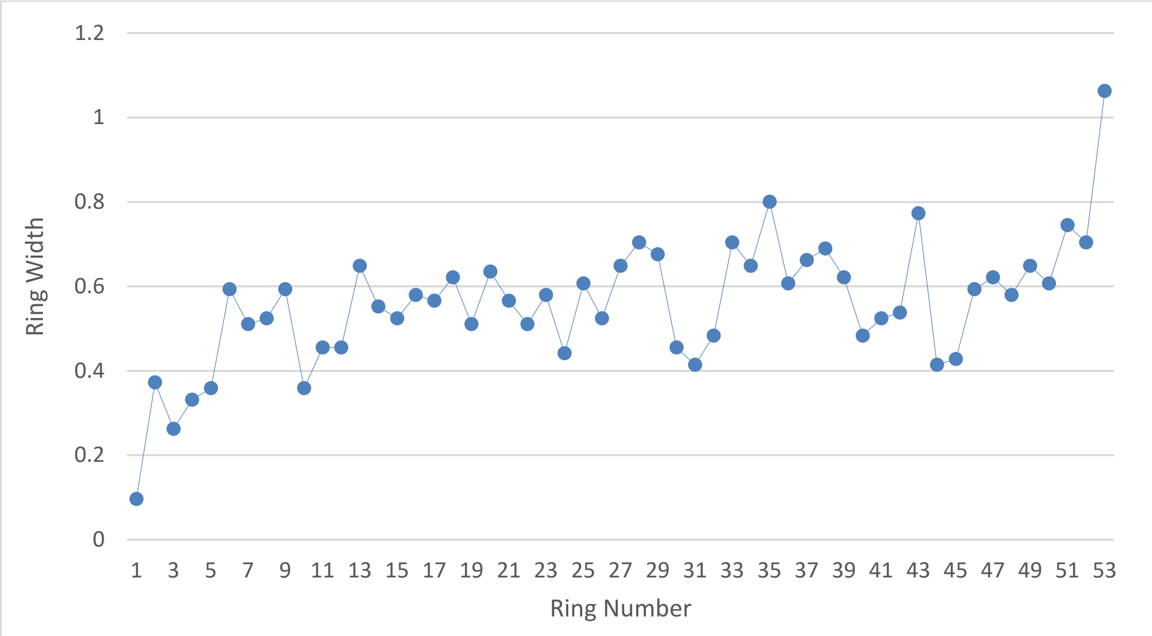


Figure 5-5 (Top) Graph showing the ring widths measured across centre slice of 21MRA3 showing the change in ring width across the ROI scan. This replica had the most obvious divide of all those scanned. Change in mean approximately 20 mm across the scan of 0.32 mm – first 37 rings M = 0.56 SD= 0.1 compared to later 37 rings M = 0.24 SD= 0.09. (Bottom) image of the same slice from scan showing divide.



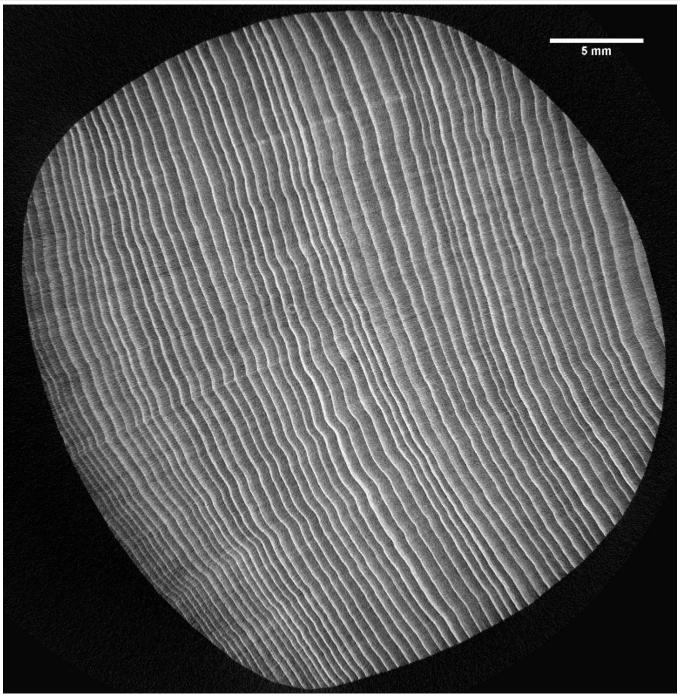


Figure 5-6 (Top) Graph showing the ring widths measured across centre slice of 81A1602 showing the consistency of ring width across the ROI scan. (Bottom) Image of same slice from scan.

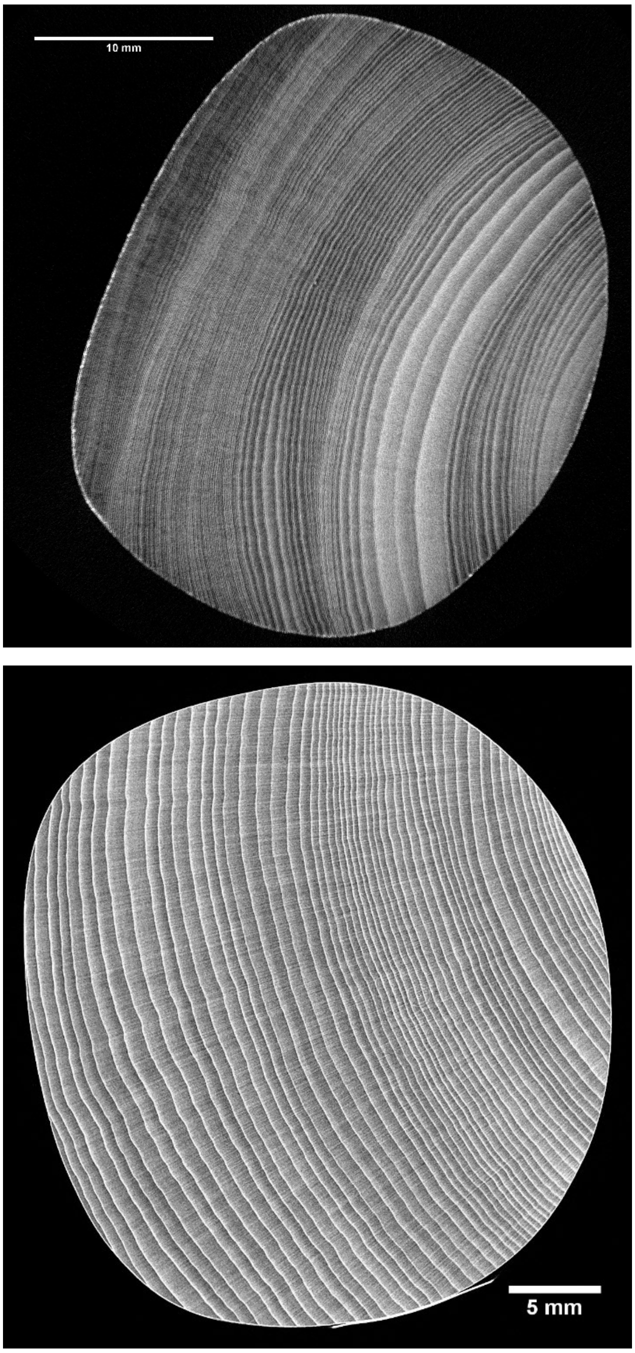


Figure 5-7 Images from CT scans of 21MRA (Top) and 80A0907 (Bottom) showing examples of the overall contrast differences between the replica longbows and the *Mary Rose* longbows.

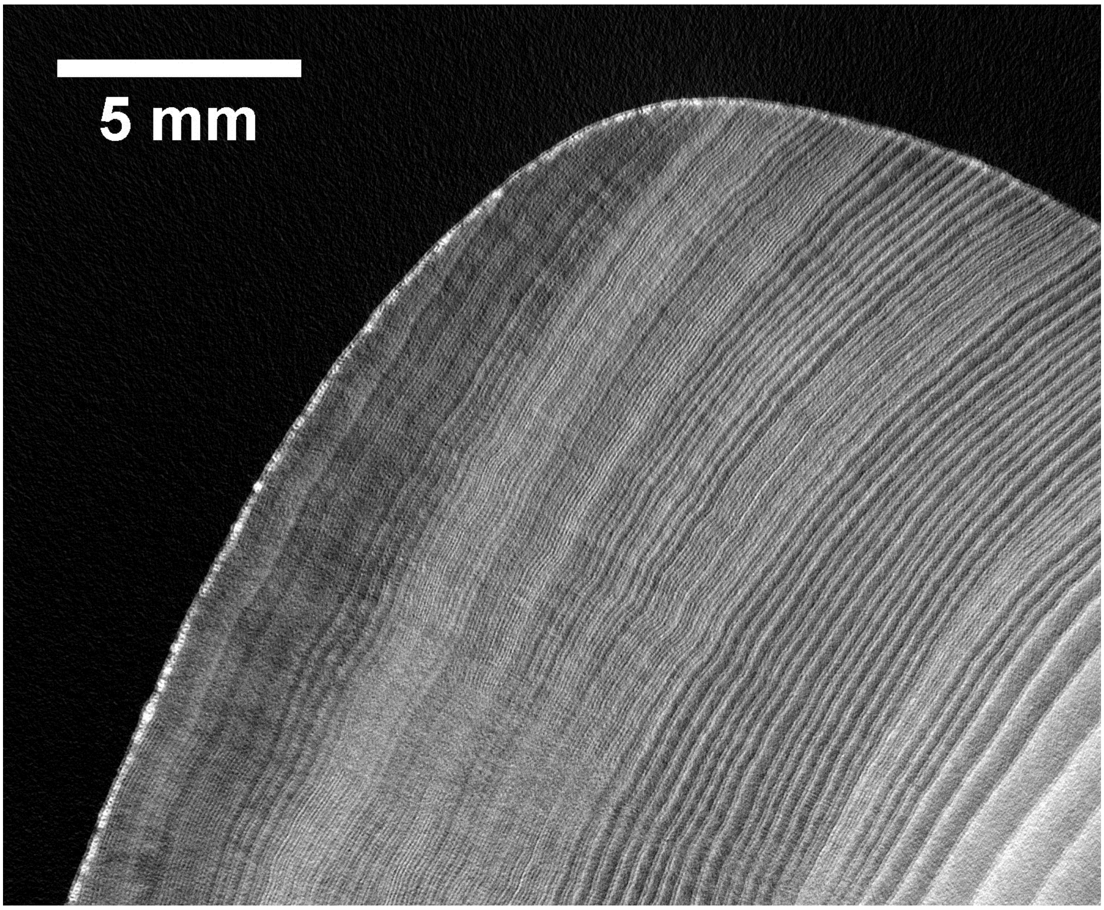


Figure 5-8 Image from CT scan of 80A0907 showing an example of tightly packed rings observed in the Mary Rose longbows.

The perimeter of the *Mary Rose* longbows' cross-section also often contained bright inclusions as well as within cracks that originated from the edge (Figure 5-12). As these were also not present on the replica longbows, it unlikely to be a feature of the wood but rather mineral deposits from the sea or possibly from other surrounding artefacts that were corroding.

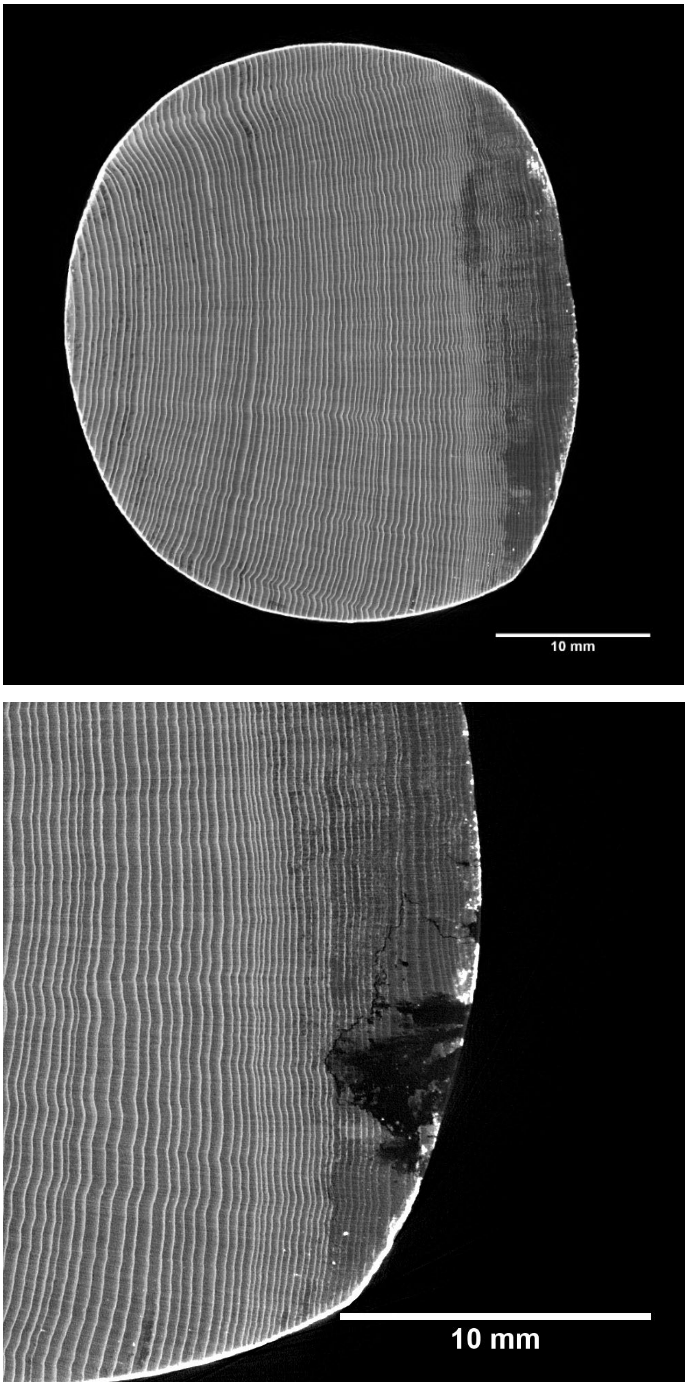


Figure 5-9 Images from CT scan of longbow fragment 80A0513 showing deterioration of the wood on the left-hand side of the cross-section.

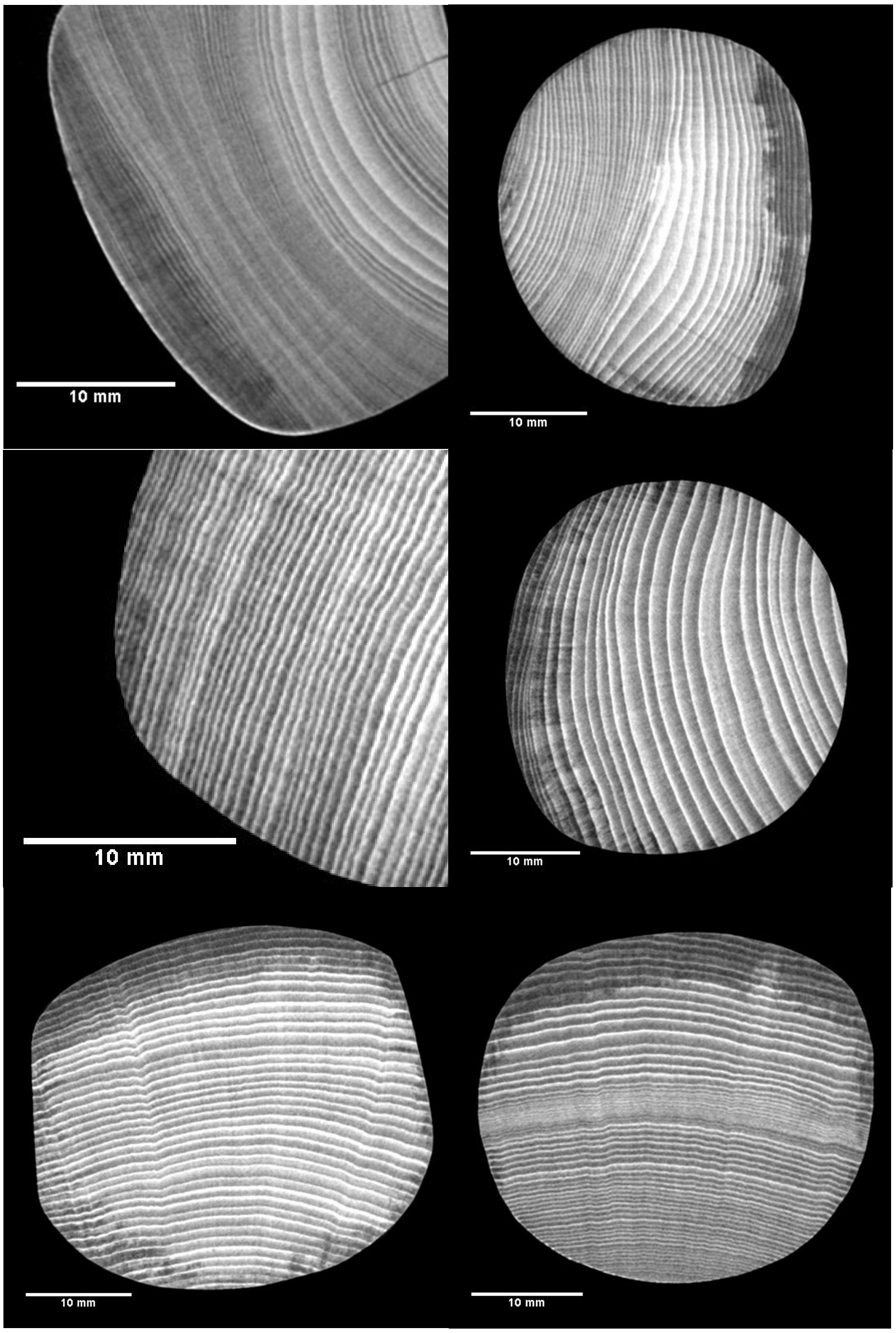


Figure 5-10 Images from the CT scans of Mary Rose longbows (80A0907, 80A1298, 81A1602, 81A1614, 81A3960, 81A3965 – left to right, top to bottom) showing areas of voids within the wood.

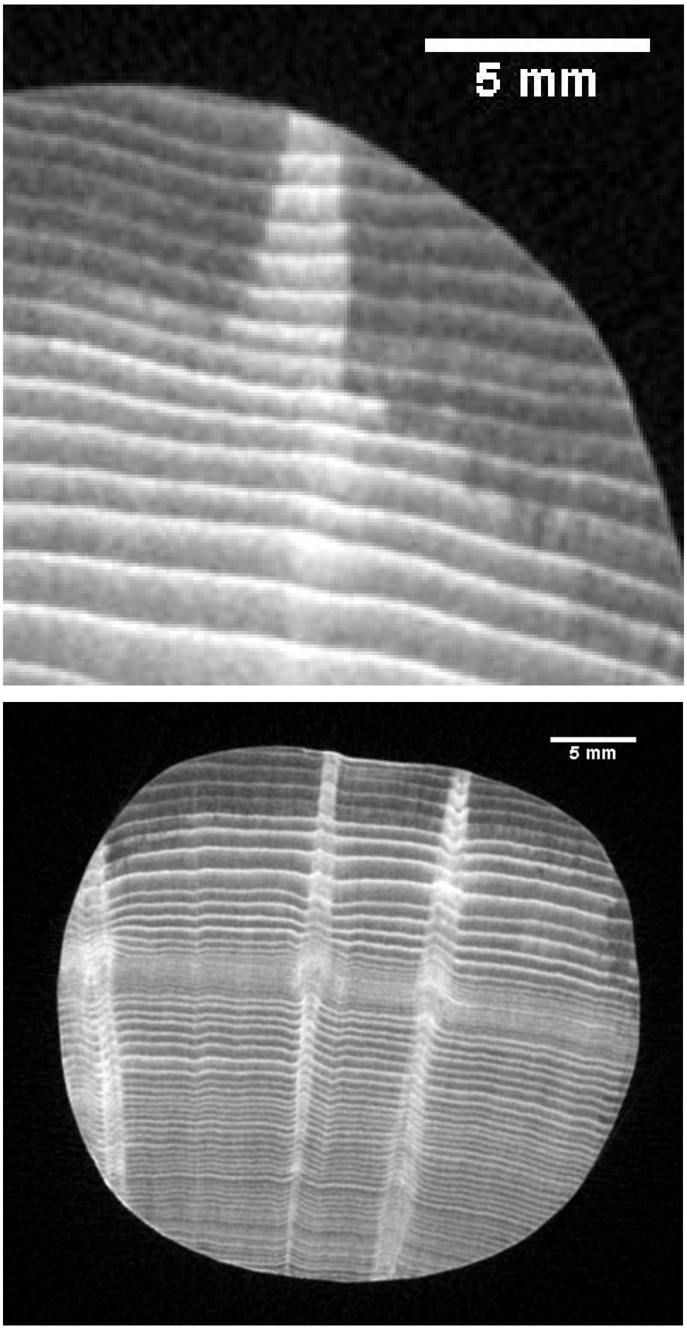


Figure 5-11 Images from CT scan of 81A3965 showing two cross-sections where the area covered by voids is interrupted by the presence of other features in the wood.

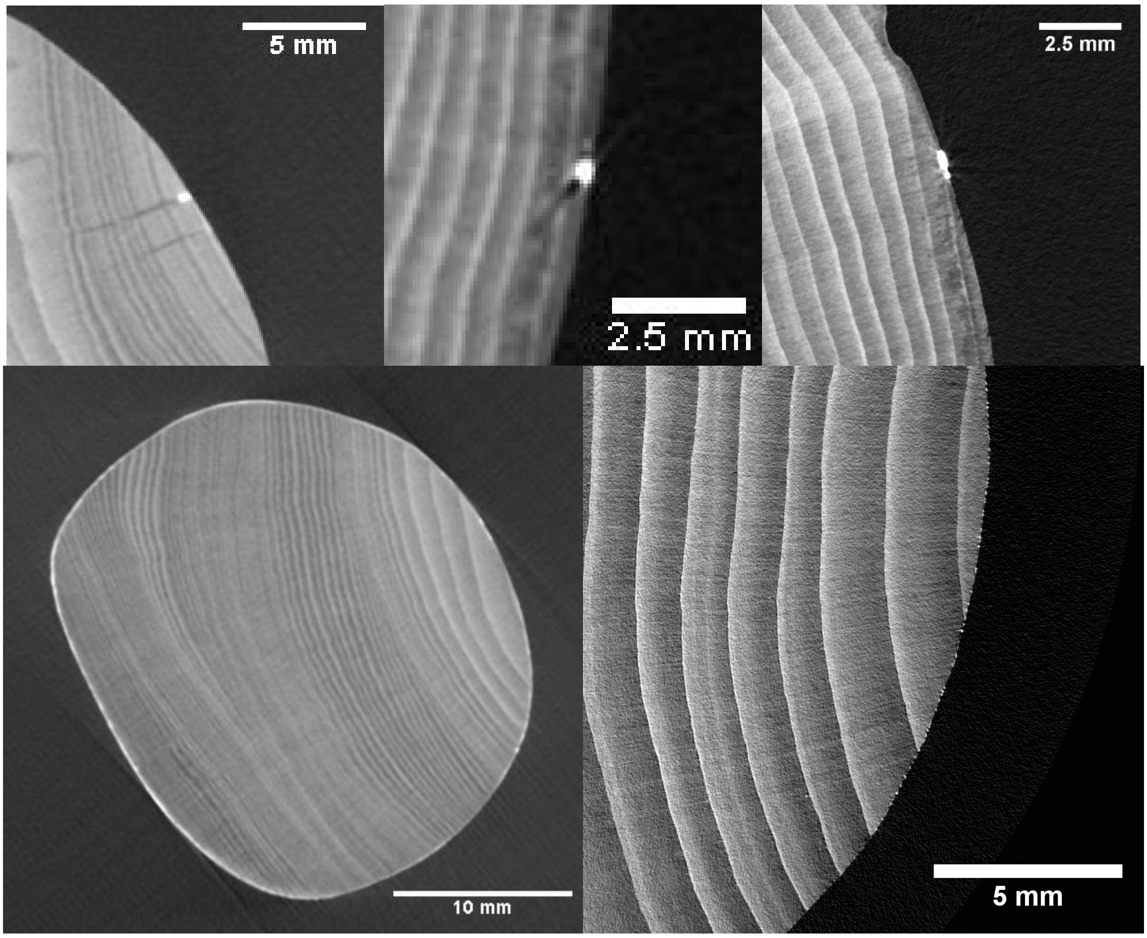


Figure 5-12 (Top) Images showing bright inclusions in cracks observed in 80A0907 and 80A1298, as well as on the surface of 80A1298. (Bottom) Images showing bright perimeter of 80A090, particularly on the left-hand side (left) and a close-up of 81A1614 showing a pattern of small bright inclusions along the perimeter of cross-section (right).

5.2.1 Replica Longbows

Table 5-3 shows the average ring count, ring width and cross-sectional area measured, and calculation of the number of rings per mm^2 from five slices of the ROI scans for each of the replica longbows. 21MRA3 had the highest number of rings per mm^2 (M = 0.089, SD = 0.005) with the second smallest cross-sectional area (M = 865.4 mm^2, SD = 7 mm^2) but the highest ring count (M = 74.2, SD = 3.9) and smallest average ring width (M = 0.399 mm, SD = 0.02 mm). Meanwhile, 21MRA2 had the lowest ring count per mm^2 (M = 0.057, SD =

0.0009). Its area was the second largest (M = 917 mm^2, SD = 8.5 mm^2) but it had the highest ring width (M = 0.608 mm, SD = 0.013 mm), meaning there were only 52.6 rings on average (SD = 1.3) across the cross-section.

Statistical analysis in the form of single factor ANOVA and t-tests, including proceeding f-tests to determine the correct form of t-test to use, were carried out on the ring count per mm^2 and ring width results (for full p-values of these tests see Appendix A.3). ANOVA showed that there was a significant difference in the ring count per mm^2 between the replicas (P value = 6.44 $\times 10^{-13}$) and this was confirmed to be true between all individual pairs of longbows through the t-tests. Some of the pairs were found to have equal variances from the proceeding f-test, so a mixture of t-tests for equal and unequal variances was used. This result is different comparing the ring count without factoring in the differing cross-sectional area between the longbows. In this case, 21MRA1 (M = 53.8, SD = 0.8) and 21MRA2 (M = 52.6, SD = 1.3) as well as 21MRA4 (M = 29.2, SD = 1.3) and 21MRA5 (M = 67.6, SD = 0.9) were found to have no difference between them (p = 0.13 and p = 0.05), showing the importance of factoring in the area for comparison. The single factor ANOVA of ring width also showed that there was a statistically significant difference between the replicas (P value = 6.31 $\times 10^{-26}$). However, comparing pairwise statistical significance was found between all longbow pairs except 21MRA4 and 21MRA5 (p = 0.23). This is unsurprising considering that their average values are 0.499 mm (SD = 0.276 mm) and 0.478 mm (SD = 0.277 mm) respectively.

	21MRA1	**21MRA2**	**21MRA3**	**21MRA4**	**21MRA5**
Ring Count	53.8	52.6	74.2	69.2	67.6
Ring Width	0.553	0.608	0.399	0.499	0.4780
Cross-section Area (mm^2)	849.3	917.0	865.4	1014.9	869
Rings per mm^2	0.063	0.057	0.086	0.068	0.078

Table 5-3 Average ring measurements taken from the ROI scan for each of the five replica bows.

Table 5-4 shows the number of features measured from the replica longbows 21MRA2 to 21MRA5, broken down by the type of feature. 21MRA1 is excluded from the table as not all features were measured. This longbow contained a large amount of very small features (Figure 5-13), both in terms of their area and depth, which were not comparable to those identified in the other replica longbows or the *Mary Rose* longbows. Of the first 23 features that were initially recorded, 21 of them were under 5 mm in distortion depth with an average of 2.3 mm (SD = 0.9 mm), under 2 mm in knot depth (M = 0.8 mm, SD = 0.3 mm) and under 10 mm^2 in area (M = 2.5 mm^2, SD = 2.2 mm^2). These features were not necessary to fully record as this longbow was not used for any other testing due to warping. Across all replicas, a majority of the features identified were knots. 21MRA4 was the only replica with cracks visible. These cracks are visible on the surface of the longbow and occurred during field testing (Figure 5-14).

Table 5-5 shows the average depth, area, width, and height of the knots measured in each of the replica longbows. As discussed in the method, depth is separated into the depth of the feature itself and the depth of surrounding distortion to the rings as it was common for knots in particular to have large areas of distortion before and after associated with them. Across the replicas, the depth of a knot ranged between 0.3 mm and 20 mm. The distortion depth was naturally larger, ranging between 1.5 mm and 45 mm, with a single exception in 21MRA3 where the distortion depth was 112 mm. This knot was surrounded by a V-shaped distortion pattern, not seen in any of the other longbows.

		Knots	Distortion Only	No Distortion	Cracks	Total Features
21MRA2		28	7	0	0	35
21MRA3		14	1	0	0	15
21MRA4		66	1	1	2	70
21MRA5		40	0	1	0	41

Table 5-4 Feature count by type from each of the five replica bows.

Knots observed in 21MRA2, 21MRA4 and 21MRA5 had a similar average distortion depth, with most knots being quite shallow and a few large exceptions. Of these, and overall, 21MRA2 had the greatest maximum area (M = 43.1 mm SD = 4.6 mm) and 21MRA4 had the largest number (66). Meanwhile, 21MRA3 generally had deeper penetrating knots, with most over 4.5 mm, but the smallest number (14). It is important to note that these numbers are from only a portion of the longbows (1.5 m of the length) and so it is highly likely, particularly for those with a higher frequency of features within the scanned area, that there are more in the full length of the longbow.

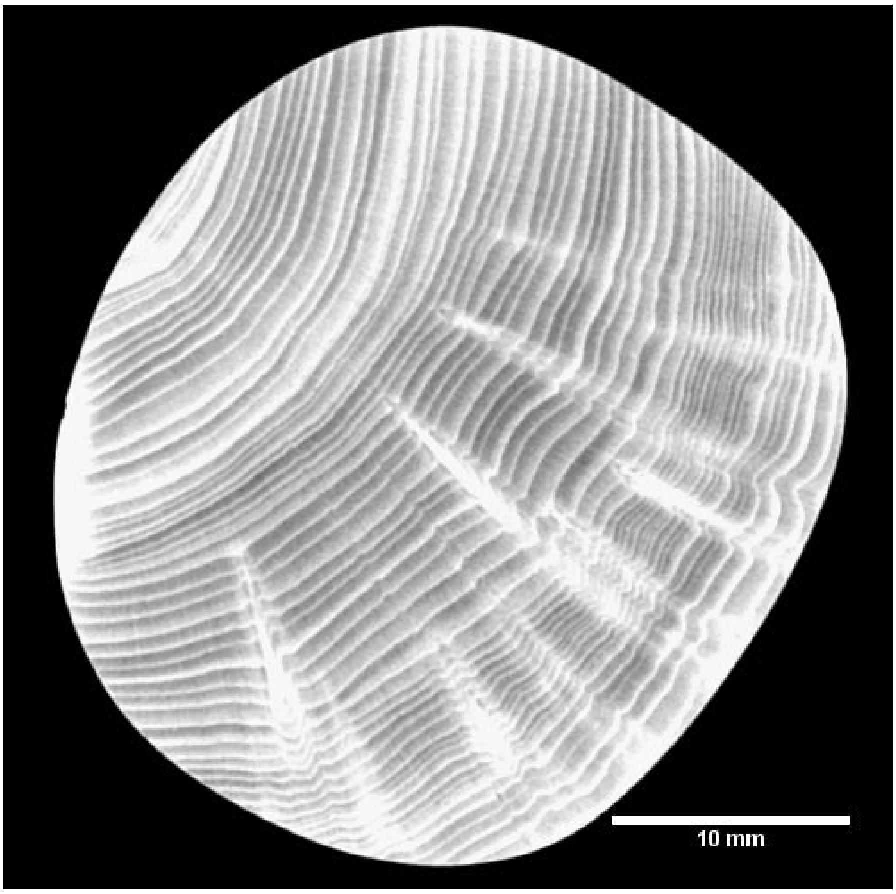


Figure 5-13 Image from CT scan of 21MRA1 showing one of the collections of small features seen throughout the length of this longbow

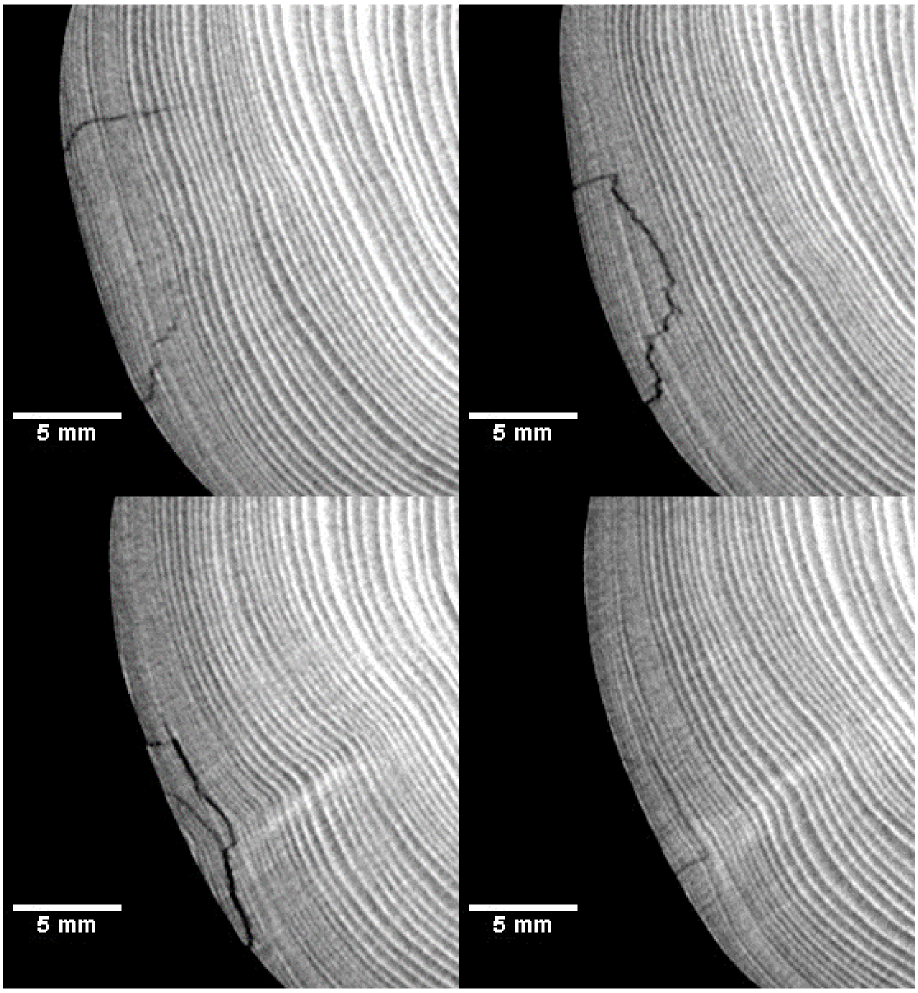


Figure 5-14 Images of crack observed in 21MRA4 (in sequence through the CT scan left to right, top to bottom).

	Distortion Depth (mm)	Knot Depth (mm)	Max Area (mm)	Max Width (mm)	Max Height (mm)
21MRA2	14.5	3.9	43.1	5.8	15.5
21MRA3	24.0	6.1	25	9.2	5.8
21MRA4	8.5	3.6	34.2	9.1	8.3
21MRA5	6.9	3.1	21	6.4	7.2

Table 5-5 Average depth, area, height, and width of knots measured in the five replica longbows. Total knot count for each can be seen in table 5-4.

5.2.2 *Mary Rose* Longbows

The average ring count, ring width and cross-sectional area measured, and calculation of the number of rings per mm^2 from five slices of the *Mary Rose* ROI scans are shown in Table 5-6. 80A0907 had the highest number of rings per mm^2 (M = 0.15, SD = 0.005) with the smallest cross-sectional area (M = 784 mm^2, SD = 16 mm^2) but the highest ring count (M = 117.2, SD = 1.5) and smallest average ring width (M = 0.233 mm, SD = 0.006 mm). Meanwhile, 81A1614 had the lowest ring count per mm^2 (M = 0.031, SD = 0.0006). Its area was third smallest (M = 845.9 mm^2, SD = 1.5 mm^2) but it had the highest ring width (M = 1.1 mm, SD = 0.02 mm), meaning there were only 26.6 rings on average (SD = 0.5) across the cross-section.

	80A0907	80A1298	81A1602	81A1614	81A3960	81A3965
Ring Count	117.2	57.6	52.8	26.6	37.4	71.6
Ring Width	0.233	0.504	0.557	1.144	0.838	0.428
Cross-section Area (mm^2)	784.0	822.2	933.7	845.9	993.8	873.0
Rings per mm^2	0.150	0.070	0.057	0.031	0.038	0.082

Table 5-6 Ring measurements taken from the ROI scans of the *Mary Rose* Longbows included in this study.

Correspondingly to the replica longbows, single factor ANOVA and t-tests, including proceeding f-tests to determine the correct form of t-test to use, were carried out to assess the statistical significance of the differences in the ring count per mm^2 and ring width results between the *Mary Rose* longbows (for full p-values of these tests see Appendix A.3). The results of these tests were similar. The ANOVA showed that the difference in the ring count per mm^2 was significant (P value = 1.85 x 10^{-29}), with the t-tests confirming this to be true for all individual pairs of longbows. Again, a mixture of t-tests for equal and unequal variances was used as there were a mixture of results for the preceding f-test for variance.

For the ring width, the ANOVA also had a positive result (P value = 1.05 x 10^{-304}), indicating statistical significance to the differences between the *Mary Rose* longbows CT scanned. The t-tests were once again in agreement that this was true between each individual pairing.

All of these were carried out assuming unequal variances, except for between 81A3960 and 80A1298, where the f-test showed there was no statistical difference between the variances.

The count of the different features identified in the *Mary Rose* longbows are shown in Table 5-7. Most of the longbows had less than twenty identified features, with the highest number of total features including a significant number of cracks. 80A0907 in particular contained a large number of cracks, which had an average length of 4.643 mm. On the other hand, 81A1614 contained the fewest cracks but they were the largest in length (Table 5-8). In addition to cracks, the scans of 80A1298 contained large dark areas (areas of lower density) which appear to be areas of significant damage or degradation to the longbow (Figure 5-15). These were difficult to characterise in terms of area, maximum height and maximum width as the appearance changed rapidly between slices and they were not a clear shape, unlike that observed with the recorded features.

	Knots	**Distortion Only**	**No Distortion**	**Cracks**	**Total Features**
80A0907	18	2	0	29	49
80A1298	14	2	0	9	25*
81A1602	13	1	0	0	14
81A1614	9	0	0	2	11
81A3960	7	2	2	0	11
81A3965	6	10	2	0	18

Table 5-7 Feature count by type for each of the *Mary Rose* Longbows included in this study.

The dimensions of the knots measured from the *Mary Rose* longbows is shown in Table 5-9. Knot depth ranged from 0.6 mm to 18 mm, with most under 10 mm, while the distortion depth ranged between 2.5 mm and 36 mm, with most under 20 mm. Knots measured in 81A3960 and 81A3965 were generally shallower, with most under 3 mm deep with one exception each (5.6 mm and 17.8 mm deep respectively).

The overall size of the knots in terms of area, width and height was generally consistent between the *Mary Rose* longbows, with each containing a range of sizes within the range of data. Most even contained at least one of the largest knots (over 100 mm²) with the exception of 80A1298 and 81A3960. In comparison to the replica longbows the size of the knots is generally larger, with 60 % of the knots observed in the replica longbows having an area smaller than 20 mm² in comparison to only 27 % of the *Mary Rose* longbows.

Images of crack observed in 21MRA4 (in sequence through the CT scan left to right, top to bottom).

	Cracks	Average Crack Length (mm)	Standard Deviation
80A0907	29	4.64	2.15
80A1298	9	2.54	0.64
81A1614	2	5.69	1.69

Table 5-8 Average Crack length for three Mary Rose longbows in which they were observed.

	Distortion Depth (mm)	Knot Depth (mm)	Max Area (mm)	Max Width (mm)	Max Height (mm)
80A0907	11.1	3.1	31.6	13	6.8
80A1298	14.1	4.1	41.6	16.3	7.7
81A1602	12.3	3.2	48.4	18.4	12
81A1614	14.4	4.3	62.7	23.1	7.3
81A3960	15	2.8	36.7	6.7	19.5
81A3965	13.6	4.4	51	5.9	16.9

Table 5-9 Average depth, area, height, and width of knots measured in the Mary Rose longbows included in this study.

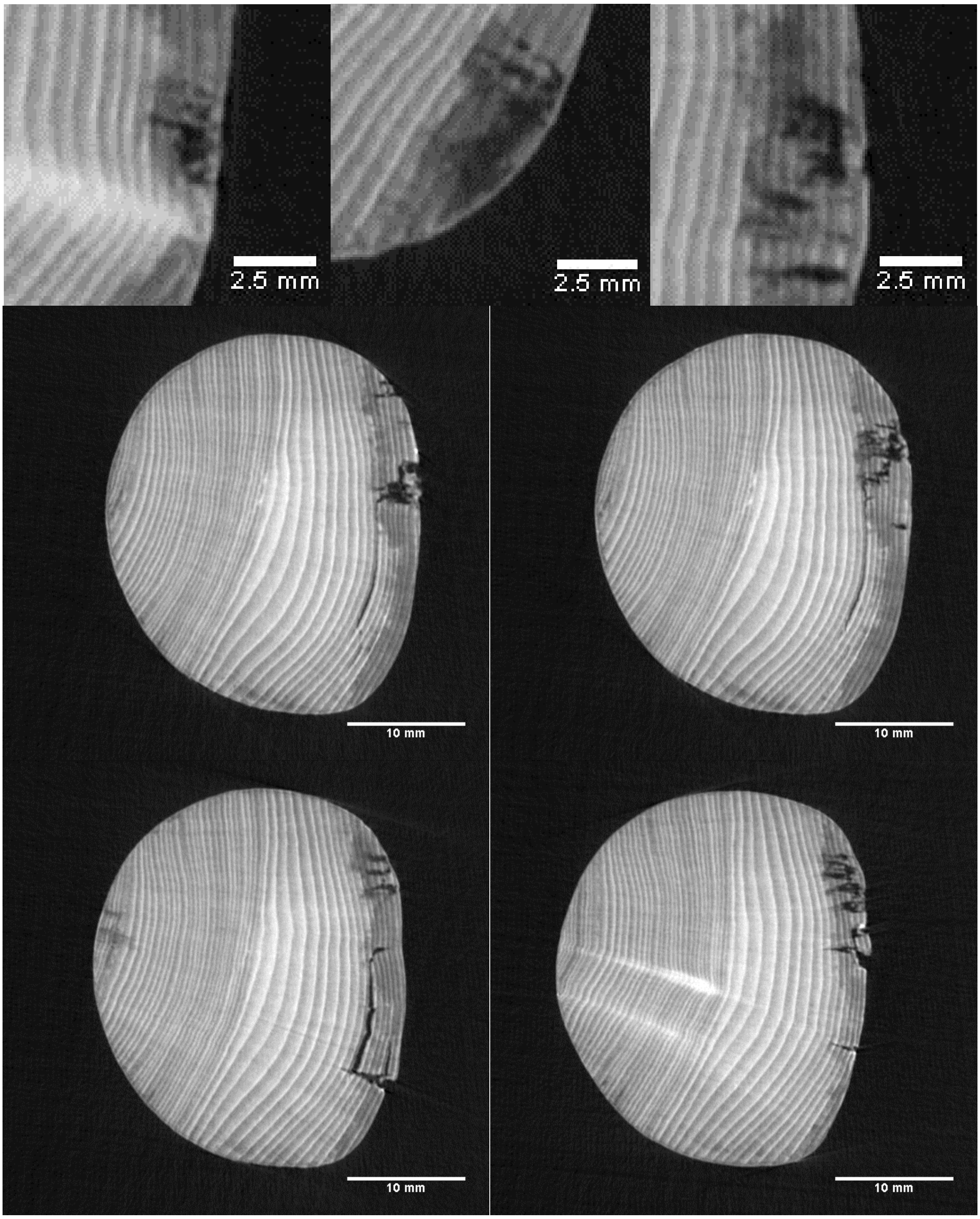


Figure 5-15 Images from CT scan of 80A1298 showing the areas of damage observed on this longbow. These were present over 842 slices of the scan or 63.15 mm of the length.

5.2.3 Bowstring

Both the hemp and linen bowstring scans clearly showed the three strands which made up the overall structure, and their internal structure (Figure 5-16). For both, each strand is then made up of four clear sub-strands but the nature of these is very different between the samples. Hemp is much less densely packed than the linen bowstring, with clear individual fibres present in the scan. Linen is more densely packed, with less visible space within the sub-strands. These results give a good indication that comparison of structure as seen using CT is a viable method for fibre identification.

In comparison, the overall structure of the *Mary Rose* bowstring is less clear (Figure 5-17). The shape of the cross-section, particularly in the lower half, is very irregular indicating that during the deposition of the string it was either compacted or damaged causing loss of material. Differences in the structure as compared to the samples may be explained by this, or by differences in manufacturing process. In terms of material identification, the densely packed material is most comparable to the structure of the linen bowstring out of the two samples. However, more samples of different materials would be ideal to confirm the identification.

Some bright, high-density inclusions were also present in the *Mary Rose* bowstring. This was also noted as present on the *Mary Rose* longbows. These were not consistent throughout the length scanned so do not appear to be a different type of material purposefully included in the string. Similarly, to the longbows, they are likely mineral deposits from the submersion of the material or from materials corroding around it.

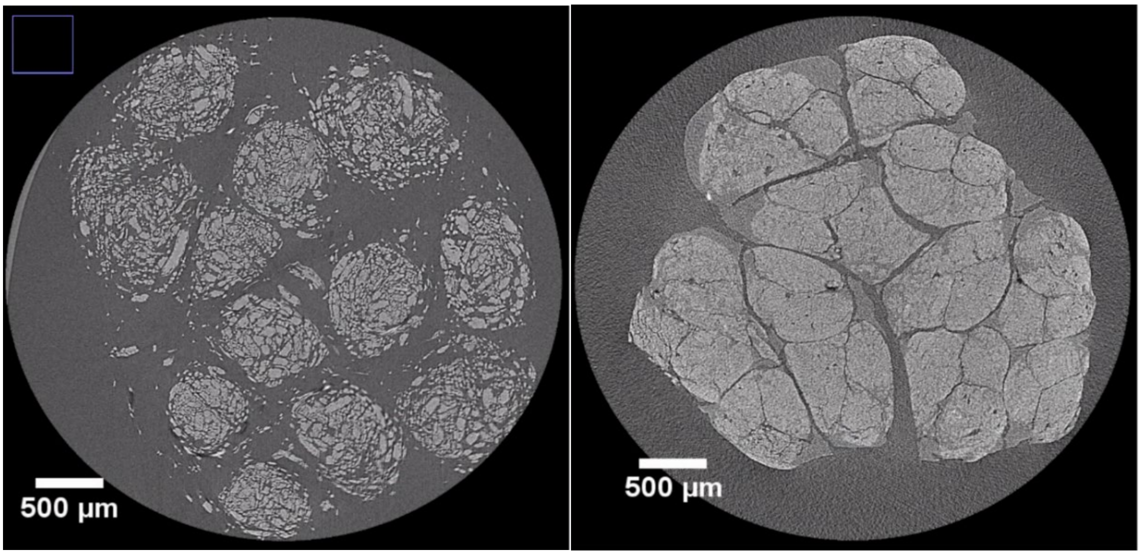


Figure 5-16 Centre slice from the CT scans of hemp bowstring (left) and linen bowstring (right).

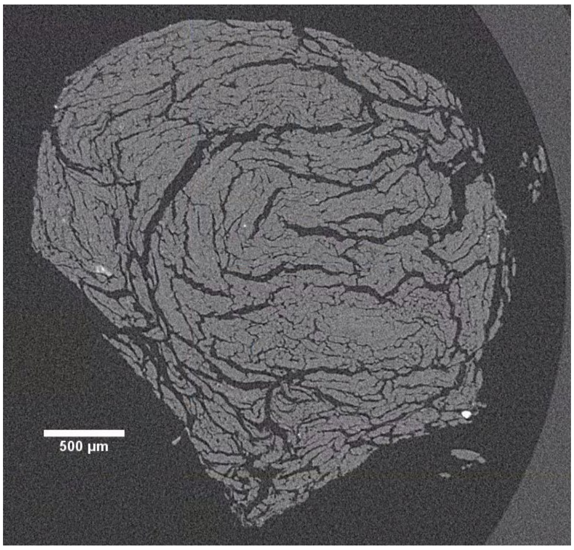


Figure 5-17 Centre slice from the CT scan of the Mary Rose bowstring fragment.

5.3 Discussion

5.3.1 Wood Structure and the Performance of the Replicas

Relating the findings of the CT scans to the performance of the replica longbows, the difference in wood, specifically in terms of the density of rings, between 21MRA2 and 21MRA3 may be a factor in the difference in draw weight. It is perhaps surprising that the longbow with the higher density of rings, 21MRA3, is the one with smaller draw weight (115 lbs). However, the common association of higher number of growth rings produces a denser wood due to the higher proportion of latewood over early wood is actually only applicable to some species (Cramer, 2019), and in many there is no or inconsistent correlation between growth rate and wood density (Davies, 2016).

Confirmation of the effect of the wood should have come from the comparison of 21MRA1 and 21MRA5, which are replicas of the same longbow, 80A1298. With the same dimensions and overall shape, the only factor between these is the wood itself. Due to the eventual warping of both longbows, it was not possible to measure the draw weight for both and gather any field data on either. If there was the same pattern as between 21MRA2 and 21MRA3, we would have expected to see 21MRA1 have a slightly higher draw weight than 21MRA5's 85 lbs. We would likely also have found that this did not cause a difference in initial arrow speed, as there was no difference between 21MRA2 and 21MRA3, but that both were slower as the difference between the draw weight of 21MRA2/3 and 21MRA5 is similar to the difference between 21MRA2/3 and 21MRA4, which – as discussed in the previous chapter – resulted in a higher initial speed recorded from 21MRA4.

5.3.2 Condition of Mary Rose Longbows

Internal degradation of the *Mary Rose* longbows was visualised for the first time in this study. When compared to modern wood, it was clear to see an overall lower contrast of the wood, likely indicating overall degradation of the wood. As well as areas where the wood had begun to degrade completely, leaving small voids within the longbow. These elements were consistent across all *Mary Rose* longbows and can inform the general preservation of the collection. In addition to this, some of the examples scanned had a significant number of cracks, which are of further concern for preservation of the longbows for future generations. The longbows that contained the most cracks, 80A0907 and 80A1298, were longbows that were found loose aboard the ship. Considering that the only replica longbow containing cracks was 21MRA4, which was scanned after being tested, this high frequency may indicate that these longbows had been in use prior to the sinking of the ship. In the case of 80A0907 in particular, possibly for a long time (relative to the average life of the longbow). This may suggest that these were personal longbows, which had been brought aboard the ship by their owners. However, 81A1602 that was speculated by Hardy as being a used longbow did not contain any cracks, and 81A1614 from the same chest had two. Cracks may also be a sign of the degradation of the longbows whilst submerged, with the chest longbows having more protection from the elements than the loose longbows; 80A1298 did sustain a large amount of damage as well as having cracks.

The results from 81A1614 are of particular interest as this longbow was noted by Robert Hardy in his notes as being different from the others, he speculated that this was an English Yew longbow as opposed to the common understanding that all the longbows were made from Yew imported from Europe due to its knobbly nature, open grain, and pale colour. However, the results of this study do not indicate it is significantly different to the other longbows. While the ring count was low, this was not the only longbow with this value, 81A3960 had a similar number of rings per mm^2. It may be the case that both of these longbows were English Yew. However, there were also not a large number of features identified within the longbow. A similar result was found for 81A3965, which was scanned as a particularly knobbly example from the same chest as 81A3960. Discounting cracks this longbow did have one of the highest number of features. These were primarily distortion only features, which may be caused by the visible surface level knots leading to its knobbly appearance, while it only contained 6 full knots; the smallest number from all longbows studied.

There seemed to be no pattern between the wood of the longbow and the cross-section shape chosen, or the markings that were present.

5.3.3 Comparison of Replicas to Mary Rose Longbows

The average cross-sectional area measured as part of the ring count data further shows that the replicas are larger, as is discussed in chapter 3.2.1 on the accuracy of the replicas. The replicas have a range of 849.3 mm^2 to 1014.8 mm^2, while the *Mary Rose* longbows have a range of 784 mm^2 to 993.8 mm^2. While the range is smaller for the replicas (165.5 compared with 209.8) they overlap and exceed the upper end of the range for the *Mary Rose* longbows. However, this only equates to a 2% difference, continuing to give an acceptable level of accuracy between the original artifacts and their replicas. As there are some larger still longbows in the *Mary Rose* collection than the largest studied here, 81A1614, it is likely that these are still representative of the collection.

The *Mary Rose* longbows had a larger range of values for the rings per mm^2 (0.031 - 0.15) when compared to the replicas (0.057 - 0.078). As the values for the replicas sit within the range of values for the *Mary Rose* longbows, they can be considered representative of the collection in this regard. However, in terms of features identified the replica longbows are much more different to those identified in the *Mary Rose* longbows. The *Mary Rose* longbows contained fewer features, particularly in terms of knots, which were generally smaller those in the replicas. They were also generally more consistent in size, with smaller ranges in knot depth (0.06 – 17.8 mm) and maximum area (4.9 – 175.3 mm^2) compared to the replicas (0.2 – 111.6 mm depth, 0.1 – 285.8 mm^2 maximum area). As knots are the product of the growth of branches, these differences represent the different growing conditions between Europe in the 1500's and modern America. It is well known that yew from continental Europe was preferred for the making of longbows over that sourced from England due to the growing conditions producing more knotty wood; this is the same case here. The number of knots present is generally related to the growth speed of the tree, with faster grown wood featuring less knots than slower grown wood. This association is even shown by some of the longbows studied in this thesis; 80A0907 for example had the highest ring count per mm^2 and the highest number of knots from *Mary Rose* longbows. Knots are strongly associated with the quality of the wood. Studies have found that knots can affect both the tensile and compression strength of wood – both of importance to a longbow – and that the degree to which this occurs can vary dependant on the knot size (Cao, et al., 2019).

Rocha, et al. (2018) showed that larger knots caused a greater difference between the modulus of elasticity and the compressive strength than smaller knot, which were almost equal to normal wood. These studies are on specific wood types and for the purposes of construction materials, so it is unclear how directly this relates to the yew longbow. However, historical precedent suggests medieval bowyers found the same results when working with knotted yew.

Other than what can be ascribed to growing conditions there appeared to be no noticeable differences in the wood that was related to the different subspecies of yew used for the replicas and *Mary Rose* longbows. Therefore, when relating the results of the replicas to the longbows recovered from *Mary Rose,* it is only the likely weakening caused by increased knots that need to be considered. However, to what degree this has had an effect is unclear. 21MRA3 is a replica with less knots, more similar to the number of knots in the *Mary Rose* longbows. However, it has a smaller draw weight than its counterpart in length 21MRA2. If knots had a significant impact on the strength of the longbow, we would expect this to be the other way round. That said, the effect of knots is not clear between this pair as there are other factors at work, namely the number of rings per mm^2 and the cross-sectional shape, discussed above. More work is needed to fully assess and quantify the effect of knots on the performance of the longbow, but for this thesis it will be assumed that knots have a negative effect on this – from where else would the medieval belief that English yew did not make the best longbows come? Why else would one go to so much effort to import the ‘best’ staves from Europe?

Chapter 6

From Lab to Lethal: Experimental Insights on Longbow Performance

Presented throughout this thesis is a series of measurements and experiments that sought to answer questions about the longbows recovered from *Mary Rose* and, more generally, deepen the understanding of this iconic weapon. Specifically, this research was aimed at addressing the question “were the longbows a standardised weapon anyone could use or were there specialist arches aboard the ship?”, which both addresses the main complexity surrounding the longbows – is there meaning behind the variation in the collection? – and to begins to examine how this weapon was used tactically at sea.

Initial investigation into this question using statistical analysis of the longbows’ physical dimensions as presented in Weapons of Warre (Hildred, 2011) showed that data on the performance of the longbows was needed to provide an answer. However, previous mathematical models of the longbows did not provide sufficient depth of information to allow analysis of potential groups because they were aimed at providing an overview of the collection, rather than individual longbow data. Furthermore, they used wood measurements that can only be obtained destructively, such as the modulus of elasticity, which needs a small sample of wood to be extracted from the artefact. This thesis sought to examine whether this could be replaced by entirely non-destructive methods by instead using an understanding of how the physical properties of the longbow influence its performance.

For this, five replicas of *Mary Rose* longbows were created and tested. The use of replicas to experiment with the performance of longbows is well known, both for hobbyist archers and for academic research. Typically, these experiments use general 'historical' replicas, with the main property considered being the draw weight, and have focused on the ultimate outcome of the shot, penetration into a target, particularly in order to test the effectiveness of arrows against armour. This work primarily looks at the other end: the longbow itself and the initial arrow speed it produces so as to analyse the relationship between the measurable dimensions of the longbow and the performance, which has not been investigated elsewhere.

The series of lab- and field-based experiments carried out collected data on the replica's dimensions, draw weight, initial arrow speed and internal wood structure, including number of rings and ring width. Analysis of this data indicated a connection between the length of the longbow and the draw weight. However, it was also clear that there was more complexity within this, particularly highlighting a need to understand the effect of wood variation on performance with all other factors the same. Issues with two of the replicas caused this to not be fully explored during this study. Additionally, the results revealed further complexities that were not considered. Field testing showed a nonlinear relationship between the draw weight of the longbow and the initial arrow speed, which needs further investigation to establish fully.

Matching data on the physical properties of their *Mary Rose* counterparts was also gathered, to enable inference of historic performance from the replica longbows in order to evaluate the tactical use of the longbow aboard the warship, which will be discussed further within this chapter. Though this study was not able to fully model the performance of the *Mary Rose* longbows, the data collected still offers insights into the range of draw weights could be expected from the collection. As well as into additional questions that were not a main aim of the study, such as whether used longbows can be identified. The x-ray computed tomography (CT) used to collect the internal structure data also allowed an initial assessment of the internal condition of the *Mary Rose* longbows, which has never been visualised before.

Furthermore, during these experiments, data was additionally collected on the limb deformation over a longbow's draw, arrow dispersion, the effect of differences between arrows, and the possible natural bowstring materials that may have been used in the Tudor period, in order to create a more well-rounded image of the bow-and-arrow system. Exploration into the possibility to use CT scanning for bowstring material identification showed that this is a promising non-destructive method that could lead to successful identification with an improved reference bank.

6.1 Interpreting Results from Replica Experiments

6.1.1 The Relationship Between Physical Properties and Performance

Table 6-1 shows the data collected from replicas 21MRA2, 21MRA3 and 21MRA4. These three replicas have the most complete data as they were used in all experiments. As discussed in Chapter 3, 21MRA2 and 21MRA3 were designed to be similar in length (longest length measurement discrepancy is discussed in 3.2.1.1), representing the average length of the collection whilst having different cross-section shapes, in order to evaluate the impact of this on performance. The CT scans also showed that the staves of yew used for each were also different as expected due to natural wood variation. During lab testing, a 12 lbs difference in draw weight was measured between the longbows. However, in the field, there was no difference between the initial arrow speed produced. Meanwhile, 21MRA4 represents the larger longbows in the collection – both longer and larger in cross-section than the other replicas. The ring count per mm² was average for the replicas, but there was a significantly higher number of internal features counted. It also measured with the highest draw weight, a further 24 lbs higher than 21MRA2, and produced a higher initial arrow speed by 4 m/s.

From these results, several things can be said about the complex relationships at play between the longbow design, the material used to craft it and its performance. Firstly, that the relationship between draw weight and initial arrow speed is non-linear. Published material on this subject is limited, especially for longbows as a subcategory of bow. As discussed in Chapter 2, mechanical studies of bows generally focus on theoretical physics for the modelling and maximising modern bow efficiency, or the flight of the arrow itself. Meanwhile, historical longbow studies are most interested in the final result, answering the question “does the arrow penetrate armour?”. However, this topic is popular among hobbyist archers, and multiple threads on archery forums discuss people’s personal findings with their equipment as well as sharing sources that are not available online. One user on Archery Talk shared data published in the June 2015 issue of Bowhunting Magazine that found [for modern bows] on average every pound the draw weight is decreased, the speed of the arrow is reduced by 2 f/s (0.6 m/s) (Hunter, 2015). Other users appear to have similar knowledge of this relationship on other threads (for example bowtech2006 (2015), thread under anaconda (2003)). This indicated that for modern bows at least, there is a linear relationship between the draw weight and the arrow speed.

Replica Number	Cross-section	Longest Length (mm)	Mean Draw Weight (lbs)	Mean Initial Arrow Speed (m/s)	Total Features Counted	Rings per mm²
21MRA2	Deep D	1993	127.4	52.2	35	0.057
21MRA3	Flat D	2030	115.1	52	15	0.086
21MRA4	Deep D	2087	151.1	56.5	70	0.068

Table 6-1 Key information and measurements from the three of the replica longbows used in this project; 21MRA2, 21MRA3 and 21MRA4. Due to issues with 21MRA1 and 21MRA5 these three longbows were the only ones to be used in all tests.

However, there is also discussion of a similar relationship between the arrow weight and the arrow speed. As discussed in Chapter 4, there is an important relationship between draw weight and the spine of the arrow, which allows the arrow to bend around the bow when released and fly straight – known as the archer’s paradox. In general, forum users agree that this perfect relationship is 10 grains to the pound and when decreasing draw weight, if grains are also decreased to match the speed of the arrow should be unaffected. If the arrow weight is not decreased to match, the speed loss is 1 f/s (0.3 m/s) for every 3 grains (henro, 2015). This may indicate that in the case of 21MRA4, which had a higher initial speed, that the arrows provided were not as well matched as for the other two replica longbows. Table 6-2 shows the average grain of the arrows used for each of the replica longbows, though these do not quite match 10 grains to the pound, they are roughly similar to one another so should be equally as well matched to the replicas. Another indication that the arrows are well matched to the bow is their dispersion (Joff Williams, Personal Communication). Analysis of the dispersion of arrows measured during this study showed there was no statistically significant difference between the three replicas (see 4.2.1 for more detail), further indicating that, while they may not be perfectly matched, they are all equally as well matched.

	Grain of Arrows (Mean)	Grain of Arrows (SD)	Grains per Pound	Dispersion (cm) (Mean)	Dispersion (cm) (SD)
21MRA2	920	17	7.2	19	9
21MRA3	1018	4	8.9	30	19
21MRA4	1094	8	7.2	26	11

Table 6-2 Grain of arrows supplied to the three replica longbows used in field testing and their dispersion on the target after shooting

Tomka (2017) conducted experiments into the speed of traditional Native American bows – these are a type of self-bow similar to the longbow but with rectangular limbs, known as a flatbow (see Chapter 1, Figure 1-2) – which showed that as draw weight increased, the speed of arrows increased. This was true for all combinations of draw weight (40 lbs, 45 lbs, 50 lbs) and arrow weight (23 g, 28 g, 33 g). However, the relationship between the two was more linear at arrow weights 23 g and 28 g than when using the 33 g arrow. The results of this larger weight arrow are similar to those found in this study (Figure 6.1).

With that said, comparing between different bow types is not ideal. Lepers and Rots (2020) showed that identical arrows shot from a modern Merlin bow and a flatbow of the same draw weight had a lower average speed when the latter was used by 6 m/s. Though they also included a longbow in their study, this had a higher draw weight than the flatbow and the Merlin bow, so a comparison to the longbow is not possible. Therefore, there is need for future work to explore the relationship between longbow draw weight and arrow speed further. Or to examine performance differences between modern bows and longbows in order to use findings from modern bows to make approximations about longbows.

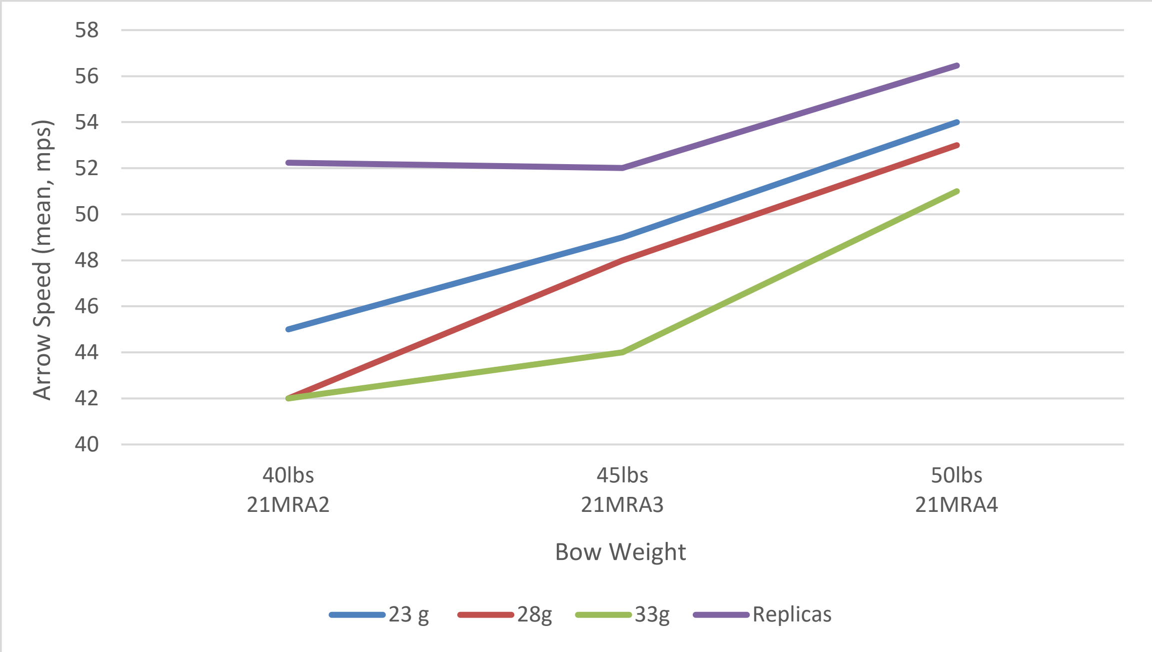


Figure 6-1 Average speed of three different arrow weights shot from three different draw weight flatbows taken from Figure 2, Tomka (2015). Average arrow speeds from the replica longbows also shown for comparison.

Secondly, these results suggest that there is little significance to the different cross-section shapes in terms of performance. In the study of the longbows presented in Weapons of Warre (Hildred, 2011), the *Mary Rose* longbows are classified into four cross-section groups that are variations in the classic longbow D shape: flat D, deep D, round D and slab-sided (shown in 1.3.1, Figure 1-5). This is a classification specific to the *Mary Rose* longbows that has not been applied to other longbows, leading to questions around whether these are true groups or superimposed on the collection by the human tendency to look for patterns. A preliminary study to this thesis was carried out to investigate this question using geometric morphometrics to analysis the robustness of these groups. The results of which showed that the two most distinct groups were the flat D and deep D groups, and thus it was believed that if there were to be a functional difference between longbows of different cross-section shapes, it would likely be the most obvious between these two groups. 21MRA2 and

21MRA3 were designed specifically for the analysis of this factor, representing the flat D and deep D groups respectively.

During the course of this research, no other references to these particular shapes – either through the same name or different descriptions of the same shape – were found. Other works that discuss ideal longbow cross-section, for example Strickland & Hardy (2005), generally refer to the size in terms of the width to depth ratio rather than shape variation. The width to depth ratio of the *Mary Rose* longbows specifically is discussed in Gorman (2016), who showed that the ideal ratio of 1.1:1 was true of the central grip area but had much larger variation down the length of the limbs. This is also reflected in the shapes to some degree; for each group the shape as depicted in Figure 1-5 is more pronounced at the centre and generally becomes more rounded towards the tips of the limbs. However, analysing the relationship between the cross-section shape and the average central width to depth ratio (Table 6-3) indicated there was no difference between the different groups (single factor ANOVA p-value = 0.2).

Width: Depth Ratio	Deep D	Flat D	Round D	Slab-sided
Average	1:1.07	1:1.11	1:1.03	1:1.1
SD	0.06	0.07	0.05	0.04

Table 6-3 Average and Standard Deviation of the Width to Depth Ratio of each of the cross-section groups

While it is true that there was a significant difference between the draw weight of 21MRA2 and 21MRA3, this did not translate to a difference in speed. So, while statistically significant, this result is not practically significant. Most likely it is the case that the width to depth ration may impact the performance of the longbow, and since there is no significant difference to this as a result of the variance in shape, this is irrelevant to the performance. The lack of references to any shape variation in the contemporary archery guide, Toxophillus (Ascham, 1545), further suggests that this is not an intentional typology of longbows, and likely rather a result of personal preference among bowyers or the nature of the wood they were working with. Therefore, for the understanding of the *Mary Rose* collection, the cross-section groupings can provide no insight around longbow performance and possible groups of archers

On the other hand, the draw weight results do indicate a relationship between the size of the longbow and the draw weight. Despite all other variations between the replica longbows, the draw weight follows a distinct pattern; the shortest longbow, 21MRA5, has the smallest draw weight, while the longest, 21MRA4, has the largest (Table 6-4). The average length replicas sit between them - in the case of 21MRA3, almost perfectly (midpoint being 118.53 lbs and 21MRA3 measuring 115.1 lbs). There is a known relationship between the draw weight and the draw length, in modern bows this is approximately 2 pounds for every inch above and below a draw length of 28 inches. Naturally, longer length limbs allow for a longer draw length (Einsmann, 2020). In this project, 21MRA5 had a shorter draw length of 28 inches, while the other three replicas had a longer draw length of 30 inches. Using the numbers from modern bows, this does not fully account for the differences between the replicas and since the draw length is the same between 21MRA2, 21MRA3 and 21MRA4, there are clearly additional factors influencing the draw weight.

One such factor is likely the weight of the longbow. The three longer draw length replicas follow that the higher their weight, the higher their draw weight is (Table 6-4). This pattern is highly logical – the more wood there is, more force will be needed to bend it. Yet, 21MRA5 poses an outlier to this; despite being shorter, it has a greater weight than 21MRA2. Online sources, such as the Legend Archery Blog (2023) and contributors to a post about factors affecting draw weight on the forum Quora (Hunter, 2018), discuss that the length and weight of a bows limbs both contribute to overall draw weight but not in a quantifiable manor. The results outlined here indicate that there is a point at which increasing longbow weight does not increase draw weight if the limbs remain the same length. However, there is not enough data to establish the relationship between these two elements of size and the draw weight. It is possible that studying the length and weight of the *Mary Rose* longbows might be sufficient as a proxy to approximate relative draw weight, but the accuracy of the weight measurements may pose an issue here. As shown by the CT data gathered from the *Mary Rose* longbows, they are internally degraded – some to more extent than others. This will affect the weight measured, which could lead to some misleading results.

Replica	Longest Length	Weight	Draw Weight
21MRA2	1993	881	127.38
21MRA3	2030	860	115.07
21MRA4	2087	1178	151.07
21MRA5	1911	895	85.99

Table 6-4 The size in terms of length and weight, and the draw weight in lbs of four replica longbows used in this project.

6.1.2 Longbow Warping

During the course of this project, there was a problem with warping of the smaller longbows. In total, three longbows warped; one occurred before the longbows were supplied and so was remade, one warped shortly after being received (21MRA1) and one that warped after lab testing, during submersion for planned wet testing (21MRA5). Posts on archery forums, for example Archery Interchange and Reddit, r/Archery, show that warping is not an uncommon problem within the community. However, much discussion surrounds how to correct a warped longbow, rather than the causes.

Since this occurred only with longbows of the same dimensions, one suggestion might be that smaller longbows are more susceptible to this problem or that there is an issue with this particular combination of shape and size. However, if warping due to the size and shape of longbows was occurring this frequently, it is reasonable to assume this would be known amongst contemporary bowyers – especially those who were commissioned to supply for Henry VIII's army. In a conversation with Pip Bickerstaffe, another bowyer, he suggested that the staves for these longbows had originally been large branches instead of the trunk of the tree. The weight of the growth off this main branch will have caused it to bend while the tree was growing. The cutting branch from the tree and removing the subbranches meant that this force was no longer present, and the branch appeared straighter. However, once the stave was slimmed down into the shape of the longbow the reduced mass allowed the wood to return to its original growing shape (Pip Bickerstaffe, Personal Communication, 2022). For 21MRA5, this was likely exacerbated by the submersion of the longbow in water.

As there are limited contemporary sources on the longbow in the context of crafting and usage knowledge, it is difficult to say whether or not this is a problem that was encountered historically. To the authors knowledge, the problem of warped longbows is not mentioned in Toxophillus (Ascham, 1545), which would be expected if this was a prevalent issue. Due to the commonality of the longbow, this is highly likely something that medieval bowyers would be aware of as an issue and therefore able to avoid. Particularly in terms of the *Mary Rose,* Henry VIII's keenness for ensuring that only the best staves were imported to England from Europe may have prevented the import of staves cut from branches as opposed to trunks. It was perhaps only cheaper or personal use longbows, or longbows made by less experienced bowyers that might face this problem. With that said, it is difficult to say for certain whether any of the *Mary Rose* collection are warped without stringing the longbows and due to the fact that some have faced warping due to their position during the deposition of the ship.

6.1.3 Natural Bowstrings

Alongside the main research question, investigating natural bowstring material was a key element of this research. As discussed in 1.3.3, the possible bowstring fragment recovered from the *Mary Rose* site has not been identified for material and there had been no investigation of how the suggested natural bowstring materials perform. Typically, experimental archery will employ modern bowstrings for longevity and reliability. However, it is necessary to understand how natural bowstring behaves. For one, this can affect the efficiency of the shot as potential energy is sorted in the string. For modern bowstring, this is low and can be ignored (Meyer, 2015), but this is related to the string tension and how much it contracts after the draw. For natural bowstring materials this is unknown. Moreover, the tensile strength of the bowstring determines what draw weight of longbow would be possible. Modern best practice is to have a string with a tensile strength at least three times the draw weight of the longbow, for example the largest replica in this study would need a bowstring with a tensile strength of at least 2040 N.

The results of the lab testing of Linen and Hemp bowstring showed that neither were capable of withstanding the force needed to pull all of the replica longbows as shown in

Table 6-5. Attempts to string 21MRA3 with replica linen string cause failure of the string. This could indicate that historical longbows had a much lower draw weight than predicated and the modern replicas discussed in this study. Or that alternative materials, or a greater number of stands were used to create historical strings. A deeper exploration into this problem should start with finding the tensile strength of a single strand to calculate how many would be needed to withstand the required force. As noted in 1.3.3, the diameter of the string is known thanks to the preservation of the arrow nocks. Therefore, it would be possible to know if there are too many strands required to meet the necessary tensile strength, making the string too thick for the arrows.

Replica	Draw Weight (N)	Bowstring Tensile Strength (Min, N)
21MRA2	566.2	1698
21MRA3	512.4	1538
21MRA4	679.7	2040
21MRA5	382.5	1146

Table 6-5 The draw weight of the four replica longbows tested and the minimum tensile strength needed to meet modern standards. This study found an average Hemp bowstring tensile strength of 574.6 N (SD: 61.38) and average Linen tensile strength of 854.98 N, (SD: 198.57).

CT showed promising results for using this method to identify the string material. However, as shown in Figure 5-16 and Figure 5-17, there is not a clear match between the *Mary Rose* bowstring fragment and the two materials tested. Improving the known sample category in the future would allow a better identification of the material. Linen is the closest in appearance and was also the closest to having a tensile strength great enough to draw the replicas – two samples had a tensile strength three times that of the smallest replica. But there are some clear differences in the structure of the string. It may be the case that linen is the right material, but the manufacture of the bowstring historically is different. Theoretically, this may allow the inclusion of more strands for the same diameter, which would be needed to increase the tensile strength.

The investigation into bowstring material in this study was an initial exploration into the top two suggestions for bowstring material and the capabilities of CT for fibre identification in this context. It is now necessary to further this work in order to fully explore this topic.

6.2 Answering Questions About the *Mary Rose* Collection

Investigating unanswered questions about the *Mary Rose* longbow collection, specifically around the use of the weapon tactically aboard the ship was the ultimate aim of this research. As described in Chapter 1.4, there are a large number of unknowns around the variation in the collection, which has led to many theories and questions about whether this can tell us something more about the longbow or its use aboard *Mary Rose.* In this research, these were summarised into one key research question – were the longbows a standardised weapon anyone could use, or were there specialist archers aboard the ship? Indication of specialist archers, or sub-groups of archers with different roles aboard the ship, may come from performance differences between longbows found in different contexts (loose or in a chest) or different locations (castle, upper, orlop or main decks or the hold), or between different types of markings on the longbows or different cross-section shapes.

Data collection throughout this study aimed to allow the approximation of performance of *Mary Rose* longbows from replica longbows, from an increased understanding of the relationship between physical properties and performance. However, the data collected also answered questions in unexpected ways. This section will discuss these questions and how the data gathered in this study can offer insights into this important archaeological collection.

6.2.1 Personal and Previously Used Longbows?

During the excavation of *Mary Rose* the longbows were found in two different contexts: loose or within chests. This suggests that these two groups of longbows may be separate from one another in some way. The action of carrying a longbow around the ship would imply that there was some function of that weapon aboard the ship, or a desire to keep it with you as one of your personal belongings. The Anthony Roll (1545) shows that *Mary*

Rose was equipped with 250 longbows, but it may be the case that archers brought their own aboard the ship. Either out of personal preference, or if they were hired as a particularly skilled company.

In his personal notes about the collection, Robert Hardy (access provided by Alex Hildred, see personal communications) highlights some longbows in the collection as potentially 'used' longbows. This category contradicts the above proposition somewhat as it includes longbows from both contexts. One would expect that an archer bringing his own longbow would have used it before, while new longbows are those which were supplied in chests to the ship. But there is no contemporary documentation that details this – it may be that leftover longbows previous battles were reused in the chests supplied. Additionally, there is no detail in Hardy's notes on the reason for classification as 'used' so it is not possible to evaluate the accuracy of this. However, the CT data collected in this project may offer some insight into these questions.

Of the replica longbows, the only longbow to be CT scanned after the experimental field testing was 21MRA4. This was also the only replica to contain cracks, which were observed to have occurred during testing. Within the data collected from the *Mary Rose* longbows, the two loose longbows (80A0907 and 80A1298) had the highest frequency of features, a large portion of which were cracks. This suggests that these longbows had been used prior to the sinking. Considering that the replica longbows went through considerable lab testing prior to the field testing suggests that a large amount of usage is needed to cause the wood to crack in this way. This would imply that the loose longbows studied, particularly 80A0907, had a lot of use before the sinking. As *Mary Rose* sank right at the beginning of battle, it is unlikely that this would have occurred in a new longbow supplied to the ship because there was not enough time for it to have been used. Therefore, this could suggest that these were longbows brought onto the ship by their owners.

With that said, it should not be ignored that these longbows were, by nature of being loose, more exposed to the elements during the decomposition and burial of the ship. The larger number of cracks on these artefacts may also be a sign of degradation of the artefacts due to this. It was also noted from the CT scans that 80A1298 had significant damage as well as cracks. Additionally, one of the chest longbows studied, 81A1602, was noted by Robert

Hardy as potentially being a used longbow, yet it did not contain any cracks. Meanwhile another longbow from the same chest, 81A1614, did. As the accuracy of the classification cannot be established it is difficult to say establish whether 81A1602 may have been used but to a lesser degree than is needed to cause cracks or if it is incorrectly classified as used. Similarly, whether 81A1614 may have been used and this missed, or if the cracking is simply a sign of damage from submersion. However, there are 16 other longbows in the collection noted as 'used bow' by Hardy and 45 other loose complete longbows so further study of these could offer more evidence on whether cracking is a sign of use, just degradation from submersion, or a mixture of the two.

6.2.2 Use of English Yew?

Another suggestion from Robert Hardy's notes is that 81A1614 was potentially made of English Yew, rather than Yew imported from Europe. It is well documented that Henry VIII ensured the best staves were brought into England for making longbows as the warmer climate in central Europe allowed Yew to grow taller and straighter making it less knotty and better for crafting longbows. However, 81A1614 was noted as being particularly open in grain, very knobbly and pale in colour, which Hardy believed indicated that it was English Yew.

The CT scan results agreed on the grain, with this longbow having the lowest rings per mm² but did not particularly show a high number of knots. Most of the features recorded were around the perimeter of the scans, which suggests these are what are observable from the surface, but this was still one of the lowest total feature counts. 81A3960 also had a similar value for both the rings per mm² and total number of features yet was not noted as another potential English Yew longbow. It may be the case that both of these longbows were made of locally sourced wood, and this was simply missed in Hardy's assessment, particularly if colour was a primary reason for his conclusion (similarly to the used longbows there is not much detail on this). Indeed, their very similar ring count suggests that they grew in a similar climate that was distinctly different to the other longbows included in this study.

These two longbows were originally classified in the data published in Weapons of Warre (Hildred, 2011) as 'coarse' grain (up to 40 rings per inch) along with 18 other longbows. This was the smallest group with the 'medium' grain category (41 to 60 rings per inch) containing 48 longbows, and the 'fine' grain category (61 + rings per inch) containing 47, meaning only 17% of the collection studied are coarse grain. It could be the case that all longbows in this category were crafted from English Yew. The statistical analysis of this data showed no relationship between the grain and other elements, such as length or marks. There was some significance in the number of longbows of different grain counts found loose in comparison to in chests, as well as between the different decks of the ship, however this mostly related to the proportion of 'fine' and 'medium' grained longbows. Coarse longbows were generally equally distributed across context and location. The idea that this group were longbows made of English Yew therefore would imply that bowyers had a supply of staves that were a mixture of those imported from Europe and, in a smaller proportion, those sourced in England. Further analysis of this grain group could improve this logic by providing a more specific ring count for each longbow as the original categories are quite large: both 80A0907 and 81A1602 are 'medium' grain longbows but have 0.15 and 0.057 rings per mm^2 respectively. This would help identify if the two studied here are odd ones out or part of a pattern, since no other longbows were noted originally as English Yew.

It is also the case that climate is variable within Europe. Though staves are commonly quoted as coming from Italy, this is an incorrect understanding of the evidence. Documents show staves as coming from the port in Venice, but it is not truly known where the wood itself was grown. It is likely that there were multiple woodlands from which staves were sourced, which could have had different microclimates affecting tree growth. A further understanding of this, as well as potential locations for the source of the staves, could be obtained through the use of dendroclimatology.

6.2.3 Estimation of *Mary Rose* Longbow Performance

The draw weights measured from the replica longbows used in this project aligns well with the approximations made in the original analysis of the *Mary Rose* longbows. All of those measured sit within the range suggested by Watson's (2011a) analysis of the longbows, and it does not seem improbable that another longbow could have a draw weight of 185 lbs as suggested by Kooi's model (Kooi & Sparenberg, 1980; Kooi,1991; Kooi,1993; Kooi &

Bergman, 1997). There are larger examples within the collection than the longbow that 21MRA4 was replicating, and there are certainly other factors that influence the draw weight, as shown by the difference between 21MRA2 and 21MRA3.

As discussed above, the replica results indicate that the length is a dominant factor in determining the draw weight. If this is taken to be true of the *Mary Rose* collection, then the spread of draw weights will mirror that of the spread of longbow lengths. As shown in Figure 6-2, the lengths follow a rough normal distribution around 1950 mm to 1960 mm length longbows. Assuming that the draw weights follow the same pattern would indicate that the longbow was a standardised weapon around the draw weight required for this length longbow. The idea of a standardised weapon that could be used by anyone, especially if it follows the distribution of lengths, does leave unanswered questions about the markings on the longbows. In the previous statistical analysis of the collection there was no relationship found between the length and the marks. Theoretically, this would make sense as if the longbows are standardised there would not be a need to convey any information about the longbows themselves through marking. In this case, what could be the intention of the marks? If they are bowyers' makers marks, why do not all of the longbows bear them?

There are, however, more complexities to the draw weight than the length of the longbow. 21MRA2 and 21MRA3 are longbows of this length group, which had different draw weights; 127 lbs and 115 lbs respectively. While this is not a large difference and one that could easily be within the range of the desired standardised longbow, considering that 'standardisation' in this case would not be as accurate as modern day, the wood analysis data show that there may be more significant differences between the *Mary Rose* longbows of the same length.

The *Mary Rose* collection contain a much larger variety of ring counts and widths than was represented within the replica collection. Over the five replica longbows, the ring count per mm² only had a range of 0.029, while in the six *Mary Rose* longbows studied this was 0.119. If the differences in the wood did cause the 12 lb difference in draw weight between 21MR2 and 21MRA3 on this small scale, it is likely to have a much more significant impact on the *Mary Rose* longbows. Extrapolating the results of 21MRA2 and 21MRA3 to their *Mary Rose* counterparts, 80A0907 and 81A1614, for example, would suggest a 50 lb difference in draw weight between the two, despite them having a similar length. Therefore, there is a clear need to understand the effect of differences in the wood on longbow draw weight, which was not achievable during this project due to the warping of two of the replica longbows.

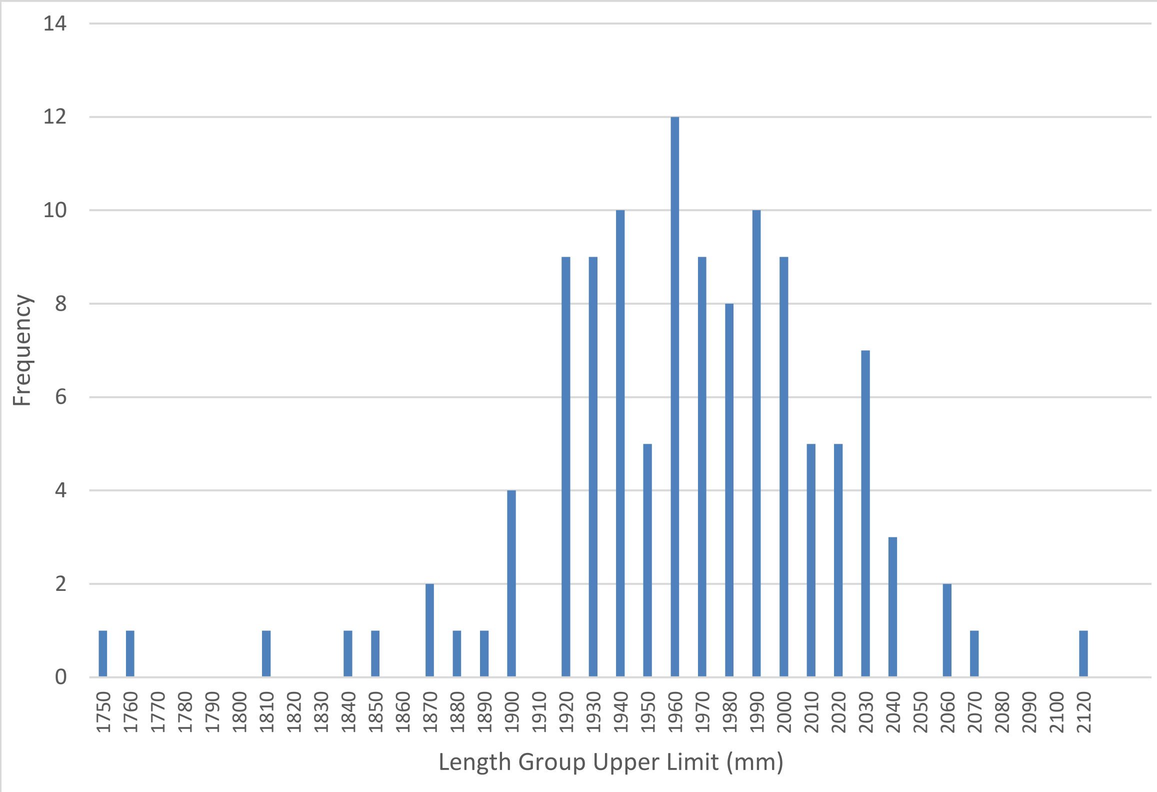


Figure 6-2 Frequency of lengths of the *Mary Rose* longbows recorded in Weapons of Warre (2011). Value shown is the group upper limit (mm < 1750 is shown as 1750, 1750 ≤ mm < 1760 is shown as 1760, etc.)

Further complexity is added when the relationship between the draw weight and the initial arrow speed is factored in. As discussed previously, the 12 lbs difference between 21MRA2 and 21MRA3 did not generate a different initial arrow speed, yet the difference in draw weight between these and 21MRA4 did (24 and 36 lbs respectively), thus indicating that there is a nonlinear relationship between draw weight and initial speed. However, there were not enough data points collected in this study to map this further, as experimental data collected was affected by changeable cloud cover causing issues with the chronograph readings. Nevertheless, what is clear from this is that if the *Mary Rose* longbows follow the pattern observed between 21MRA2 and 21MRA3, resulting in a 50 lb draw weight difference, the initial speed generated by two similar length longbows, 80A0907 and 81A1614, would be significantly different.

With that said, as highlighted above, 2MRA2 and 21MRA3 do not only have variation in the wood but were intended for the analysis of the differences between two different cross-section groups. Supposing the difference that has been observed between 21MRA2 and 21MRA3 is a product of this difference in cross-section shape, the significance of this result for the *Mary Rose* collection is less. Instead of potentially adding 50 lbs between their counterparts, this assumption would suggest a similar draw weight difference between 80A0907 and 81A1614 than observed in the replicas, and thus, no difference in initial arrow speed produced by these longbows. This works well with the theory of standardised longbows. Medieval standardisation of any product would not be as precise as modern day, and even less so with a naturally varying material such as wood. So, if bowyers were aiming for a standardised draw weight there would likely be a range rather than one exact value. With the knowledge that some level of variation in draw weight will not affect the initial speed of the arrow, this becomes an even more plausible possibility. Since the initial arrow speed will be the same, or very similar, for a range of draw weights, it would also be possible for an experienced archer to consistently and easily predict the arrow flight no matter what longbow they picked up from the chest, which is no doubt vital in battle.

Overall, the results from the replica longbows have provided some additional insights into the *Mary Rose* longbow collection. However, to really delve deeply into modelling the draw weight and initial speed of historical artefacts from their dimensions and internal wood structure some further experimentation is needed. Positively, the results do indicate that with this additional exploration into the impact of wood variation on draw weight, and the relationship between draw weight and initial speed a predication of performance from longbow dimensions would be possible. Without this it is difficult to make any strong connections between the variables of the collection, such as markings and location, to performance and potential roles aboard the ship.

Chapter 7

Concluding Remarks

The tactical deployment of longbows aboard *Mary Rose* is a complex topic with many different factors to consider, both in terms of the longbow itself and the wider bow-and-arrow system, including the archer themselves. Exploring the feasibility of non-destructive modelling through understanding the relationship between the longbows' physical properties and its performance in terms of draw weight and range has brought us closer to being able to answer questions about the collection, revealing unexpected insights as well as information related to the original research problem. Additionally, CT scanning of the *Mary Rose* bowstring showed this is a promising non-destructive technique which could enable material identification with a greater reference bank. While the collection of other surrounding data, such as limb deformation and dispersion, inform our understanding of the longbow more generally. This study can be seen as an exciting initial examination of these questions, with many avenues for future research that will continue to deepen our understanding of the *Mary Rose* collection and this impressive weapon in general.

7.1 Future Work

Throughout this study there are four distinct areas where more development would improve the interpretation of the results that have been presented here and increase our understanding of the longbow in terms of its usage aboard the *Mary Rose* and more broadly. Of highest priority is research into the relationship between natural wood variation and performance, which was originally planned to be included in this study but was not possible due to issues with the replicas. For this it would not necessarily be needed for *Mary Rose* specific replicas to be crafted, a set of any longbows would work as long as they were all approximately the same dimensions (due to the nature of the material and the manufacturing process it is not possible to create longbows that are exact copies of one another) but crafted from different pieces of wood. Testing of these longbows in a laboratory setting and field testing them as has been described in this work would provide complementary information that would not only further develop our understanding of this relationship but provide clarity to the results obtained by this study. In turn, enabling a deeper interpretation of the *Mary Rose* collection. Furthermore, the quantification of the effect of natural wood variation would be invaluable to the study of historical longbows that can only be studied non-destructively, as the internal structure can be visualised using CT.

Secondly, the data obtained during field testing described in Chapter 4, highlighted a need to examine the relationship between the draw weight of a longbow and the initial arrow speed generated. This data indicated that there is a nonlinear relationship between the two, however, more data points from the measurement of the initial speed from different draw weight longbows is needed to explore this fully. Again, there would not be a need for this to include specific *Mary Rose* replica longbows, any historically accurate longbows of different draw weights could be used for testing. Fully establishing this will add a further layer of understanding to the English longbow as it will allow the prediction of arrow performance from different draw weight longbows, in turn allowing further interpretations of effectiveness in battle and tactical planning.

Further exploration into natural bowstring is a much-needed addition to understanding of the wider bow-and-arrow system. As has been discussed, the bowstring is vastly understudied but plays a crucial part in the efficiency of the longbow. Within this study, initial tests of the viability of CT for non-destructive material analysis were carried out. The results of this were very positive and suggest that this would be a successful technique with a wider bank of known samples. There are at least two other potential bowstring materials: nettle and silk, which were not included here. CT scanning of this, as well as any other potential materials, will improve our chances of identifying the material used to craft the *Mary Rose* bowstring. This will then allow the design of improved testing of the strength of this material and what manufacturing process is needed to provide strings able to withstand the draw weights of these longbows.

Finally, the shooting machine that was built for this project was used to carry out some testing around arrow variation. The *Mary Rose* collection of arrows also contains a large amount of variation, leading to questions about how far this affects the performance of the arrow. Or whether it was simply a case of fletchers preferred shape and techniques, with whatever suitable wood was available. These questions have been explored by historical enthusiasts, headed by Joff Williams, but the shooting machine was used to remove variation caused by human archers, particularly the affect of fatigue. While there was some significance in the results obtained surrounding variance in mass, it was clear that more data points are needed to provide a full picture. Future work that seeks to develop this would provide useful data on arrow variance and its importance. Similar to the longbows, the arrows aboard *Mary Rose* were in mixed barrels, which would surely be undesirable if each arrow was going to behave differently when shot.

In addition to these, future work could also include the repeat of field tests using a human archer. Comparing these results to those taken using a machine would allow the quantification of how much influence the archer has over the shot, and how much variation occurs over time due to human error and fatigue, as well as physical variation between people. What affect can height and weight have, for example. Investigating the influence of the archer over the performance of the longbow would provide some further insight into whether the variation of the *Mary Rose* longbows would have posed a challenge when selecting a longbow from a mixed chest, and how affective a group of archers may be when not working with their preferred dimensions. This would be additionally useful in the area of arrow variance as information can be gathered on how far an archer can correct for differences in the arrow.

Appendix A P-values for Statistical Tests

A.1 Chapter 3

	21MRA2	21MRA3	21MRA4	21MRA5
21MRA2	-	0.004337	3.04E-06	5.95E-07
21MRA3	0.004337	-	0.013927	2.5E-13
21MRA4	3.04E-06	0.013927	-	0.013927
21MRA5	5.95E-07	2.5E-13	0.013927	-

A.1 1 P- values for draw weight f-tests

	21MRA2	21MRA3	21MRA4	21MRA5
21MRA2	-	3.88E-56	8.61E-42	2.3E-116
21MRA3	3.88E-56	-	4.34E-57	1.29E-73
21MRA4	8.61E-42	4.34E-57	-	4.57E-53
21MRA5	2.3148E-116	1.29449E-73	4.57187E-53	-

A.1 2 P values for draw weight t-tests

100 mm	200 mm	300 mm	400 mm	500 mm	600 mm	700 mm	800 mm	900 mm	Tip
1.9E-07	4.3E-08	7.3E-15	2.1E-13	2.3E-11	2.4E-09	3.5E-10	6.4E-09	1.3E-09	4.0E-10

A.1 3 P-values for ANVOVA tests comparing displacement between 21MRA2, 21MRA3, 21MRA4 and 21MRA5 every 100 mm along limb from centre point

A.2 Chapter 4

	P value F-Test	P value t-Test
615 grains, 535 grains	0.040919	0.153001
615 grains, 465 grains	0.138056	0.04212
535 grains, 465 grains	0.210345	0.124688

A.2 1 P values for the F-Tests and t-Tests comparing the strike height results from the different groups in the Mass category

A.3 Chapter 5

	21MRA	21MRA2	21MRA3	21MRA4	21MRA5
21MRA1	-	0.481569	0.003763	0.307306	0.337352
21MRA2	0.481569	-	0.003426	0.29154	0.320848
21MRA3	0.003763	0.003426	-	0.010334	0.008745
21MRA4	0.307306	0.29154	0.010334	-	0.466143
21MRA5	0.337352	0.320848	0.008745	0.466143	-

A.3 1 P-values for f-tests comparing ring count per mm^2 between replica longbows

	21MRA	21MRA2	21MRA3	21MRA4	21MRA5
21MRA1	-	1.18E-05	0.000694	0.000177	3.89E-08
21MRA2	1.18E-05	-	0.000276	4.28E-07	2.33E-09
21MRA3	0.000694	0.000276	-	0.000741	2.39E-06
21MRA4	0.000177	4.28E-07	0.000741	-	2.39E-06
21MRA5	3.89E-08	2.33E-09	2.39E-09	2.39E-06	-

A.3 2 P-values for t-tests comparing ring count per mm^2 between replica longbows

	21MRA	21MRA2	21MRA3	21MRA4	21MRA5
21MRA1	-	0.001631	2.18E-06	0.070363	0.059728
21MRA2	0.001631	-	0.087807	2.23E-06	3.1E-06
21MRA3	2.18E-06	0.087807	-	5.38E-11	3.44E-11
21MRA4	0.070363	2.23E-06	5.38E-11	-	0.460891
21MRA5	0.059728	3.1E-06	3.44E-11	0.460891	-

A.3 3 P-values for f-tests comparing ring width between replica longbows

	21MRA	21MRA2	21MRA3	21MRA4	21MRA5
21MRA1	-	0.006256	8.97E-16	0.000535	0.011724
21MRA2	0.006256	-	2.28E-32	1.21E-10	4.23E-08
21MRA3	8.97E-16	2.28E-32	-	1.8E-05	4.38E-08
21MRA4	0.000535	1.21E-10	1.8E-05	-	0.32048
21MRA5	0.011724	4.23E-08	4.38E-08	0.32048	-

A.3 4 P-values for t-tests comparing ring width between replica longbows

	80A0907	80A1298	81A1602	81A1614	81A3960	81A3965
80A0907	-	0.043548	0.002998	0.00068	0.000922	0.002562
80A1298	0.043548	-	0.091353	0.026099	0.034146	0.080601
81A1602	0.002998	0.091353	-	0.23861	0.284906	0.469288
81A1614	0.00068	0.026099	0.23861	-	0.441863	0.262403
81A3960	0.000922	0.034146	0.284906	0.441863	-	0.311124
81A3965	0.002562	0.080601	0.469288	0.262403	0.311124	-

A.3 5 P-values for F-tests comparing ring count per mm^2 for the 6 *Mary Rose* longbows included in this study.

	80A0907	80A1298	81A1602	81A1614	81A3960	81A3965
80A0907	-	6.01E-07	2.62E-06	9.76E-07	1.22E-06	9.35E-06
80A1298	6.01E-07	-	8E-07	1.61E-07	0.034146	1.96E-06
81A1602	2.62E-06	8E-07	-	3.65E-11	4.29E-10	9.56E-11
81A1614	9.76E-07	1.61E-07	3.65E-11	-	5.28E-07	1.09E-13
81A3960	1.22E-06	0.034146	4.29E-10	5.28E-07	-	3.85E-13
81A3965	9.35E-06	1.96E-06	9.56E-11	1.09E-13	3.85E-13	-

A.3 6 P-values for T-tests comparing ring count per mm2 for the 6 *Mary Rose* longbows included in this study.

	80A0907	80A1298	81A1602	81A1614	81A3960	81A3965
80A0907	-	0.000296	1.01E-20	9.69E-34	0.007929	0.000709
80A1298	0.000296	-	6.79E-09	1.97E-37	0.317443	4.46E-09
81A1602	1.01E-20	6.79E-09	-	4.11E-64	7.79E-09	1.3E-28
81A1614	9.69E-34	1.97E-37	4.11E-64	-	5.18E-27	9.33E-18
81A3960	0.007929	0.317443	7.79E-09	5.18E-27	-	3.71E-06
81A3965	0.000709	4.46E-09	1.3E-28	9.33E-18	3.71E-06	-

A.3 7 P-values for F-tests comparing ring width for the 6 *Mary Rose* longbows included in this study.

	80A0907	80A1298	81A1602	81A1614	81A3960	81A3965
80A0907	-	1.27E-64	2.6E-111	5.7E-49	1.2E-121	1.47E-29
80A1298	1.27E-64	-	0.000112	3.61E-33	7.61E-60	1.53E-05
81A1602	2.6E-111	0.000112	-	8.23E-30	1.37E-47	2.45892E-15
81A1614	5.7E-49	3.61E-33	8.23E-30	-	1.53E-11	3.83E-38
81A3960	1.2E-121	7.61E-60	1.37E-47	1.53E-11	-	7.09919E-70
81A3965	1.47E-29	1.53E-05	2.45892E-15	3.83E-38	7.09919E-70	-

A.3 8 P-values for t-tests comparing ring width for the 6 *Mary Rose* longbows included in this study

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