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Archery's Lasting Mark: A Biomechanical Analysis of Archery

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ARCHERY'S LASTING MARK: A BIOMECHANICAL ANALYSIS OF ARCHERY

A Thesis presented
by
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ARCHERY'S LASTING MARK: A BIOMECHANICAL ANALYSIS OF ARCHERY

A Thesis Presented
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DEDICATION

To my incredible family and fiancé,

Mom, Dad, Tori, Tia, and Sam, I would not be where I am today without your loving support and encouragement. I feel truly blessed to have you all in my life.

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This thesis would not have been possible without the support and guidance provided by my advisor Dr. Brigitte Holt and my committee members, Dr. Eric Johnson and Dr. Joseph Hamill, along with the motion capture and electromyography training I received from Dr. Gillian Weir. I am truly grateful for all of the time and dedication you have provided. I would like to express my gratitude to Dr. Joseph Hamill for access to the Biomechanics Laboratory, and to Dr. Gillian Weir and Vikram Norton for assisting in data collection and analysis.

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ABSTRACT

ARCHERY'S LASTING MARK: A BIOMECHANICAL ANALYSIS OF ARCHERY

SEPTEMBER 2019

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The physical demands of archery involve strenuous movements that place repetitive mechanical loads on the upper body. Given that bone remodels in response to mechanical loading (Ruff, 2008), it is reasonable to assume that repetitive bow and arrow use impacts upper limb bone morphology in predictable ways. The introduction and increased use of archery have been suggested to impact bilateral humeral asymmetry (Rhodes and Knüsel, 2005; Thomas, 2014). However, this claim is yet to be tested *in vivo*. This project aims to use kinematic and electromyographic approaches to validate claims inferring that, 1. archery places mechanical loading on the non-dominant arm resulting in lowered asymmetry, and 2. the dominant arm in archery has more mechanical loading placed in the anterior-posterior direction while the non-dominant arm has more mechanical loading placed in the medial-lateral direction.

Some muscles (i.e. Pectoralis major and posterior Deltoid) act symmetrically on both humeri, while most muscle groups (i.e. Biceps brachii, Triceps brachii, Deltoid (lateral), and Latissimus dorsi) are activated asymmetrically on the humerus. On the whole, asymmetrically acting muscle groups acting on separate arms result in similar

overall directional bending. Therefore, the overall cross-sectional shape of the bone would be similar for the draw and bow arm. Repeated bow use would undoubtedly induce humeral modification consistent with increased non-dominant arm robusticity, which in turn would lower asymmetry. Findings from this project thus support the hypothesis that the adoption of the bow and arrow results in decreased humeral asymmetry and strengthen morphological approaches to behavioral reconstruction.

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CHAPTER 1 INTRODUCTION

1.1 Overview

Archery is a complex activity that played a role in nearly every culture spanning from pre-history to the present (Sisk and Shea, 2011; Whitman, 2017). Throughout time, archery, also known as “bow and arrow”, has been used as a tool for hunting, a weapon of warfare, and, more recently, as a competitive sport. The physical demands of archery involve strenuous movements that place repetitive mechanical loads on the upper body. Given that bone remodels in response to mechanical loading (Ruff, 2008), it is reasonable to assume that repetitive bow and arrow use impacts upper limb bone morphology in predictable ways. The introduction and increased use of archery have been suggested to impact bilateral humeral asymmetry (Rhodes and Knüsel, 2005; Molnar, 2006; Thomas, 2014). However, this claim is yet to be tested *in vivo*. Inferring specific activities based purely on skeletal morphology can be difficult, especially considering the complexity and variability of movements involving the upper limb. For instance, pronounced right-dominance in the humeri of Neandertals was previously believed to be a result of spear thrusting. However, using an *in vivo* experiment, Shaw et al. (2012) demonstrated that scraping tasks may provide a more accurate explanation based on the muscle activation involved in scraping tasks versus spear thrusting.

This project aims to use an *in vivo* approach to validate claims inferring archery’s impact on bilateral humeral asymmetry and morphology using kinematics and electromyographic analyses.

1.2 Background

1.2.1 The evolutionary importance of archery

The overall evolutionary success of *Homo sapiens* is, in part, due to behavioral adaptations that allowed for strategic and ecological versatility. New technological innovations, such as projectiles, represent important moments within human biological and cultural evolution (Ambrose, 2001). Both the “Upper Paleolithic Revolution” (Bar-Yosef, 2002) and “behavioral modernity” (Henshilwood and Marean, 2003) represent events in time that include projectile technology as a defining characteristic. Early hominins used simple projectiles, including throwing sticks and hand-cast spears that depended purely on human mechanical energy. The bow and arrow, in contrast, is a complex projectile that takes advantage of a non-projectile component by storing and redirecting energy and appears to have been used exclusively by *Homo sapiens* (Sisk and Shea, 2011). Bows and arrows are universally seen across human societies ranging from hunter-gatherers to industrial states (Shea, 2006). Archery has also been used in diverse ecological contexts, such as the arctic, forest, and desert (Williams et al., 2014). Clearly, the bow and arrow has proven to be a versatile tool and important piece of our evolutionary history.

Examining the progression of tools throughout time provides valuable insights into the cognitive evolution of humans. While a majority of weapons have been used by other species in the genus *Homo*, the bow and arrow has been exclusively wielded by *Homo sapiens* (Sisk and Shea, 2011; Lombard, 2011). The reason no other species used bow and arrow technology remains unclear; however, there could be a cognitive component associated with archery that

is uniquely modern. Neuroarchaeological studies have shown enhanced executive functions in the brain in arrow-shooting tasks compared to spear throwing (Williams et al., 2014). Archery is also associated with more advanced cognition because of the multi-stage planning required for manufacture (Ambrose, 2010). The appearance of archery within the archaeological record thus represents an important shift in the cognitive complexity that defines modern humans (Osiurak and Massen, 2014; Williams et al., 2014).

The adoption of archery also coincides with changes in hunting strategies (Tomka, 2013). Prior to bows, darts and spears were the primary projectiles in use, and it is often assumed that the emergence of the bow resulted in the abandonment of other projectiles like the atlatl dart (Lombard and Phillipson, 2010). One advantage assumed with the bow and arrow is the increased distance at which a hunter can effectively kill their target. The traditional bow and arrow, however, does not appear to provide a significant advantage for distance. Throwing spears have been shown to achieve ranges from 8-18m while traditional bows only range slightly better at 9-25m (Lombard and Phillipson, 2010). The most beneficial aspect of using a bow and arrow would be the opportunity for hunters to take multiple shots in quick succession. The bow and arrow are lightweight and portable which allowed hunters to follow prey greater distances with less energy cost (Lombard and Phillipson, 2010; Tomka, 2013).

Another factor influencing the cultural adoption of the bow was the types of prey available in an area. Experimental results demonstrate that the atlatl, which is heavier and results in more momentum upon impact, is more effective in killing larger prey than the bow and arrow (Tomka, 2013). In contrast, the lightweight bow is more effective with small agile

prey. Therefore, in regions with decreasing numbers of larger prey, the bow and arrow would have been more readily adopted. When the atlatl and the bow and arrow are used in combination, hunters had a broader hunting capacity (Tomka, 2013) that would have allowed humans to occupy more diverse environments.

1.2.2 Archaeological evidence of archery

Limitations of preservation make finding archaeological evidence of early archery challenging. The organic materials typically used to construct bows and arrows preserve poorly within the archaeological record. Archaeologists generally rely on durable stone or bone projectile points as an indication of archery. Unfortunately, multiple projectile points including arrowheads, spearheads, and darts appear similar in structure, making it difficult to differentiate among them. In addition, tools were often used for multiple purposes and it may not be accurate to assume discovering a presumed projectile point equates to projectile tool use. Project points only offer weak, indirect evidence of archery compared to sites where the actual bows or arrow shafts were discovered. Bows provide stronger and more direct evidence of archery.

Analyzing residues and microwear traces potentially provides insights, albeit somewhat ambiguous, into stone point functionality (Shea, 2006; Lombard, 2005). Morphometric analysis appears to be fairly effective experimental techniques for differentiating between varying functions of projectile points. Thomas (1978) measured tip cross sectional area (TCSA) across a collection of arrowheads and dart tips housed at the American Museum of Natural History and quantified significant variation in TCSA values among them. In additional studies, optimally

shaped Levallois spear points displayed higher TCSA values compared to Native American dart tips and arrow heads (Shea, 2006), further demonstrating TCSA's potential to infer projectile point function. Even though some techniques show promise, the inferred presence of projectile points alone does not offer definitive evidence of archery use.

The oldest proposed arrowheads in the archaeological record were excavated from Sibudu Cave in Kwazulu-Natal, South Africa and date to approximately 61.7 ± 1.5 thousand years BP (Lombard, 2011; Lombard and Haidle, 2012). The small size of these stone-tips suggest they were used as projectiles and further examination of microscopic ochre, resin distribution patterns, and micro-residue analysis suggests hafting strategies consistent with arrows (Lombard, 2011). However, as previously stated, these suggested arrowheads only provide weak, indirect evidence of archery, and whether these points were functioning as arrowheads should be questioned.

Although inferred evidence of arrowheads in Africa date back 50-100,000 BP, there is no evidence of archery in the Levant region on the Eastern Mediterranean Sea until approximately 12,000 BP (Johannes, 2004). While the Natufian culture in the Levant is one of the first to move towards increasing sedentism (Yeshurun and Yarosheich, 2014), the Natufians still relied on hunting. There appears to be a shift in hunting strategies with the Natufians that incorporated the use of bows with stone blades and dogs (Johannes, 2004). The necessary drives for hunting gazelles required a large number of people. Bows allowed individuals to wound animals from a distance and then track them using dogs, which decreased the number of people required (Clutton-Brock, 1961). Similar to the evidence of archery at Sibudu Cave, there is no direct evidence consisting of material bows in the Levant, but circumstantial evidence including

microliths with evidence of hafting and breaking patterns consistent with projectile use is an indication of archery (Peterson, 1998).

Within Europe, archery spread from East to West (Lombard and Phillipson, 2010; Shea and Sisk, 2010). At a site in Stellmoor, Germany over 100 wooden arrow shafts were found dating to approximately 10,750-10,250 BP (Clark, 1963). Similar to the other ancient sites described above, there were no physical bows located at Stellmoor, but the arrow shafts provide stronger evidence for archery than solely relying on projectile points presumed to be arrowheads. The combination of flint arrowheads along with the arrow shafts strongly suggest that the population at Stellmoor practiced archery.

There is no record of bow use until approximately 8,000 BP in Denmark and Russia. The most well-known Mesolithic bows, known as the Holmegaard Bows, were found in Denmark (Knecht, 1997; Whitman, 2017), while a number of bows have also been recovered in Russia (Bamforth and Knecht, 2006). This is the strongest and first direct evidence of archery use. Until this point, archery could only be assumed by circumstantial evidence. By the Neolithic, archery had spread throughout Europe and evidence of bows within European farm settings suggests a shift in archery's role. At the early Neolithic site of La Draga in Banyoles, Spain (7,250-6,950 BP) (Piqué et. al., 2015), one complete bow and two fragments of bows were excavated. The La Draga population relied largely on agriculture; hunting would have thus played only a minor role in food acquisition. Due to the minimal evidence of warfare (Palomo et. al., 2015), the role of archery at La Draga is questioned. Stein (1990) proposes a risk reduction strategy in which hunting was an alternative that compensated for times when the crop yields were poor. Alternatively, hunting could have had a social or political component associated with symbolic

value or prestige (Thomas, 2014). Within a society no longer based on hunting and gathering, the appearance of archery suggests archery's shifting role from survival to a more social function.

The earliest evidence of archery in the New World appears in the Arctic, although the exact timing remains unclear. Tomka (2013) posits that bows appeared in the Canadian Arctic between 4959-3550 B.P., while Blitz (1988) proposes that bows appeared between 10,950-7,950 B.P. Maschner and Mason (2013) suggest the earliest evidence of archery at roughly 12,000 B.P. and discuss four waves or phases of archery in the Arctic region. There is disagreement on when archery first started in the arctic because the earliest evidence of archery is inferred bone arrowheads at the Inuk and Lim Hills Cave sites, dating between 11,250-8,800 BP (Maschner and Mason, 2013). The small projectile points only offer indirect evidence that do not offer strong enough evidence to convince everyone of archery use. Maschner and Mason (2013) argue that early bows were present but may not have been efficient enough weapons to kill large ungulates (i.e. bison or moose), which resulted in the predominant reliance on other, more efficient weapons. There is little evidence of archery for the next four thousand years. It is not until approximately 4,500 BP that more indirect evidence of archery in the form of microlithics and blades (indications of archery) began appearing again. However, when terrestrial fauna numbers decreased and a sea mammal-based economy was adopted in the Arctic around 3,500 B.P., all evidence of archery vanished (Maschner and Mason, 2013). There is general agreement that archery was in the Arctic after 3,000 BP (Blitz, 1988; Tomka, 2013) and increased in use around 1,300 years ago mostly because of more direct evidence (i.e. bows) being discovered (Maschner and Mason (2013). Bow and arrow technology

spread throughout the New World, and by 700 A.D. it had widespread use among the indigenous peoples of North America (Tomka, 2013).

1.2.3 Archery and limb bone structure

Although the archaeological material evidence for early archery is limited and often indirect, an additional source of information can be found through human skeletal analysis. Bone is a living tissue and adapts to external mechanical stimuli (Ruff, 2008; Larsen, 2015). Bone morphology, therefore, reflects an individual's activities through life. In an attempt to maintain a level of homeostasis, the human body deposits new bone tissue in response to increased stress (i.e. amplified muscle activity) resulting in relatively stronger bones. Similarly, inactivity or sedentism stimulates bone reabsorption, thereby weakening the bone (Trinkaus et al., 1994; Ruff et al., 2006). This process of bone remodeling creates the underlying foundation for behavior reconstruction studies (Ruff, 2008; Shaw et al., 2012; Larsen, 2015; Sládek et al., 2018; Holt and Whittey, 2019).

Biomechanics, the application of mechanical concepts to biological contexts, has proven to be a beneficial approach to reconstructing a past population's habitual behaviors (i.e. Ruff, 2018; Holt et al., 2019). Long bones can be modeled as engineering beams to study the impact of habitual mechanical loads (Ruff, 2008). Beam theory predicts the internal stresses that result from external loading by using cross-sectional geometric parameters such as second moment areas (I_y , I_x , I_{min} , I_{max}), ratios of second moment areas (I_y/I_x , I_{max}/I_{min}), total cortical area (TA), and polar moment area (J) (Ruff et al., 1993; Ruff 2008; Shaw and Stock, 2013; Ruff 2018). These parameters provide information about the relative strength and shape of long bones that can

be used to predict their responses to varying types of external forces applied to them.

Reconstructing past behaviors using skeletal morphology and geometric properties provide a window into the past that cannot be achieved by solely using material artifacts.

Comparisons of cross-sectional dimensions of long bones provide information on how humans physically adapted to changes in the environment, including cultural changes such as the transition to agriculture. As humans became more sedentary, for example, the mechanical loading demands being placed on the femur decreased, resulting in relatively weaker and more circular lower limb bones (Holt, 2003; Ruff, 2008). Comparisons of the upper limb may reflect specific non-locomotive activities more accurately. For instance, in the Paris Basin, Thomas (2014) compared the upper limb of Neolithic skeletons who were ceremonially buried with arrowheads with those who were not. Individual burials associated with arrowheads had more robust forearm bones indicating more mechanical loading. According to Thomas (2014), this indicates those buried with arrowheads participated in more intense upper limb activities including archery. The skeletal morphology and ceremonially placed arrowheads suggest these individuals specialized in archery.

1.2.4 Asymmetry and Archery

Although a multitude of factors influence skeletal morphology (i.e. diet, genetics, pathologies), observing asymmetry in the upper limb clearly suggests a direct association between mechanical loading and structural bone properties due to remodeling processes (Trinkaus et al., 1994). This relationship is supported through observed differences in upper limb asymmetry in several sports that rely on a dominant arm. Shaw and Stock (2009) used CT

scans from swimmers, cricketers, and a control group to detect relationships between different behaviors and bone structure. The control group had bilaterally gracile humeri compared to both swimmers and cricketers. While swimmers humeri were bilaterally robust, the cricketers displayed higher robusticity in the dominant arm. Similarly, studies focusing on tennis players have found high levels of asymmetry in the upper arm due to increased robusticity of the dominant arm (Jones et al., 1997; Kontulainen et al., 2002).

High levels of humeral bilateral asymmetry characterize early modern human males (Trinkaus et al., 1994; Trinkaus & Churchill, 2002); however, this changes during the European transition from the Early Upper Paleolithic to the Mesolithic, in which male asymmetry significantly decreases (Sládek et al., 2016). This pattern of decreasing asymmetry is not seen in females until the transition from the Mesolithic to the Neolithic; this suggests that males engaged in bimanual activities that distributed mechanical loads on both arms earlier than females due to sexual divisions of labor (Sládek et al., 2016). The later decrease in female's asymmetry could be attributed to increased dependence on bimanual food processing techniques that appear more dominant in the Neolithic (Sládek et al., 2016). Changes in hunting strategies towards the end of the Early Upper Paleolithic involved shifts from unimanual to bimanual weapons like bows (Schmitt et al., 2003), which offer an explanation for the earlier male decrease in asymmetry.

Similarly, Rhodes and Knüsel (2005) use the introduction of the bow in the Mississippian period to explain the decrease in male humeral asymmetry between Archaic and Mississippian periods. The decrease in directional asymmetry in males from the Upper Paleolithic to the

Mesolithic could be a result of increased loading on the non-dominant arm (typically the left arm) from holding a bow while the dominant arm draws the string back.

Increased distal left humeral robusticity was observed in Medieval archers recovered from a shipwreck on the coast of England compared to a Medieval graveyard at Norwich (Stirland and Waldron, 1997), further supporting increased non-dominant arm loading. Given that bone remodels in response to mechanical loads, it is reasonable to assume that the repeated use of bows would impact the upper limb skeletal morphology in predictable ways. The chronological timeline of archery coincides with decreases in male upper limb asymmetry lends itself to support claims connecting skeletal morphology to archery; however, these claims still lack experimental validation.

1.2.5 Anatomy of archery

In order to test claims of decreasing asymmetrical humeri as a result of archery, it is first necessary to become familiar with the basic terminology used to describe the human body in space. Standing erect with eyes facing forward and arms at the side with the palms facing forward is known as the anatomical position, which is the reference point used to define body structures in relation to one another. Important standard orientational and directional terms are defined in Table 1.

Table 1: Description of orientational and directional terms (Marieb et al., 2014).

Orientalional/Directional Terms	Definition
Superior	Toward the head end or upper part of a structure or the body; above
Inferior	Away from the head end or toward the lower part of a structure or the body; below
Medial	Toward or at the midline of the body; on the inner side of
Lateral	Away from the midline or the body; on the outer side of
Anterior	Toward or at the front of the body; in front of
Posterior	Toward or at the back of the body; behind
Superficial	Toward or at the body surface
Deep	Away from the body surface; more internal

Although archery is a bimanual activity, each arm is performing different movements resulting in different muscles being activated (Peterson, 1998). An individual's dominant arm is generally the one that pulls back on the bowstring and is termed, 'the draw arm' (Figure 1). The responsibility of bracing against the bow and aiming falls to the non-dominant arm, also known as, 'the bow arm' (Peterson, 1998). Archers use various techniques depending on several factors such as bow type, individual physical characteristics, and personal preference.

The primary focus of this project is to analyze muscles that would impact changes in bilateral humeral asymmetry and morphology. Important muscles that have been considered active during archery that also impact overall humeral shape are listed in Table 2. Rhodes and Knüsel (2005) predicted the skeletal loading that some of these specific muscles associated with archery would have on the humerus (Table 3).



Figure 1: Individual at full draw. Since this individual is left-arm dominant the draw arm is his left arm and the bow arm is the right arm.

Table 2: Key muscles associated with archery and their actions.

Muscles	Actions
Triceps brachii	Arm extension; primarily impacting bow arm (Peterson, 1998)
Pectoralis major	Shoulder flexion, adduction, and medial rotation; primarily impacting bow arm (Rhodes and Knüsel 2005)
Biceps brachii	Shoulder and elbow flexion; primarily impacting draw arm (Peterson, 1998)
Brachialis	Elbow flexion; primarily impacting draw arm (Peterson, 1998)
Deltoid	Three groups of fibers (anterior, lateral, posterior) – shoulder abduction; primarily impacting bow arm Anterior fibers - primarily shoulder extension and medial rotation; primarily impacting bow arm Posterior fibers - primarily shoulder extension and lateral rotation; primarily impacting bow arm (Rhodes and Knüsel, 2005)
Latissimus dorsi	Shoulder extension, adduction, and medial rotation; primarily impacting draw arm (Hawhey and Meihs, 2003)

Table 3: Predicted muscles impact on humeral shape (Rhodes and Knüsel, 2005)

Type of Movement	Muscles involved	Resulting Bending
Flexion/Extension movements	Brachialis, Triceps brachii, Biceps brachii	Anterior-posterior bending in humerus
Adduction/abduction or rotation movements	Brachialis and Deltoid muscles	Medio-lateral bending in humerus

Previous studies evaluating muscular activity during archery have focused on forearm muscles (i.e. Flexor digitorum superficialis and Extensor digitorum) in order to assess shooting techniques, primarily during release of the arrow (Martin, Siler, and Hoffman, 1990; Ertan et al., 2005; Ertan, 2009). Lin et al. (2010) measured muscle activation for several shoulder muscles (i.e. Biceps brachii, Infraspinatus, Deltoid); however, since the goal of this particular study was to analyze shoulder tremors on the draw arm, data was only collected unilaterally. The lack of research on bilateral comparisons of muscle activation during archery weakens skeletal morphological approaches inferring the effects of bow use in past populations.

1.3 Project Goals

Archery appears to play a significant role in the evolutionary history of modern humans, but indirect and limited evidence due to poor preservation makes tracking the development of archery challenging. Using skeletal morphological approaches offers an additional source of information, but the complexities of upper limb movement make it problematic to infer specific activities. Research suggests that archery may be associated with decreased asymmetry in some skeletal samples (Rhodes and Knüsel, 2005; Molnar, 2006; Thomas, 2014), however, lacks experimental support. Additionally, Rhodes and Knüsel (2005) propose the dominant arm (draw arm) in archery will have more mechanical loading in the anterior-posterior direction from flexion/extension movements, while the non-dominant arm (bow arm) will have more

mechanical loading in the medial-lateral direction from adduction/abduction and rotation movements. If archery leaves a physical signature on the skeleton, it would provide strong evidence for archery use in past populations. These claims, however, need to first be tested *in vivo*.

The direction of mechanical loading placed on the humerus will depend on which muscles are be activated. Specific muscle activation related to archery can be tested using electromyography (EMG). Electromyography is a biomechanical technique that measures the electrical signals of muscle activation. A number of studies have used EMG to examine archery through medical and sport lenses (Ertan, 2009; Lin et. Al. 2010; Ertan et al., 2011; Horsak & Heller, 2011); no research to date has used EMG analysis to examine the bilateral asymmetrical muscle impacts of archery on the skeleton.

These behavioral models require validation from experimental studies using living humans. Shaw et. al. (2012) used electromyography to test the validity of claims suggesting the large asymmetry in Neanderthal humeri result from underhand thrusting spears. After measuring muscle activation of the Pectoralis major and Deltoid (anterior and posterior) during spear thrusting and scraping tasks in living subjects, Shaw et al. (2012) concluded elevated asymmetry is more likely due to scraping tasks than underhand spear thrusting. This study further illustrates the importance of *in vivo* experiments to confirm past behavioral inferences.

This project aims to use kinematic and electromyographic analyses to validate claims inferring that, 1. archery places mechanical loading on the non-dominant arm resulting in lowered asymmetry and, 2. the dominant arm in archery has more mechanical loading placed in

the anterior-posterior direction while the non-dominant arm has more mechanical loading placed in the medial-lateral direction.

CHAPTER 2 MATERIALS AND METHODS

A combination of kinematic and surface electromyography (sEMG) analysis was used to test the bilateral upper limb impacts of archery. Specifically, a motion capture system was used to collect kinematic data, describing joint motion, while subjects shot a bow. sEMG analyses were used to record muscle activation throughout each trial. The data were analyzed using a combination of MATLAB, Qualisys Track Manager, and Visual 3D software and statistical tests were performed through SPSS (Version 26).

2.1 Materials (Participants)

Participants consisted of nine males (averaging 22 ± 4 years old, 1.79 ± 0.07 meters tall, and 78.6 ± 8.9 kilograms in weight) who reported no major upper limb injuries or surgeries within the past year. Each subject participated in a single motion capture and electromyography testing session at the University of Massachusetts Biomechanics Laboratory. Previous studies focusing on forearm muscle activation and muscular contraction-relaxion strategies of archery have identified differences in forearm muscle activation patterns among non-archers, beginners, and elite archers (Ertan et al, 2005; Ertan, 2009). This study divided participants into two groups: beginners and experienced, based on the participant's archery experience. Beginners were classified as having started archery less than a year ago ($n = 4$), and experienced participants began archery at least eight years ago ($n = 5$) (Table 4).

The study's protocol was approved by the University of Massachusetts Institutional Review Board, and all participant completed an informed written consent prior to participation.

Table 4: Participant Demographics and self-reported years of experience

Subject ID	Age	Height (m)	Mass (kg)	Draw Arm	Years of Experience
P01	28	1.75 m	78.0 kg	Left	< 1 year Beginner
P02	20	1.74 m	77.1 kg	Right	8 years Experienced
P03	23	1.80 m	81.6 kg	Right	10 years Experienced
P04	23	1.87 m	81.6 kg	Right	15 years Experienced
P05	21	1.80 m	68.0 kg	Right	9 years Experienced
P06	20	1.70 m	63.5 kg	Right	9 years Experienced
P07	20	1.73 m	79.3 kg	Right	< 1 year Beginner
P08	18	1.80 m	94.3 kg	Right	< 1 year Beginner
P09	31	1.91 m	83.9 kg	Right	< 1 year Beginner

2.2 Methods

2.2.1 Motion Capture and EMG Set-Up

Kinematic data were collected using an 11-camera motion capture system (Qualisys, Inc., Gothenburg, Sweden), sampling at 200 Hz. The motion capture system was calibrated prior to data collection using a systematic method that covered the entire desired experimental area.

Surface electromyography (sEMG) data were collected bilaterally for eight muscles (Latissimus dorsi, Pectoralis major, Biceps brachii, Deltoid anterior fibers, Deltoid lateral fibers, Deltoid posterior fibers, Triceps long head, and Triceps lateral head) using a 16-channel Delsys Trigno Wireless EMG system. These muscles were indicated as key muscles involved in archery that cross the shoulder joint (Peterson, 1998; Rhodes and Knüsel, 2005) and were close enough to the surface of the skin to be measured with sEMG. Sensors were placed over the muscle bellies according to the SENIAM guidelines (Hermens and Freriks, 1997). Each sensor on the

skin location was prepared by shaving, surface abrasion, and cleaned with alcohol prior to sensor placement (Konrad, 2005). Sensors were secured in place with surgical tape. sEMG data was collected with at a sample rate of 2000 Hz.

2.2.2 Experimental Protocol

After sEMG sensors were placed on participants, they were asked to perform an action designed to isolate a target muscle. Three trials of isometric maximum voluntary contractions (MVC) were collected for each muscle. Participants alternated performing tasks on their right and left arm to avoid fatigue.

Following MVC collection, spherical retroreflective markers were placed on participants using double sided tape. Anatomical markers were affixed to specific bony landmarks that were identified by palpation. To limit errors from soft tissue skin artifact, which are the greatest at joints, rigid clusters were also used (De Rosario et al., 2012). Three markers were placed on the bow and one on the arrow. Figure 2 illustrates the location of each marker; Table 5 defines their specific location. Participants were instructed to stand in the center of the data collection area in anatomical position to collect a static standing trial, which was used to calculate the shoulder joint center. Additionally, the static trial was used to register cluster markers relative to the anatomical markers, giving the cluster markers anatomical significance.

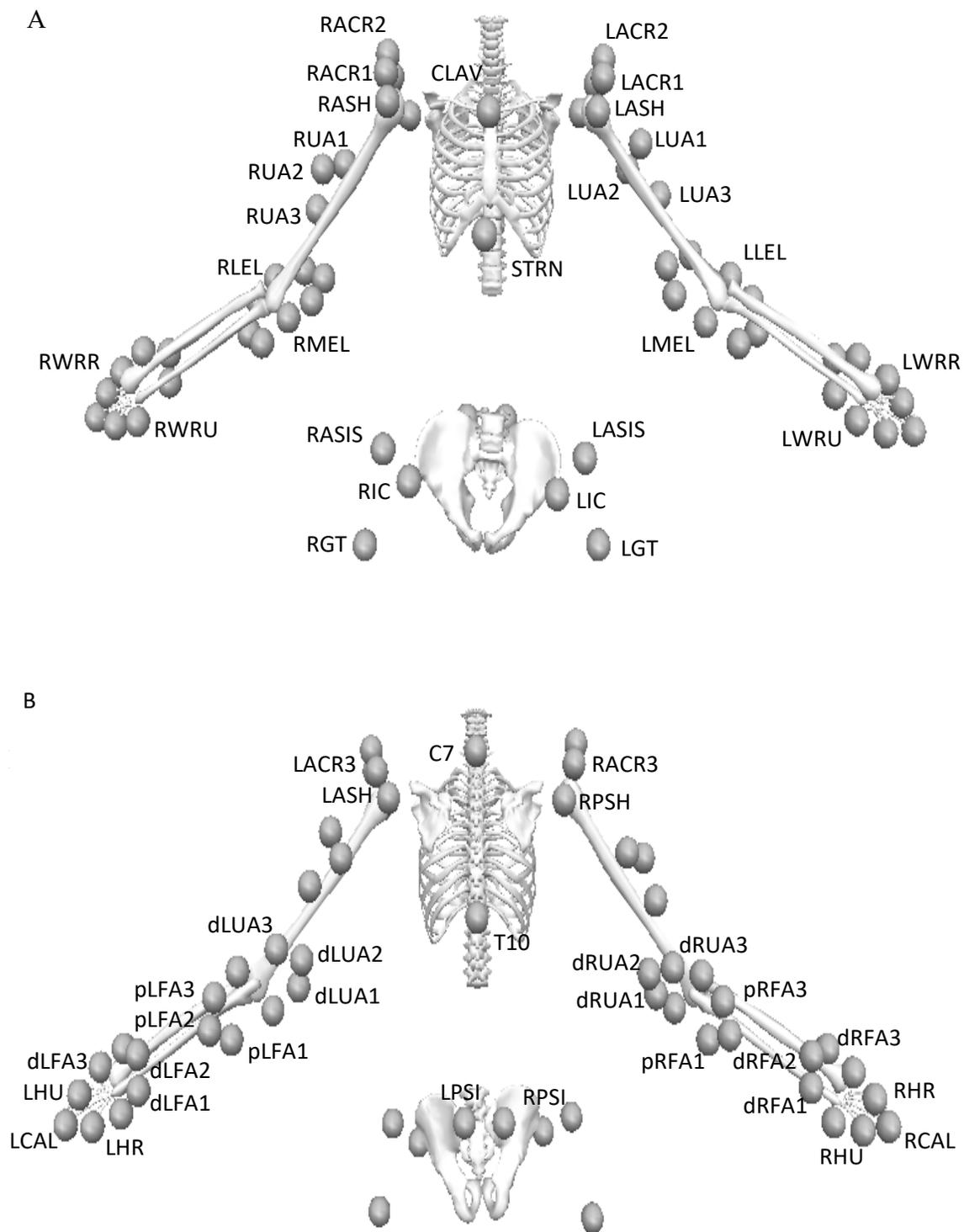


Figure 2: Models created in Visual3D illustrating (A) Anterior view (B) posterior view of a subject standing in anatomical position with anatomical and cluster markers.

Table 5: Locations for anatomical and cluster retroreflective markers

Marker Locations			
C7	Neck (7th cervical vertebrae)	T10	10th Thoracic Vertebrae
STRN	Sternum	CLAV	Clavicle
Markers on Right Side of Body		Markers on Left Side of Body	
RIC	Right Iliac Crest	LIC	Left Iliac Crest
RGT	Right Greater Trochanter	LGT	Left Greater Trochanter
RASIS	Right Anterior Superior Iliac Spine	LASIS	Left Anterior Superior Iliac Spine
RPSI	Right Posterior Superior Iliac Crest	LPSI	Left Posterior Superior Iliac Crest
RACR1	Right Acromion Process 1st Marker	LACR1	Left Acromion Process 1st Marker
RACR2	Right Acromion Process 2nd Marker	LACR2	Left Acromion Process 2nd Marker
RACR3	Right Acromion Process 3rd Marker	LACR3	Left Acromion Process 3rd Marker
RASH	Right Anterior Shoulder	LASH	Left Anterior Shoulder
RPSH	Right Posterior Shoulder	LPSH	Left Posterior Shoulder
RUA1	Right Upper Arm 1 st Marker	LUA1	Left Upper Arm 1 st Marker
RUA2	Right Upper Arm 2 nd Marker	LUA2	Left Upper Arm 2 nd Marker
RUA3	Right Upper Arm 3 rd Marker	LUA3	Left Upper Arm 3 rd Marker
dRUA1	Distal Right Upper Arm 1 st Marker	dLUA1	Distal Left Upper Arm 1 st Marker
dRUA2	Distal Right Upper Arm 2 nd Marker	dLUA2	Distal Left Upper Arm 2 nd Marker
dRUA3	Distal Right Upper Arm 3 rd Marker	dLUA3	Distal Left Upper Arm 3 rd Marker
pRFA1	Proximal Right Upper Arm 1 st Marker	pLFA1	Proximal Left Upper Arm 1 st Marker
pRFA2	Proximal Right Upper Arm 2 nd Marker	pLFA2	Proximal Left Upper Arm 2 nd Marker
pRFA3	Proximal Right Upper Arm 3 rd Marker	pLFA3	Proximal Left Upper Arm 3 rd Marker
dRFA1	Distal Right Forearm 1 st Marker	dLFA1	Distal Left Forearm 1 st Marker
dRFA2	Distal Right Forearm 2 nd Marker	dLFA2	Distal Left Forearm 2 nd Marker
dRFA3	Distal Right Forearm 3 rd Marker	dLFA3	Distal Left Forearm 3 rd Marker
RHR	Right Hand Thumb (radius) Side	LHR	Left Hand Thumb (radius) Side
RHU	Right Hand Pinkie (Ulna) Side	LHU	Left Hand Pinkie (Ulna) Side
RCAL	Right Hand Carpals	LCAL	Left Hand Carpals
RLEL	Right Lateral Elbow	LLEL	Left Lateral Elbow
RMEL	Right Medial Elbow	LMEL	Left Medial Elbow
RWRR	Right Wrist Thumb (Radius) side	LWRR	Left Wrist Thumb (Radius) side
RWRU	Right Wrist Pinkie (Ulna) Side	LWRU	Left Wrist Pinkie (Ulna) Side
Bow/Arrow Markers			
BOW1	Superior Bow Marker	BOW3	Inferior Bow Marker
BOW2	Middle Bow Marker	ARROW	Arrow Marker

Due to the individual variation of the elbow joint, a functional method was used where a helical joint axes was calculated for the elbow to define joint axis orientation and consequent joint centers (Chin et al., 2010). The functional method involved participants fully extending their elbows parallel to the ground with their thumbs pointing to the ceiling. Participants then flexed their elbows to their maximum before returning to their starting position five times. The flexion-extension helical axis was determined based on the average of the five trials and was used to calculate the elbow joint center.

Participants stood in the center of the data collection area in their preferred stance while a target was placed 6.1 m from the participants front foot and at chest level (Figure 3). A standard recurve bow with a draw weight of 0.45 kg (Figure 4) was used for each trial. Participants were allowed to take as many practice rounds as necessary to warm up and then data was collected for ten trials.

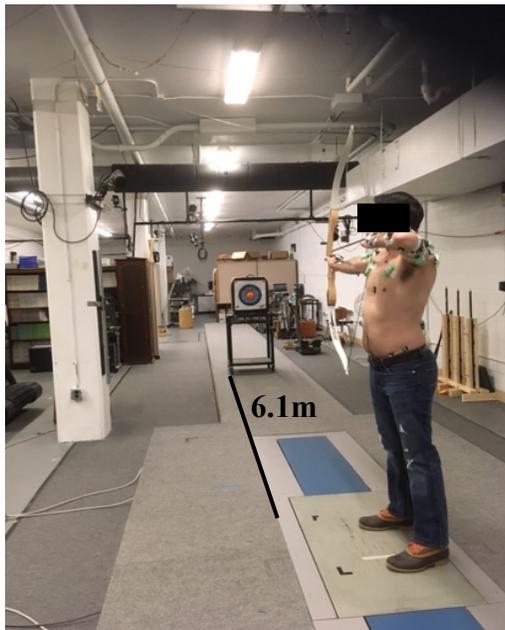


Figure 3: Image of a participant preparing to release the arrow. The target placed at chest level 6.1 m away from the participants front foot.



Figure 4: Picture of the standard 16 lb. draw back weight recurve bow and arrow used for each trial.

2.2.3 Motion Capture Data Processing

Once all of the data were collected, the markers were identified and labeled within Qualisys. The trials were trimmed to the region of interest and gap-fill was used on any markers with under 100% fill levels. Trials were exported to a .c3d file and imported into Visual 3D (C-Motion, Inc., Rockville, MD). Joint centers for the shoulder were determined using a Cardan 3D XYZ rotation sequence, while the elbow joint center was calculated using the functional helical test. Figure 5 illustrates the process from data collection to Qualisys through production of the Visual 3D model.

Based on residual analysis and visual inspection, the kinematic data were filtered with a low-pass Butterworth filter at 4 Hz. Two events, the start and the release, were identified as defining the draw phase. The start of the draw phase was defined as when the distance between the arrow marker and the middle bow marker first deviated more than one standard deviation from the resting distance between the middle bow and arrow markers (Figure 6A). After the participant reached full draw (Figure 6B), visual inspection determined the moment the arrow was released, marking the release (Figure 6C). Three-dimensional joint angles were calculated at the instant of the start and release event as well as the range of motion (RoM) for elbow (flexion/extension) and shoulder (adduction/abduction; flexion/extension; rotation). RoM was calculated as maximum joint angle – minimum joint angle during the draw phase.

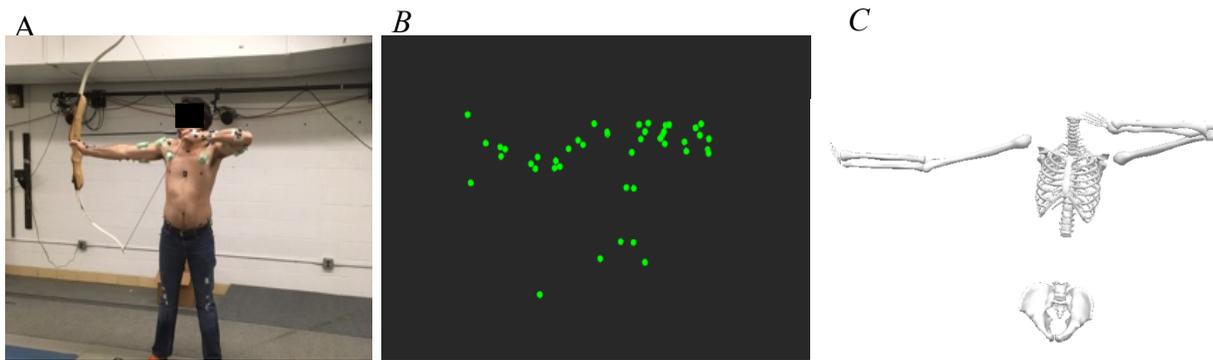


Figure 5: (A) Participant with bowstring fully drawn during data collection. (B) The retro-reflective markers as seen in Qualisys. (C) 3D model created using Visual3D.

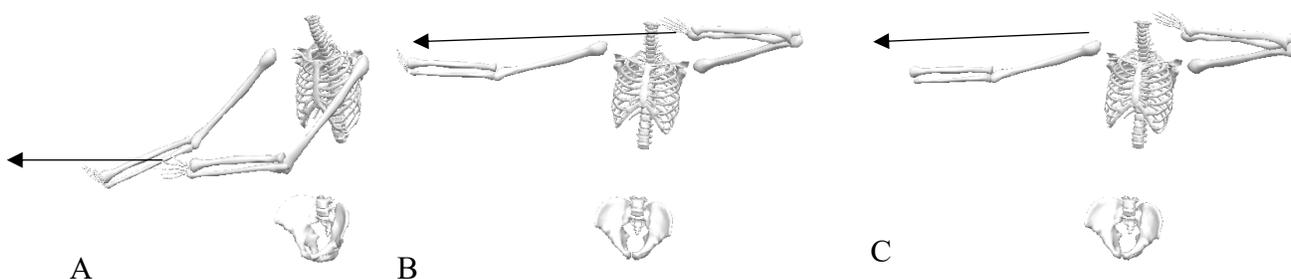


Figure 6: 3D model of participant at the (A) start phase, (B) full draw phase, and (C) release phase.

2.2.4 Electromyography Data Processing

A customized MATLAB program was used to process the sEMG data from isometric Maximum Voluntary Contraction (MVC) trials and dynamic archery trials. Peak values from each MVC trial were recorded; the highest MVC value out of the three trials used for amplitude normalization.

First, any environmental surrounding noise that was recording during testing, known as the direct current (DC) offset, was removed by finding the average value of the entire signal and then subtracting that value from each data-point. This centers the signal around zero (Figure 7B). Next, the negative amplitudes of the signal are converted to positive amplitudes,

which is called a full-wave rectification (Figure 7D) (Konrad, 2005). The next step is to remove any additional noise found in the signal. To do this, a bandpass filter from 20Hz to 500 Hz was used to remove both high frequency noise (i.e. additional electrical signals) and low frequency noise (i.e. heart beat signals, soft tissue artefact) (Figure7C). Finally, a linear envelope was created by filtering the signal with a low pass Butterworth filter at 6 Hz resulting in a smooth curve that illustrates muscle activation (Figure7E) (Devaprakash et. al., 2016).

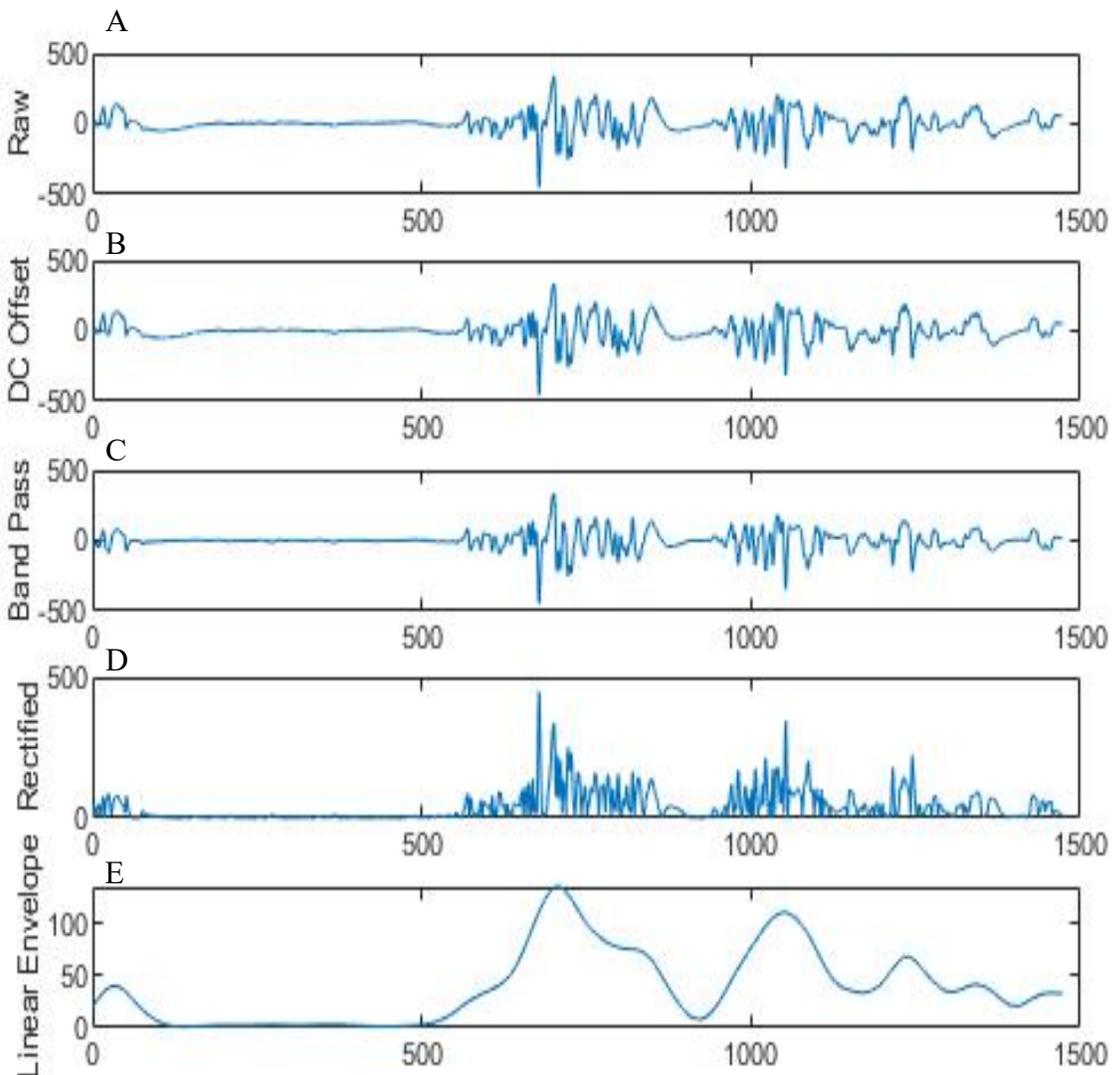


Figure 7: Example of EMG processing steps. (A) Raw data (B) DC offset removal (C) Bandpass filter removing high and low frequency noise (D) Full wave-rectification to make all values positive and (E) Linear envelope created by using low-pass filter.

Since each subject took a different amount of time from the start to the release, the data length was time normalized to 101 points of the draw phase to represent 0-100% of draw phase. Peak amplitudes and integrated EMG (iEMG) (i.e. area under the curve) were measured during the draw phase.

2.2.5 Statistical Analysis

Due to the small sample size (N=9), non-parametric Wilcoxon Signed-Rank statistical tests were performed using SPSS (version 26) and considered statistically significant at $P < 0.05$ for both joint angles and sEMG data. Effect size, which provides information on how groups differ in terms of standard deviations, was determined using Hedges' g formula: $M1 - M2 =$ difference in means, $SD_{pooled} =$ pooled and weighted standard deviation, and $N =$ sample size.

$$Hedges' g = \frac{M1 - M2}{SD_{pooled}}$$

With sample sizes, Hedges' g is naturally biased upwards, and to correct for this the following formula was used (Ellis, 2010).

$$Hedges' g = \frac{M1 - M2}{SD_{pooled}} \times \frac{N - 3}{N - 2.25} \times \sqrt{\frac{N - 2}{N}}$$

Hedges' ' g ' values are interpreted in terms of standard deviation. For instance, a g score of 1.5 means that the means of the two groups being compared are 1.5 standard deviations apart

from each other. Therefore, higher g values mean there is a larger mean difference between the two groups. Large effect sizes are typically considered when $g = 0.8$ or higher, while moderate effect size is when $g = 0.5$. A small effect size is when $g = 0.2$ or less (Ellis, 2010).

CHAPTER 3 RESULTS

There are a number of significant differences in upper limb kinematics and muscle activation patterns observed between the draw and bow arm. However, as there were no significant differences between the muscle activation for beginner and experienced archers, the data for these groups were pooled for further statistical analysis.

3.1. Joint Angles During Archery

The differences in the joint angles between the draw and bow arm exemplify the different actions of each arm and provide information on whether the muscle is shortening or lengthening. EMG data only provides information on when muscles are activating but not in what direction (muscle shortening or lengthening), which is why having the joint angles is important. Joint angles illustrate direction of movement and therefore, offer information about muscle action. For instance, in Table 6 the positive values for the elbow joint indicate the joint is flexing and when combined with EMG data from the Biceps it is clear the Biceps are shortening. Similarly, the positive values for the shoulder joint indicate adduction, flexion, and internal rotation movements.

Range of motion was only significantly different between the draw arm and bow arm for elbow flexion/extension ($g = 2.16$, $p = 0.008$). At release, the draw arm had significantly greater elbow flexion ($g = 10.99$, $p = 0.012$), shoulder flexion ($g = 2.82$, $p = 0.008$), internal shoulder rotation ($g = 2.26$, $p = 0.008$), and less shoulder abduction ($g = 2.66$, $p = 0.008$). The draw arm at the start also had significantly greater elbow flexion ($g = 2.16$, $p = 0.012$), shoulder flexion ($g = 0.69$, $p = 0.015$), and internal shoulder rotation ($g = 1.62$, $p = 0.008$).

Table 6: Mean joint angles and SD for the start, release, and range of motion during the draw phase of archery

Joint Angle (°)	Phase	Draw Arm		Bow Arm		P-Value	g-Value
		Mean	Std. Deviation	Mean	Std. Deviation		
Elbow Flexion (+) /Extension (-)	Start	81.5	23.8	23.9	17.4	0.012 *	2.16
	Release	141.7	9.3	14.4	8.8	0.012 *	10.99
	ROM	106.6	31.3	12.8	10.5	0.008 **	3.15
Shoulder Adduction(+) /Abduction (-)	Start	-1.8	14.8	-24.2	11.4	0.051	1.33
	Release	-42.2	7.3	-64.6	5.8	0.008 **	2.66
	ROM	46.9	13.5	41.5	11.9	0.374	0.33
Shoulder Flexion(+) /Extension	Start	74.1	19.0	55.3	23.6	0.015 *	0.69
	Release	130.9	22.7	59.8	16.1	0.008 **	2.82
	ROM	69.1	27.1	42.3	17.3	0.139	0.92
Shoulder Rotation Internal (+) External (-)	Start	40.7	18.8	7.6	12.4	0.008 **	1.62
	Release	73.3	28.9	2.2	19.4	0.008 **	2.26
	ROM	39.3	20.5	31.2	15.7	0.314	0.35

*Significance at $p < 0.05$, **Significance at $p < 0.01$; Hedges' g calculation: small effect $g = 0.2$, medium effect $g = 0.5$, large effect $g = 0.8$ or higher.

3.2. Muscle activation during the Draw Phase of Archery

Integrated EMG (iEMG), which is the area under the linear envelope curve and peak EMG amplitudes were calculated from processed and normalized EMG data (Figure 8). Statistically significant differences between draw arm and bow arm for iEMG (% of MVC) were observed for several muscles during the archery draw phase (Table 7 and Figure 9). iEMG values for the Latissimus dorsi ($p = 0.008$, $g = 0.87$) and Biceps brachii ($p = 0.008$, $g = 0.83$) were greater in the draw arm compared to the bow arm. In contrast, greater iEMG values for the Deltoid (lateral) ($p = 0.008$, $g = -0.089$) and Triceps brachii (long head; $p = 0.021$, $g = -0.077$ and lateral head; $p = 0.011$, $g = -0.083$) were observed in the bow arm when compared to the draw arm. While there were no statistically significant differences between arms observed for

posterior Deltoid ($p = 0.139$, $g = -0.48$) and anterior Deltoid ($p = 0.26$, $g = -0.54$), there were moderate effect sizes.

Peak sEMG amplitude patterns mirror those of iEMG (Table 8 and Figure 10). The peak sEMG amplitude of both the Latissimus dorsi ($p = 0.038$, $g = 0.72$) and the Biceps brachii ($p = 0.021$, $g = 1.25$) were greater in the draw arm than the bow arm. Similar to the iEMG results, the peak amplitude for the Deltoid (lateral) ($p = 0.011$, $g = -1.02$) and the Triceps brachii (long head; $p = 0.011$, $g = -0.76$ and lateral head: $p = 0.011$, $g = -1.21$) were greater in the bow arm compared to the draw arm. Moderate effect sizes were observed in the posterior Deltoid ($p = 0.139$, $g = -0.56$) and the anterior Deltoid ($p = 0.374$, $g = -0.42$) for peak amplitude, even though there were no statistically significant differences between arms. There were no differences observed for peak amplitude of the Pectoralis major ($p = 0.594$, $g = -0.19$).

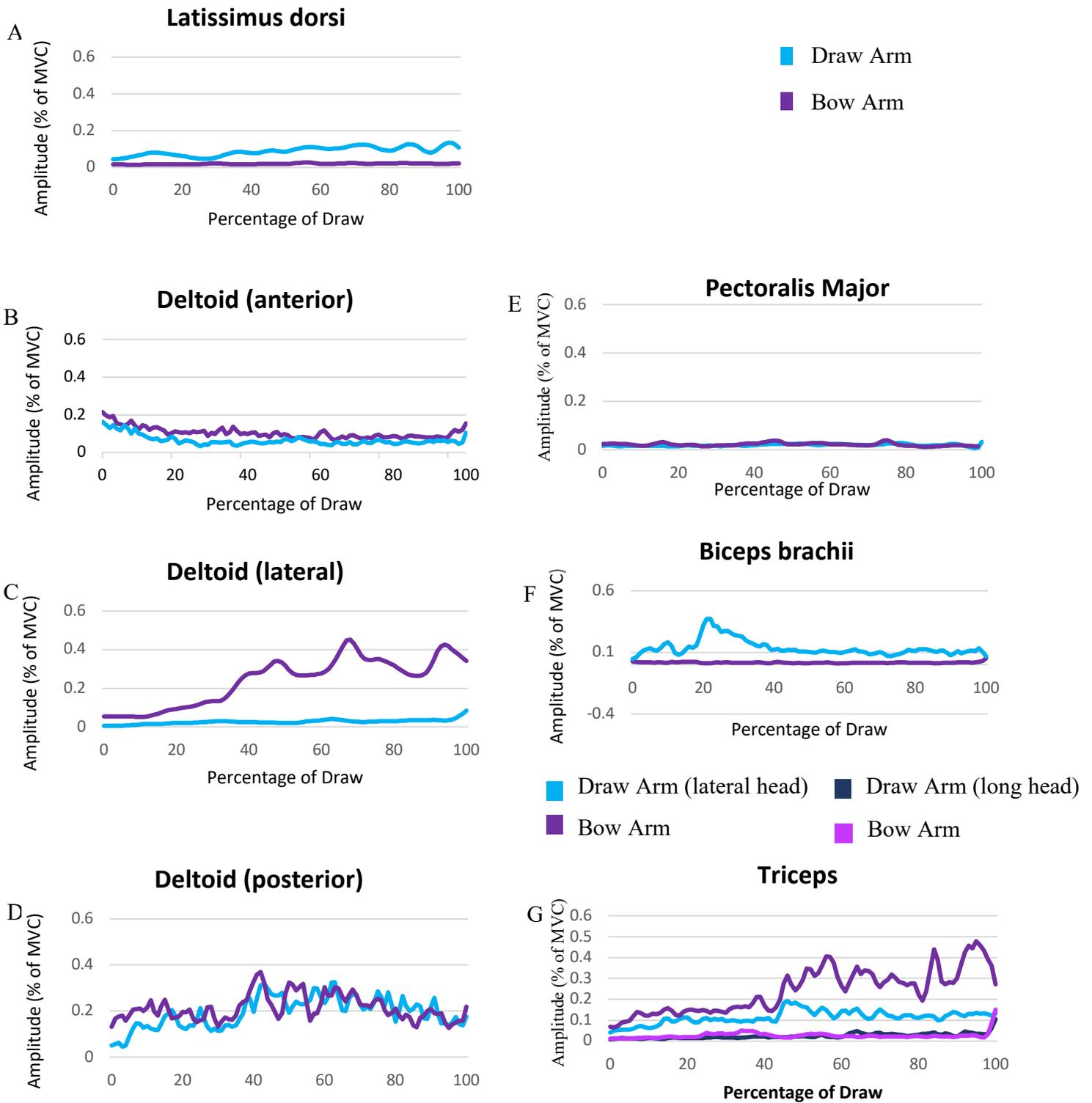


Figure 8: Examples from one trial of normalized EMG data for (A) Latissimus dorsi, (B) Deltoid (anterior), (C) Deltoid (lateral), (D) Deltoid (posterior), (E) Pectoralis major, (F) Biceps brachii, and (G) Triceps (lateral and long head).

Table 7: iEMG (% MVC)

Muscle	Draw Arm		Bow Arm		P-Value	g-Values
	Mean	Std. Deviation	Mean	Std. Deviation		
Pectoralis major	222.3	183.9	306.8	269.83	0.173	-0.29
Latissimus dorsi	669.9	662.5	140.0	125.9	0.008**	0.87
Posterior Deltoid	949.7	519.2	1412.9	932.82	0.139	-0.48
Lateral Deltoid	1020.3	660.3	2152.4	1243.24	0.008**	-0.89
Anterior Deltoid	453.9	331.5	775.1	571.85	0.26	-0.54
Biceps	1268.3	1091.5	396.0	404.56	0.008**	0.83
Triceps (long head)	111.9	89.4	1024.6	1307.12	0.021*	-0.77
Triceps (lateral head)	291.2	233.9	2366.95	2757.69	0.011*	-0.83

*Significance at $p < 0.05$, **Significance at $p < 0.01$; Hedges' g calculation: small effect $g = 0.2$, medium effect $g = 0.5$, large effect $g = 0.8$ or higher.

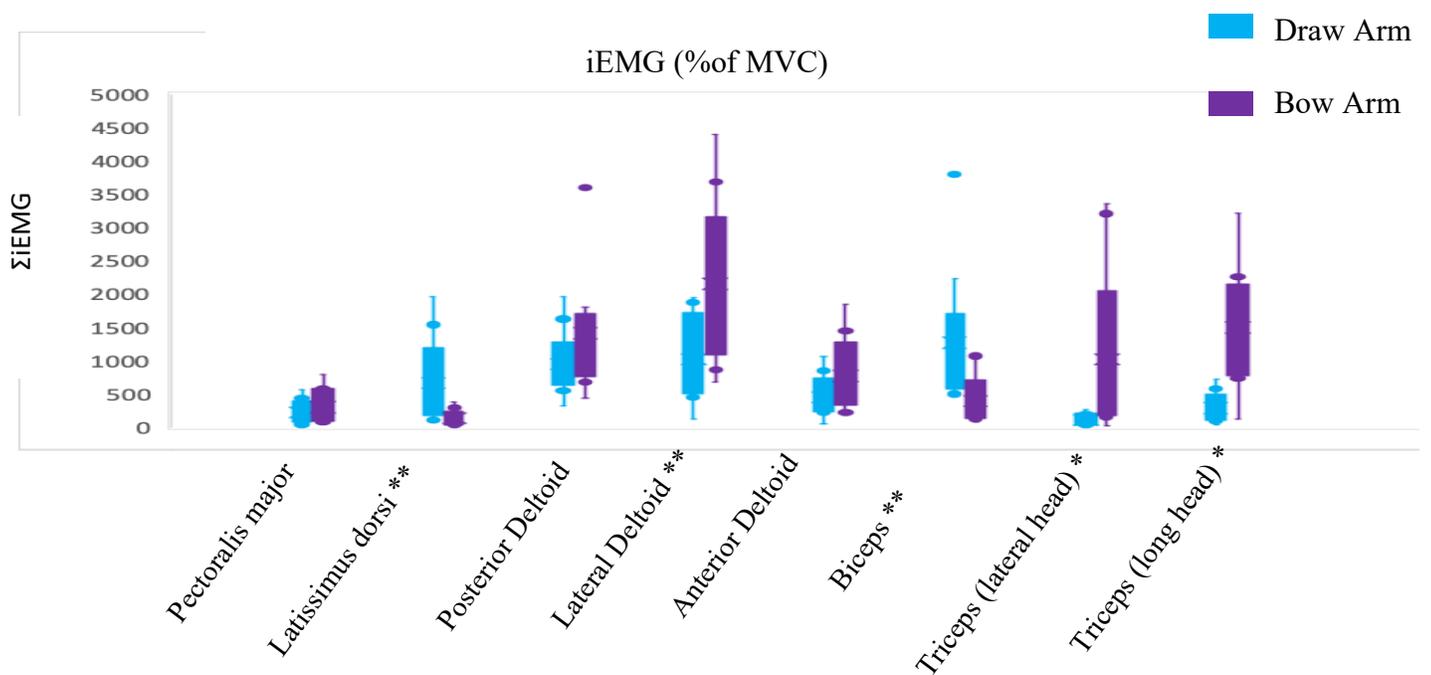


Figure 9: Mean (SD) integrated EMG normalized to % of MVC across all subjects for each muscle.

*Significance at $p < 0.05$; **Significance at $p < 0.01$

Table 8: Peak Muscle Activation

Muscle	Draw Arm		Bow Arm		P-Value	g-Value
	Mean	Std. Deviation	Mean	Std. Deviation		
Pectoralis major	0.08	0.06	0.10	0.09	0.594	-0.19
Latissimus dorsi	0.19	0.19	0.05	0.08	0.038*	0.72
Posterior Deltoid	0.27	0.08	0.36	0.15	0.139	-0.56
Lateral Deltoid	0.26	0.16	0.49	0.18	0.011*	-1.02
Anterior Deltoid	0.14	0.07	0.19	0.09	0.374	-0.42
Biceps	0.48	0.22	0.19	0.11	0.021*	1.25
Triceps (long head)	0.03	0.02	0.31	0.40	0.011*	-0.76
Triceps (lateral head)	0.08	0.05	0.59	0.46	0.011*	-1.21

*Significance at $p < 0.05$, **Significance at $p < 0.01$; Hedges' g calculation: small effect $g = 0.2$, medium effect $g = 0.5$, large effect $g = 0.8$ or higher.

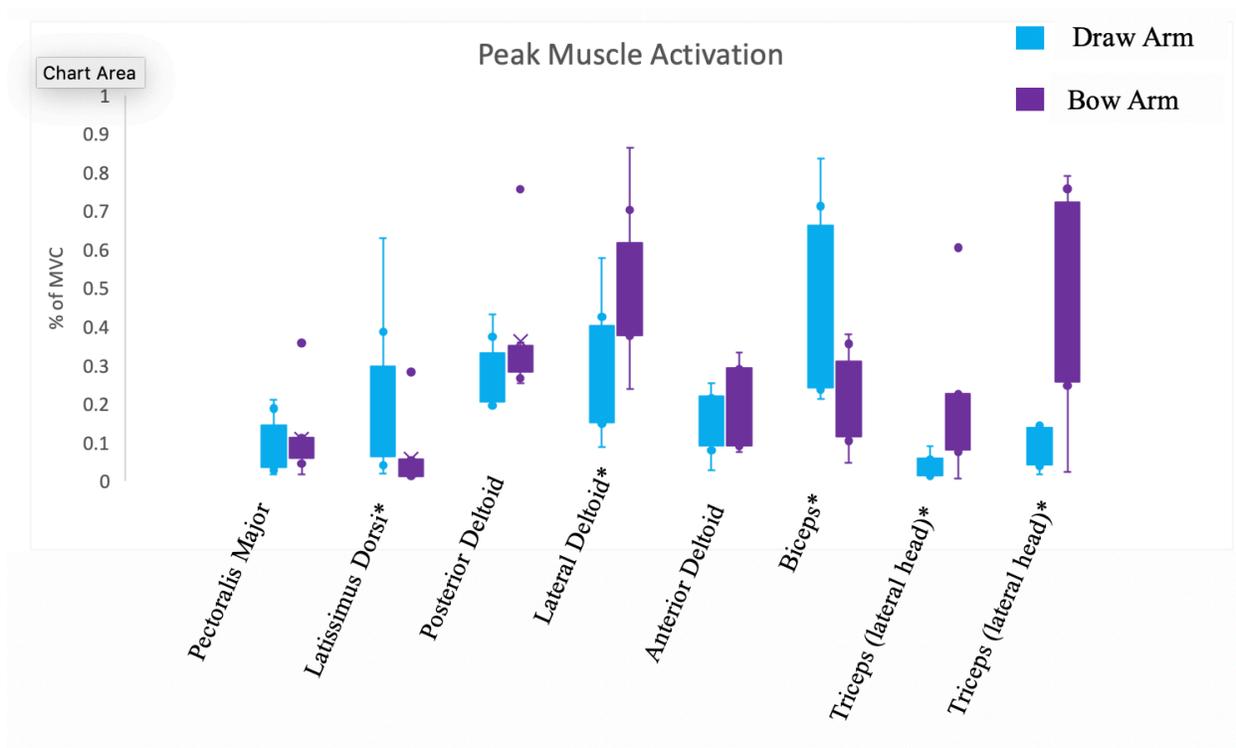


Figure 10: Graph illustrating the differences between draw arm and bow arm for peak EMG values across all subjects for each muscle. In accordance with Wilcoxon Signed-Rank test, *Significance at $p < 0.05$.

CHAPTER 4 DISCUSSION

There were two main purposes of this project, the first was to test the validity of claims connecting archery to decreases in humeral asymmetry from increased mechanical loading being placed on the non-dominant (bow) arm. Decreases in humeral asymmetry observed in the transition between the European Upper Paleolithic and the Mesolithic (Sládek et. al., 2016) coincides with increased archaeological evidence of bow use (Lombard and Phillipson, 2010; Whitman, 2017). Given that archery is a bimanual activity, mechanical loads are placed on both the dominant and non-dominant arms (Peterson, 1998). Therefore, it is assumed that the increased loading placed on the non-dominant bow arm would result in lowered observed humeral asymmetry. The peak muscle values and iEMG results observed on the non-dominant (bow) arm in this study, especially the significant role of the Triceps, would increase non-dominant arm robusticity much more than with the use of unimanual weapons providing experimental validation for these claims.

The range of motion for the shoulder joint, in regard to flexion/extension was not significantly different between the draw and bow arm, which parallels the muscles responsible for those movements. Both the anterior fibers of the Deltoid and Pectorals major muscles flex the arm, while the posterior fibers of the Deltoid extend the arm. There were no significant differences observed for these muscles between arms, which further supports archery's influence on decreasing humeral symmetry.

According to Rhodes and Knüsel (2005), movements involving abduction/adduction and rotation would apply medial-lateral bending to the humerus. Interestingly, the lateral fibers of the Deltoid, which act to abduct the arm were significantly more active in the bow arm than the

draw arm that reached a mean peak value of 49% of individuals MVC. However, the Latissimus dorsi, which counteracts the lateral fibers of the Deltoid by adducting the arm was significantly more active in the draw arm, albeit only reaching mean peak values of 19% of individuals MVC. Therefore, the increased activation of the lateral fibers of the Deltoid in the bow arm should lead to increased lateral bending, underscoring again the increased robusticity of the non-dominant arm during archery.

The second purpose was to test the validity of claims associating archery to specific humeral morphology, more specifically increased anterior-posterior bending in the dominant (draw) arm and increased medial-lateral bending in the non-dominant (bow) arm. The direction of bending or torsion placed on the humerus can be represented as the ratios of second moment areas (I_y/I_x , I_{max}/I_{min}), providing information on the shape of the long bones (Ruff, 2018). According to Rhodes and Knüsel (2005), movements of the upper limb involving flexion/extension result in anterior-posterior bending of the humerus. In archery, the major muscles performing these actions include the Biceps brachii, Brachialis, and Triceps brachii.

Across the eight muscles examined, the largest mean peak amplitude and iEMG were found in the Triceps brachii on the bow arm followed closely by the Biceps brachii on the draw arm. The draw arm is responsible for pulling the bowstring back, which involves greater flexion at the elbow joint than the bow arm that remains relatively straight. Additionally, Brachialis and Brachioradialis muscles were not analyzed in this study but would also be active in the draw arm during the draw phase. Even though the Biceps brachii and Triceps brachii are being activated in different arms, they both result in anterior-posterior bending. The increased muscle activation of the Biceps in the draw arm support claims suggesting greater anterior-

posterior mechanical loading on the draw arm; however, the significantly large muscle activation of the Triceps on the bow arm refute claims of increased medial-lateral directionality in the bow arm.

When comparing the humeri from a group of individuals from Towton, England (15th century) to a comparative group of individuals from Fishergate, England (12th century), Rhodes and Knüsel (2005) concluded that the average left humerus from the Towton sample indicated greater medio-lateral bending resistance. This suggests the left arm had more mechanical loads acting to abduct/adduct or rotate the arm in the Towton sample, which could be explained by the increased bow arm loading involved in archery. During the 14th century in England, every male from the age of 7-17 years old were required by law to practice with a longbow (Rhodes and Knüsel, 2005), which means archery would have been required for individuals from Towton but not from Fishergate.

The results from the present study, however, suggest the bow arm undergoes more antero-posterior mechanical loading based on muscle activation of the Triceps brachii. Although the lateral Deltoid fibers that abduct the arm displayed high iEMG and peak amplitude values in the bow arm, they were not the highest value. The largest iEMG and peak amplitude values for the bow arm arose from the Triceps brachii, which extends the forearm and therefore contributes to antero-posterior bending. It should be taken into consideration that this study was limited to analyzing only a few muscles, and additional muscles contributing to adduction/abduction (i.e. rotator cuff muscles) could play a significant role during archery.

In contrast to previous studies (Ertan et. al., 2005; Ertan, 2009; Simsek et al., 2018), the results from this project do not demonstrate any statistically significant differences between

beginner and experienced archers. Simsek et al., (2018) noted differences between elite archers and non-archers in muscle activation of the draw arm while the bowstring was pulled back. Elite archers tended to use proximal shoulder and axial muscles more than their distal forearm muscles, while non-archers relied more heavily on their distal forearm muscles. These differences could be attributed to technique. More experienced archers, for example, have been trained to use their shoulder and axial muscles more than non-archer, since these muscles are larger, typically producing more power (Peterson, 1998). This muscle pattern was not seen in this study, most likely due to differences in the qualifications used to define skill level. For instance, Simsek et al., (2018) used very specific international scoring methods (FITA) to categorize elite archers. On the other hand, this study defined experienced skill level by whether or not the participant had more or less than eight years of archery experience. This self-reported method only takes how many years of experience an individual has and not how frequently or precisely they practice into consideration. This could lead to a potential circumstance in which an individual reported over eight years of experience while having not used a bow within the last three years. On the contrary, another individual starting archery this year could be training with a club and practicing every day yet be categorized as a beginner.

In regard to archery technique, it remains unclear how different bow types affect muscle activation and therefore skeletal adaptations. For the purpose of consistency in this study, all subjects were required to use a recurve bow. Bradford (1982), present a case study of Medieval England, in which archers used longbows to keep their draw arm steady and apply the weight of their entire body to the bow through the bow arm in order to draw the string. Stirland (2005) hypothesized that this technique placed increased stress on the acromion

process of the scapula, resulting in higher frequencies of os acromiales. Os acromiales is the failure of the acromion process to fuse with the scapula, which typically occurs between the ages of 14-22 years old (Buikstra and Ubelaker, 1994). When the acromion process fuses with the scapula during adolescence, regular pressure placed on the shoulder from practicing with a longbow could increase the frequency of os acromiales, especially if there was a law in place requiring young men to practice.

Stirland (2005) compared the scapula of archers from the *Mary Rose* shipwreck, which sunk in 1545 off the coast of England, to the scapula of individuals from a cemetery in Norwich. Not only were the left humeri of the archers from the *Mary Rose* more robust, but there was also a higher frequency of individuals with os acromiales. Stirland (2005) suggests that individuals who specialized in archery would be more likely to exhibit os acromiales. This raises questions as to how large a role technique and bow type play in skeletal adaptations of archery. Furthermore, what skeletal signatures could archery leave on bones besides the humerus? Supplementary studies comparing different bow types and techniques would be a starting point for answering these questions. Looking closer at the shoulder during archery and the specific muscles that attach to the acromion process (i.e. Trapezius) would provide more information on the mechanical loads, potentially leading to abnormalities such as os acromiales.

Muscle activation for this project was collected using sEMG- a non-invasive method that involves little risk of harm to participants. With that in mind, there are limitations on which muscles can be recorded with sEMG. Barkhaus and Nandedkar (1994) estimate that sEMG is only effective in recording signals ranging from 10-20 mm below the surface of the skin. Therefore, collecting muscle activation data for deeper muscles (i.e. Brachialis) require more

invasive techniques, such as fine-wire electrodes. When sEMG is used with small muscles, it can be difficult to discerning signals from adjacent muscles (Kamen, 2014), limiting the muscles that could be analyzed. Muscle activation signals, for instance, could not be collected for the Brachialis and Brachioradialis using sEMG because the Brachialis is deep to the Biceps brachii and the Brachioradialis is small. Biceps brachii and the Brachioradialis are forearm flexors that are important for archery (Peterson, 1998); additional research that includes data for these muscles would contribute to the overall understanding of the muscle activation involved in archery.

As with many techniques in biomechanics, certain assumptions are required when using motion capturing systems. First and foremost, the body is assumed to be made up of rigid segments. Using a rigid segment model also assumes that each segment has a fixed mass located at the segmental center of mass. This technique also assumes that there are no deformations and that the skin moves congruently with the underlying bone. The results from this study, therefore, only provide information on the activation of muscles and not the muscle force acting on the bone. Applying data from this study to musculoskeletal models that are able to calculate force could provide more accurate representations of the mechanical loading placed on the humerus throughout archery.

CHAPTER 5 CONCLUSION

Homo sapiens' exclusive use of bows are speculated to have cognitive and social implications that aided in the evolutionary success of our species. Transitioning from a tool of survival to representing social status, archery has played a powerful role in human societies throughout time. Skeletal morphological analysis is a common approach used to reconstruct behavior, and a number of studies suggest a connection between decreasing humeral asymmetry and the increased use of archery (Rhodes and Knüsel, 2005; Molnar, 2006; Thomas, 2014). This study tested these claims by comparing peak muscle activation and iEMG of eight muscles associated with archery on the draw and bow arm.

Some muscles (i.e. Pectoralis major, anterior Deltoid, and posterior Deltoid) act symmetrically on both humeri, while most muscle groups (i.e. Biceps brachii, Triceps brachii, Deltoid (lateral), and Latissimus dorsi) are activated asymmetrically on the humerus. On the whole, asymmetrically acting muscle groups acting on separate arms result in similar overall directional bending. For instance, even though the Biceps brachii and the Triceps brachii muscles are more active on the draw arm and bow arm respectively, they both result in anterior-posterior bending of the humerus. Therefore, the overall cross-sectional shape of the bone would be similar for the draw and bow arm. Repeated bow use would undoubtedly induce humeral modification consistent with increased non-dominant arm robusticity, which in turn would lower asymmetry. Findings from this project thus support the hypothesis that the adoption of the bow and arrow results in decreased humeral asymmetry and strengthen morphological approaches to behavioral reconstruction.

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