5-2024

Bilateral Asymmetry in the First Metacarpal: The Influence of Handedness in Humans and Non-Human Primates

Lucyna A. Bowland
University of Arkansas, Fayetteville

Citation

Bowland, L. A. (2024). Bilateral Asymmetry in the First Metacarpal: The Influence of Handedness in Humans and Non-Human Primates. *Graduate Theses and Dissertations* Retrieved from https://scholarworks.uark.edu/etd/5246

Bilateral Asymmetry in the First Metacarpal: The Influence of Handedness in Humans and Non-Human Primates

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Anthropology

by

Lucyna Bowland
University of West Florida
Bachelor of Arts in Anthropology, 2013
University of Colorado, Denver
Master of Arts in Anthropology, 2018

May 2024
University of Arkansas

This dissertation is approved for recommendation to the Graduate Council.

Joseph M. Plavcan, Ph.D.
Dissertation Director

Lucas K. Delezene, Ph.D.
Committee Member

Kathleen S. Paul, Ph.D.
Committee Member

ABSTRACT

Muscle attachment sites (entheses) are often used to infer soft tissue anatomy and reconstruct behaviors within skeletal populations, but there remains a significant debate about whether and to what degree muscle use is accurately reflected in bony morphology. One of the most difficult problems in establishing the relationship between variation in muscle use and entheseal development is the inability to exclude a variety of external factors thought to influence enthesis development, including age, sex, body mass, and activity patterns. One way around this is to take advantage of the fact that humans are handed (preferentially using one hand over another, regardless of task), therefore showing asymmetrical patterns of muscle recruitment in the hands. If a direct relationship between bony morphology and muscle recruitment does exist, one would expect to find strong asymmetry in entheseal development within human hands. Conversely, non-human primates do not exhibit handedness and should not show asymmetrical manual entheseal development. The *m. opponens pollicis* is heavily used in many key grips employed during precision manipulation and is active during flexion, abduction, and adduction during thumb opposition. As such, the muscle insertion on the radial aspect of the first metacarpal is an ideal site for testing if enthesis development is reflective of repetitive muscle recruitment. This study examines if lifetime activity patterns influence bony morphology by comparing opponens pollicis muscle enthesis asymmetry between handed (*Homo sapiens*) and non-handed (*Hylobates lar, Gorilla spp., Macaca fascicularis*) primates to identify if differences exist between dominant and non-dominant hands. Additionally, since thumb flexion and opposition span all three joints, the functional signal from precision pinch and grasps should not be confined to a single bony region. Enthesis asymmetry is therefore hypothesized to serve as a predictor for asymmetry in the proximal and distal ends due to their role in flexion and stabilization during key grips.

This study measured enthesis size between the right and left first metacarpals in a sample (*n*=197 pairs) of adult modern humans and catarrhine primates using both measurements obtained from calipers and from distance-based heat maps generated from 3-D renderings. Results demonstrated right-directional asymmetry in the opponens pollicis enthesis in modern humans and symmetry for non-human primates for enthesis size. However, it demonstrated that increased muscle recruitment alone is not sufficient to induce significant differences between sides; rather, this study established there is a threshold for enthesis size that most individuals do not exceed, and that, to infer muscle use based on enthesis size, the individual must exceed this threshold. Further, this study found that asymmetry in the opponens pollicis enthesis can predict a moderate amount of asymmetry within the proximal and distal ends of the metacarpal, but also found that ligamentous recruitment contributes to asymmetry within those areas. Overall, this study found support for inferring muscle use based on enthesis size but cautions against making large generalizations based on size alone, as further research is needed to better understand the roles that both muscle recruitment frequency and intensity play in enthesis development.

TABLE OF CONTENTS

CHAPTER 1: ENTHESIS FORMATION AND HANDEDNESS IN PRIMATES

INTRODUCTION

An enthesis refers to a site where muscles, tendons, and ligaments attach to bone (Schlecht, 2012). The attachments leave visible scarring on the cortical surfaces of bone in the forms of ridges, tuberosities, and pitting, leading researchers to originally refer to them as "musculoskeletal stress markers" though this term has generally been replaced in favor of the more objective term "enthesis" in recent years (Cashmore and Zakrewski, 2013; Schlecht, 2012; Henderson et al., 2013). They serve to both dissipate stress at the interface between hard and soft tissue (Shaw and Benjamin, 2007), as well as to provide muscle anchorage (Benjamin et al., 2002; Benjamin et al., 2006; Schlecht, 2012).

Use of entheses to infer lifetime activity patterns within skeletal populations is based on the theory of bone functional adaptation, which proposes that increased strain at the insertion site results in increased bone deposition (Ruff et al., 2006). As strain at the muscle insertion site increases, there is a corresponding increase in the number of capillaries supplying the periosteum, which triggers an increase in bone remodeling. The increase in bone remodeling results in increased bone deposition at the site relative to areas under less local strain, resulting in visible bone hypertrophy at the insertion site (Hawkey and Merbs, 1995; Ruff et al., 2006; Schlecht, 2012). This theory has been supported in studies of both cortical and trabecular bone; findings indicate higher levels of bone remodeling in areas of the bones that experience higher loads of mechanical strain versus those under lower levels of strain (Stephens et al., 2016).

BACKGROUND

Diagnosis of activity-induced stress began in the Middle Ages and a proper medical literature began with the Industrial Revolution. Anthropologists first became interested in entheseal development with the first discovery of fossil hominids (Kennedy, 1998). Early studies used enthesis development (termed “musculoskeletal stress markers”) to identify specific patterns of behavior, such as “atlatl elbow” (elbow osteoarthritis associated with throwing) (Angel, 1966) and were mainly focused on how osteoarthritis in the skeleton could be used to infer activity patterns in past populations. The hope was to provide more insight into populations on which there was little demographic or historical evidence and thereby infer specific occupations based on bony remains, such as an identifiable “weaver’s pattern” (Becker, 2020).

One of the earliest publications on entheseal changes comes from Dutour (1986), which used entheseal changes in the elbow and ankle to infer activity patterns in Neolithic Saharan populations (Shrader, 2019). Hawkey and Merbs (1995) introduced the first systematic method for scoring entheseal changes, which soon after became the standard scoring system within the field (Shrader, 2019). However, researchers soon realized the need for further contextual data when interpreting activity patterns from enthesis development. Early studies did not (and sometimes could not) account for confounding variables such as age, sex, hormone levels, or intensity of muscle use when reconstructing activity patterns, which greatly limited the interpretations that could be made based on skeletal remains alone.

Enthesis Types

There are two main types of entheses: fibrous and fibrocartilaginous (Benjamin et al., 2002; 2006). Fibrous entheses insert over large areas on the diaphysis of long bones and either insert directly into the bone or via the periosteum. In contrast, fibrocartilaginous (FC) entheses insert onto the apophyses and epiphyses near joints and lack the periosteum typically found at fibrous enthesis sites. The following section will explore the ways in which entheses are formed and the differences between fibrous and fibrocartilaginous entheses, including their formation and presentation on skeletal remains.

Fibrocartilaginous Entheses

Fibrocartilaginous (FC) entheses insert onto apophyses and epiphyses near joints and generally have much smaller attachment areas than fibrous entheses. The “classic description” of FC entheses describes the sites as consisting of fibrocartilage cells in the zone of uncalcified cartilage, which are arranged in longitudinal rows between parallel bundles of collagen fibers. However, Benjamin et al. (2006) note this arrangement is oftentimes not evident, possibly because the cells reflect the arrangement of the fibroblasts from which they originate (Gao et al., 1996; Benjamin et al., 2006). Most of the background information on the different types of entheses comes from the medical field, which has typically centered on fibrocartilaginous entheses (Benjamin et al., 2002; Shaw and Benjamin, 2007) as they are commonly the site of sports injuries. FC entheses can be important for avulsion fractures, which are common sports injuries at sites such as the Achilles tendon. Enthesis organs can help mitigate avulsion fractures because the tendon is pressing on the bone next to the attachment zone, dissipating stress away from the enthesis itself and reducing risk of injury (Benjamin et al., 2006). The heavier focus on FC within the medical literature has resulted in similar skew within the anthropological literature towards studying FC entheses over fibrous ones.

FC entheses include four types of tissue at the attachment site: calcified cartilage, uncalcified cartilage, tendons, and bone. Collectively, the four tissues are known as an “enthesis organ” and serve the common function of stress dissipation at the insertion site (Benjamin et al., 2002, 2006;

Villotte et al., 2010; Weiss, 2015b). Contact between the tendon/ligament and the bone occurs next to the insertion site, helping to dissipate stress away from the enthesis itself (Benjamin et al., 2006; Shaw and Benjamin, 2007). Fibrocartilage promotes gradual bending of collagen fibers at the insertion site, and the amount of this tissue present at an enthesis site correlates with the degree of change in the angle of insertion relative to the bone (Benjamin and Ralphs, 1998; Benjamin et al., 2006). For example, there is more fibrocartilage at the supraspinatus insertion than at the deltoid, as there is a large change in angle between supraspinatus and the humerus as the arm is abducted through 90 degrees, but little change in the position of the deltoid relative to the humerus (Benjamin and Ralphs, 1998). The calcified and uncalcified fibrocartilage are avascular zones separated by a basophilic line called the tidemark, which serves as the mechanical boundary between hard and soft tissues (Benjamin et al., 2002). The tidemark presents skeletally as a relatively straight line and is the site where soft tissues fall away from the bone during maceration (Benjamin and Ralphs, 1998). It is important to note that while entheses are generally categorized as fibrous or fibrocartilaginous, entheses are not uniform throughout, and most fibrocartilaginous entheses consist of a fibrous and fibrocartilaginous portion, with the fibrous portion generally being at the most distal or superficial part of the enthesis (Benjamin et al., 2006).

Fibrous Entheses

Fibrous entheses insert over large areas on the diaphysis or metaphysis of long bones and insert either directly into the bone or indirectly via the periosteum; however, both connection types occur via a fibrous connective tissue commonly called “Sharpey’s fibers” (Benjamin et al., 2006). Sharpey’s fibers is a broad term used to describe tissues that connect tendons, ligaments, and periosteum to bone, but Sharpey himself was ambiguous in his original description, and the term is not well-defined within the literature (Benjamin et al., 2006). While muscle attachments are often described as occurring via Sharpey's fibers, Benjamin et al. (2006) note that many muscle connections occur without them, such as those on phalanges or other short bones. Understanding muscle attachment specifics is important because the means of attachment, either bony or periosteal, determines the presentation of the insertion site along the bone. Muscles that insert directly into the bone present as rugose markings such as pits or raised ridges, while those that attach via the periosteum are generally smooth in appearance (Schlecht, 2012).

Unlike fibrocartilaginous entheses, fibrous entheses are susceptible to age-related changes, both during ontogeny and into old age. Considerable bone remodeling occurs at fibrous attachment sites through ontogeny, which influences the robusticity and morphology of the attachment site. Entheses essentially act as a pulley mechanism for bones to transmit tensile loads generated by muscle contraction to bony surfaces (Benjamin and Ralphs, 1998), which requires a constant position relative to the joint to preserve the functional integrity of the bone (Figure 1.1). As bone growth occurs, fibrous entheses located on the diaphysis or metaphysis must migrate to maintain a constant position relative to the joint, which means the structural integrity of the enthesis is suboptimal until longitudinal bone growth ceases (Foster et al., 2014). Likewise, as the periosteum disappears with age, periosteal attachments can become bony over time, changing the structure of the attachment site (Benjamin et al., 2006).

Figure 1.1. Flattening of the tendons of fibularis (peroneus) longus (FL) and fibularis (peroneus) brevis (FB) in the region where they wrap around the lateral malleolus. Figure taken from Benjamin and Ralphs, 1998.

Age-related changes at fibrous enthesis attachment sites have led some authors (Robb, 1998) to speculate that fibrous entheses might not be as informative about activity patterns as are their fibrocartilaginous counterparts. Weiss (2015a) tested this by examining both types of entheses in both the upper and lower body in a sample of Amerinds and found that both types of entheses correlate positively with age and body size. However, she cautioned that fibrocartilaginous sites may be more helpful in reconstructing activity patterns because they display greater asymmetry within the upper limbs (suggesting they more accurately reflect asymmetrical limb usage) and are less affected overall by body size as they do not migrate through ontogeny.

Bone Functional Adaptation

Enthesis formation is the result of bone's tendency to remodel in response to increased levels of strain during in vivo muscle recruitment, a process commonly referred to as "bone functional adaptation" (BFA) (Ruff et al., 2006). Wolff's Law is often incorrectly cited as the theoretical basis for BFA (Ruff et al., 2006), but the law refers most strictly to the remodeling of trabecular bone, and so is not directly applicable when talking about cortical bone remodeling (Bertram and Swartz, 1991). BFA is based in mechanostat theory (Frost, 1987) and states that bone remodels in response to increased levels of strain (physical deformation of bone tissue) during lifetime muscle recruitment (Ruff et al., 2006, Stephens et al., 2016). According to BFA, areas of greatest strain will undergo increased levels of bone remodeling, resulting in these areas having greater bone deposition (hypertrophy) than areas under relatively smaller amounts of strain (Figure 1.2).

As bone deposition increases, strain levels are reduced and resorption rates increase, thus returning the bone to the "optimum" strain level (Ruff et al., 2006: 485).

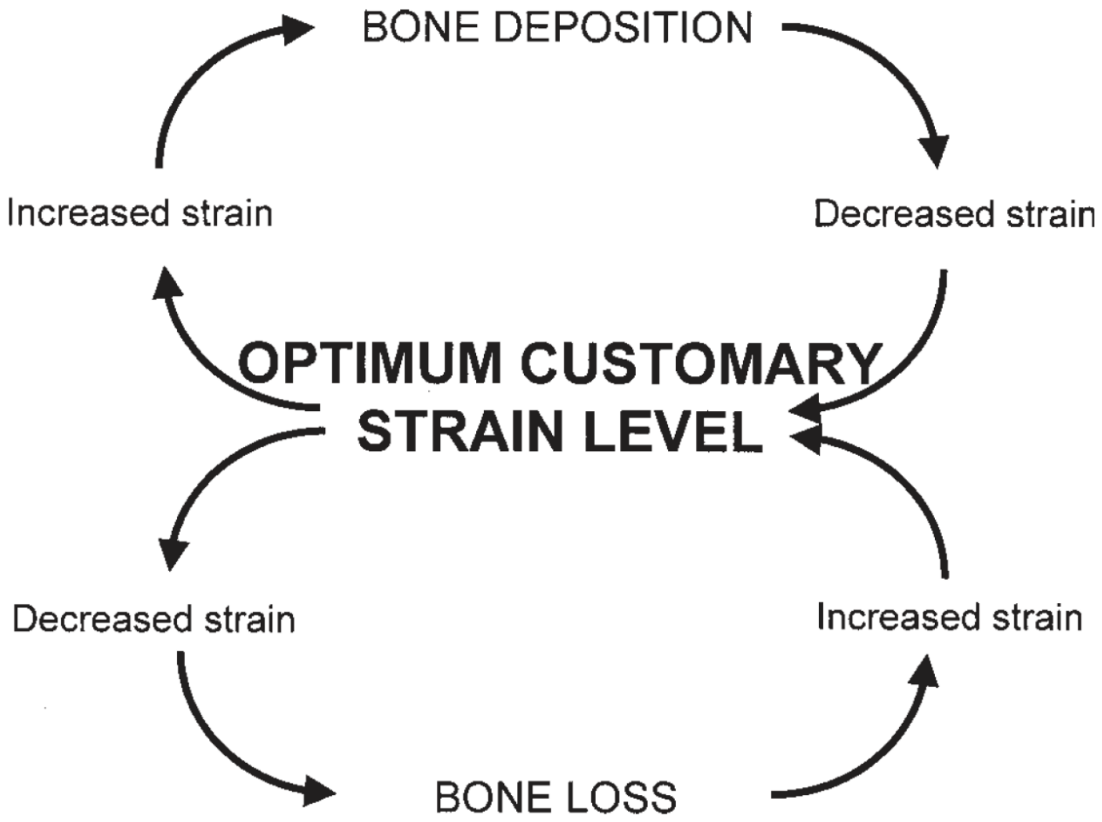

Figure 1.2. A simple feedback model of bone functional adaptation. Figure taken from Ruff et al., 2006 (originally from Lanyon et al., 1982.

Mechanostat Theory

Much of the modern understanding of bone functional adaptation relies on mechanostat theory, first proposed by Frost (1987). His seminal work attempted to explain the underlying mechanisms controlling how bone adapts to changing mechanical stresses which ensure that bone mass can "be over adequate but never inadequate" (Frost, 1987:1). Frost hypothesized that some at-the-time-unknown cellular monitoring system controlled and regulated bone remodeling, and he attempted to explain the underlying process long before much was known about it on a cellular level (the cellular process is still poorly understood today; see [Sims and Gooi, 2008; this paper for more]). Mechanostat theory can be summarized as the following: a "normal" bone undergoes mechanical loading that exceeds some predetermined upper strain limit, which generates a primary signal informing the cells that mechanical overload has occurred, and which then induces a secondary signal to initiate the bone remodeling process. The process only begins when load exceeds the "normal" strain threshold, which Frost refers to as a "setpoint" (Frost, 1987). Only strains above this threshold should induce bone remodeling, meaning that increased bone deposition should solely be the result of abnormal mechanical loading, not everyday use (Lanyon et al., 1982). The goal of mechanostat theory is to explain how the body, as a mechanical unit, can recognize, and subsequently respond to, these abnormal loads to maintain homeostasis.

The above summary of mechanostat theory applies to healthy, adult bone, but Frost (and others before him) recognized that multiple factors, including age and pathology, could affect or even impede this process. Notably, he explained how postmenopausal hormonal changes could negatively affect the bone remodeling process. He hypothesized that increased endocrine levels would falsely register increased bone level setpoints as normal, resulting in a skewed remodeling process because the mechanostat could no longer adequately gauge normal bone deposition levels. As a result, remodeling would be suppressed because the mechanostat falsely perceives there is already an excess of bone at the site, meaning there would be no need for further bone deposition. While Frost was correct in proposing that postmenopausal hormonal changes negatively affect bone remodeling and result in weaker, thinner bones, how this happens is not quite what Frost proposed. Post-menopausal hormone changes do indeed result in generally weaker bones in older women, but it is likely because increased estrogen levels induce apoptosis, limiting the number of osteoblasts laying down new bone, not because the mechanostat is unable to adequately gauge preexisting bone levels (Florencio-Silva et al., 2015).

Bone Formation

Bone is a highly dynamic tissue that is continuously being reformed throughout the lifetime in a cyclical process known as bone remodeling (Hadjidakis and Androulakis, 2006; Sims and Gooi, 2008). The cycle consists of three phases: (1) initiation of bone resorption by osteoclasts; (2) transition from resorption to new bone formation; and (3) bone formation by osteoblasts (Sims and Gooi, 2008; Florencio-Silva et al., 2015). Bone remodeling acts to adjust bone architecture to meet changing mechanical needs while maintaining plasma calcium homeostasis (Hadjidakis and Androulakis, 2006). Disruptions in the bone remodeling process can lead to certain bone diseases such as osteoporosis, where bone resorption exceeds new bone formation, or osteopetrosis, in which genetic mutations inhibit proper osteoclastic resorption and lead to disproportionate accumulations of new bone (Florencio-Silva et al., 2015).

Osteoclasts are large, terminally differentiated multinucleated cells derived from hematopoietic mononuclear cells of the stem cell lineage (Hadjidakis and Androulakis, 2006; Florencio-Silva et al., 2015). They are found on bone surfaces within shallow depressions called

Howship's lacunae and are regulated both locally and systemically by hormones (Hadjidakis and Androulakis, 2006). Osteoblasts are cuboidal bone-forming cells located within the bone matrix. The bone matrix consists of mainly type I collagen fibers and accounts for approximately 90% of the overall organic bone tissue (Hadjidakis and Androulakis, 2006). Osteoblasts are derived from mesenchymal stem cells and comprise roughly 4-6% of bone cells. There are two main steps involved in osteoblast synthetization of bone matrix: (1) deposition of organic matrix and (2) the subsequent mineralization process. After reaching their maturation phase, osteoblasts undergo apoptosis (cell death) or become either bone lining cells or osteocytes (Florencio-Silva et al., 2015). Bone lining cells are flat osteoblasts that cover bone surfaces where neither bone resorption nor formation occurs. While their function is not fully understood, they are known to prevent direct interactions between osteoclasts and bone matrix at times when bone resorption should not occur. Osteocytes are terminally differentiated osteoblasts (Sims and Gooi, 2008) and comprise most bone cells (90-95%) (Florencio-Silva et al., 2015). While osteoclasts and osteoblasts are short-lived (~3 months) (Frost, 1987), osteocytes have a lifespan of up to 25 years. They are located within lacunae surrounded by mineralized bone matrix and their morphology is dependent on bone type. For instance, trabecular bone osteocytes are more rounded than the elongated morphology typical of cortical bone osteocytes (Florencio-Silva et al., 2015).

The process of bone remodeling is the result of collective action from the osteoclasts, osteoblasts, osteocytes, and bone lining cells. Together, they form the anatomical structure known as the basic multicellular unit (BMU), which is only temporarily present during the bone remodeling cycle (Florencio-Silva et al., 2015). It is important to note that while the general process of bone remodeling is known, many of the specific details are still unclear. Theoretically, the amount of bone resorbed by osteoclasts should be equal to the new bone formed by osteoblasts, but since bone formation is dependent on multiple factors which change throughout life, it is possible the theorized 1:1 relationship is only accurate for short periods of time (Sims and Gooi, 2008). Mechanical loading of both human and rat bones has shown an increase in osteocyte apoptosis and correlated bone remodeling, demonstrating a connection between osteocytes and osteoclasts and suggesting that microcracks stimulate osteocyte apoptosis which possibly provides a signal to bone surface cells to initiate resorption at the site. Osteoblasts have been suggested to control osteoclastic activity in multiple ways. The attachment of osteoclasts to the bone surface is dependent on osteoblastic activity, which in part determines the makeup of the bone matrix. Osteoblasts could control how much bone is resorbed and could control osteoblast survival, as several protein factors produced by osteoblasts have been shown to inhibit osteoclast apoptosis (Sims and Gooi, 2008).

After resorption of bone by osteoclasts, osteoblasts must then refill the missing bone, but it remains unclear how osteoblasts know the required amount of new bone formation. Osteocytes are attracted to microdamage in the bone, whether as the result of pathology or mechanical loading. Experimental evidence has shown that microdamage is more likely to induce osteocyte apoptosis, which possibly sends a signal to begin resorption. As bone matrix is resorbed by osteoclasts, growth factors stored within the bone matrix are released, thereby regulating how much bone is laid down. It is unclear whether osteoblasts form new bone as a response to sensing a change in physical dimensions or because they sense a change in the composition of the surface (Sims and Gooi, 2008).

LITERATURE REVIEW

Studies of entheseal development have dominated the bioarcheological literature for decades, where they are used to infer activity patterns within past populations (Hawkey and Merbs, 1995; Munson Chapman, 1997; Weiss, 2007; Lieverse et al., 2009). Research within bioarcheology on entheses has addressed a wide range of topics, including the sexual division of labor (Weiss, 2007), evaluation of proposed habitual activity patterns (Lieverse et al., 2009), and interpersonal relationships among ancient populations (Hawkey, 1998), among others. Enthesis morphology has also been widely used within paleoanthropology, addressing questions relating to shifts in hominin locomotor patterns (Eliot and Jungers, 2000) and hominin tool use (Susman, 1998). Unfortunately, these studies are all hampered by at least two important problems. First, most enthesis morphology studies rely on a presence/absence criterion for scoring entheseal development (Henderson et al., 2013), which is inherently subjective. Studies have recently started to move away from binary methods (Karakostis and Lorenzo, 2016; Karakostis et al., 2017), though no consensus has formed for a standardized method to measure enthesis development. More pressing is the lack of consensus on whether enthesis morphology does in fact reflect activity patterns within an individual's lifetime. Williams-Hatala et al. (2016) for instance, found no relationship between the size of the opponens pollicis enthesis and muscle architecture, though it is important to note their sample consisted of entirely cadaveric, geriatric specimens, whose muscles had likely undergone some degree of atrophy prior to time of death. In contrast, Karakostis et al. (2019) found that repetitive muscle loading is in fact reflected in enthesis size. Still other studies suggest that if there is a relationship between enthesis morphology and muscle size, it is not as linear as once thought, with other factors such as age, weight, and body size likely playing a role as well (Zumwalt, 2006; Weiss, 2007). While the literature on enthesis formation and morphology is vast, spanning decades, there is still no consensus on the correct methodology used to measure the sites, or whether they reflect repetitive muscle loading, a central tenet of every study.

As previously mentioned, entheses (often referred to as “musculoskeletal stress markers” or “MSMs” within bioarcheological studies) are commonly used within bioarcheology (Hawkey and Merbs, 1995; Steen and Lane, 1998; Lieverse et al., 2009; Villotte et al., 2010) to make inferences about lifetime activity patterns but to date, the direct, causal association between muscle activity and entheseal development remains debated and unproven (Schlecht, 2012; Williams-Hatala et al., 2016). The literature is rife with conflicting studies, which have identified several external confounding factors that have been shown to possibly affect enthesis size and morphology, including age, sex, body mass, and hormones. By comparing enthesis morphology within, rather than between, individuals, this study will be able to minimize the impact of most of these factors.

Age

Milella et al. (2012) assessed upper limb enthesis development in an Italian skeletal sample and found that age influenced enthesis development, with older individuals having more marked enthesis morphology than younger ones. Likewise, Mariotti et al. (2007) scored enthesis development in the upper limbs of an Italian skeletal sample and found age was the most important causal factor in enthesis development, more so than even muscle recruitment. Finally, Wilczak (1998) scored upper limb enthesis development and found that older individuals had more marked entheses than younger ones, particularly among women. Wilczak (1998) suggested this is likely due to the influence of increased levels of estrogen in older women. Estrogen induces homeostasis during bone remodeling by inducing apoptosis of both osteoblasts and osteoclasts, thus limiting the rate of bone remodeling in individuals with increased estrogen levels (Florencio-Silva et al., 2015). Ontogeny has also been proposed to influence enthesis development, as some authors argue that juveniles remodel bone more quickly than do older individuals (Mariotti et al., 2007; Foster et al., 2014). Ruff et al. (2006) state that periosteal bone remodels more often in younger individuals, while endosteal bone remodels more often in older individuals. Endosteal bone is not as efficient at counteracting loads as is periosteal bone, and it takes a relatively larger amount of endosteal bone than periosteal bone to counteract strains (Ruff et al., 2006). The slower rate at which endosteal bone remodels in older individuals could possibly cause a negative relationship between muscle recruitment and bone remodeling in older samples.

Sex

Multiple studies (Wilczak, 1998; Weiss, 2007; Lieverse et al., 2009; Santana-Cabrera et al., 2015) have examined the relationship between sex and enthesis formation and generally agree that sex influences enthesis development in some way. However, these influences could be due to differences in activity patterns between men and women (Steen and Lane, 1998; Lieverse et al., 2009; Santana-Cabrera et al., 2015), body size (Weiss, 2007; Goode and Taylor, 2011), or possibly to hormonal differences through ontogeny (Wilczak, 1998; Wiess, 2007; Foster et al., 2014). For example, Lieverse et al. (2009) scored upper limb enthesis development between populations in the Cis-Baikal region of Siberia and found differences between sexes, but also noted these populations likely practiced sexual divisions of labor. Wiess (2007) proposed body size was responsible for differences in enthesis development between sexes, and so regressed enthesis development against estimates of humeral size and found that controlling for size yielded more accurate results. On the other hand, Godde and Taylor (2011) tested the relationship between body size and enthesis development in obese individuals, proposing overweight individuals would use “sit and stand” muscles more frequently than non-obese ones, and so should exhibit more marked enthesis development in those muscles. Their study found no relationship between muscle recruitment and enthesis size for the “sit and stand” muscles, but did note greater remodeling of the tibia, consistent with greater strain in that region because of increased body mass.

The current literature on enthesis formation suggests that multiple factors influence the size and morphology of entheses within individuals. Currently, no study has successfully been able to eliminate these possibly confounding external factors when comparing enthesis morphology, which has greatly hampered the current understanding of how and why enthesis formation occurs. This study will eliminate these factors by comparing enthesis formation within individuals, thus removing the effects of inter-individual variables.

Non-human Primates

Most of the extant literature on enthesis development considers only modern human populations, and it is not clear how comparable enthesis development is between species. Further, most of the literature on enthesis development outside of modern humans has considered only distantly related taxa, likely due to the increased availability of these specimens for experimental studies. Zumwalt (2006) exercised sheep on treadmills for 90 days and measured enthesis development before and after exercise against a control group of unexercised sheep. The study found no relationship between muscle recruitment and enthesis development, though the study’s short time frame might account for these findings (Ruff et al., 2006). Likewise, Wallace et al. (2017) measured enthesis development in exercised versus non-exercised turkeys and found no relationship between the two, though Karakostis et al. (2019) scored enthesis development in rats and found muscle recruitment can reliably be measured using enthesis development for this taxon. However, Ruff et al. (2006) cautioned against the use of distantly related species that do not share similar evolutionary trajectories when comparing bone remodeling processes and noted that comparisons involving more closely related species are less likely to be subject to the possible confounding variables which are introduced by making broad comparisons of distantly related taxa. To date, studies of primate enthesis development have focused solely on humans and non-human hominids (Drapeau, 2008; Milella, 2014; Bucchi et al., 2020a). Drapeau (2008) tested the hypothesis that hand preference would result in asymmetrical recruitment of the upper limbs in a sample of modern humans and great apes, using sites on the lower limbs as a control, and found asymmetries in the upper limbs of all species, which she attributed to possibly being due to hanging from branches with a preferred hand for the great apes. Milella (2014) studied rates of enthesis formation within humans and great apes through ontogeny and found that life history patterns between these taxa do not influence enthesis development. These are the only two studies that measure enthesis morphology within non-human primates, highlighting the need to expand this area of study.

LATERALITY AND HAND PREFERENCE WITHIN NON-HUMAN PRIMATES

Before discussing evidence for hand preference within primates, it is important to clarify terms used within the literature, as there is currently no consensus across studies. Fagot and Vauclair (1991) use the term “handedness” to refer only to low-level tasks, and state it should not be used to refer to a population-wide bias for hand use, instead preferring the term “manual lateralization” to refer to population-wide hand preference. This contrasts with many other studies (McGrew and Marchant, 1997; Cashmore et al., 2008; Cashmore, 2009; Foster et al., 2014) that use “handedness” to refer to a population or species-wide preference for hand use, while “manual lateralization” refers to individual preferences within samples. For the sake of simplicity, this paper will use the term “handedness” to refer to preferential hand usage within primates at the species level.

What is handedness?

Humans display a 90-95% preference for right-hand dominance (Fitch and Braccini, 2013), which has been linked to important evolutionary milestones, including the advent of stone tool use and manufacture and the role that possible visuo-cognitive functional asymmetries played in the rise of manual dexterity within the hominin lineage (Williams-Hatala et al., 2016; Stephens et al., 2016). Outside of modern humans, though, the expression of handedness is poorly understood. There is currently no consensus as to whether population-level handedness is a uniquely human trait, or whether non-human primates (or any other mammal) display any level of handedness across populations (Fitch and Braccini, 2013; Bardo et al., 2015). To date, observational studies have failed to find evidence for hand preference above the individual level within non-human primates (Stephens et al., 2016). Additionally, the literature regarding handedness within non-human primates is inconclusive and plagued by a variety of contradictory findings stemming from inconsistencies around study design, methodological issues, and sample size (McGrew and Marchant, 1997; Chapelain et al., 2012). Most studies on non-human primates contend that while a hand preference might exist for an individual, it is not species-wide, and is dependent upon multiple factors, including the task at hand, complexity of the task, and posture, among others (McGrew and Marchant, 1997; Meunier and Vauclair, 2007; Fitch and Braccini, 2013; Bardo et al., 2015).

Theories for Primate Handedness

While it is still unclear what drove the species-level right-hand preference seen in modern humans, several theories have attempted to account for it, though conclusive data supporting any single theory is currently lacking. Warren (1980) proposed that hand preference within non-human primates is ontogenetic and subconsciously transferred from caretakers to their primate charges, implying it is only present in captive populations of non-human primates. However, hand preference within non-human primates is known to emerge early in ontogeny and follow genealogical lines, suggesting it is not a learned behavior (Rawlins, 1993). MacNeilage (1987) proposed the postural origins theory, which states that an unknown arboreal primate ancestor preferentially grasped branches with the right hand and used the left for simple reaching tasks. After leaving the trees, the right hand was freed for more complex precision tasks, leading to the species-wide preference for right hand dominance present within modern humans. However, little empirical evidence exists to support the either of these theories (Papademetriou et al., 2005). Finally, Fagot and Vauclair (1991) proposed the task complexity theory, which proposes hand preference is driven by the complexity of the task at hand. According to this theory, low-level tasks, such as simple reaching tasks, are not enough to elicit a bias for hand preference, while high-complexity tasks such as the tube task should elicit asymmetrical hand use across a population. The tube task requires a primate to grasp onto a substrate with one hand while reaching into a tube with the other to retrieve an object. The task complexity theory does not state which side (right or left) should be preferentially employed in high-complexity tasks, though it is the theory most often supported by experimental evidence (McGrew and Marchant, 1997, Papademetriou et al., 2005).

HANDEDNESS IN NON-HUMAN PRIMATES

Experimental studies of non-human primate hand preference span decades, but the results from these studies are far from clear (Fagot and Vauclair, 1991; Fagot et al., 1991). Such studies are often hampered by small sample size, lack of standardization, and disagreements over terminology (McGrew and Marchant, 1997; Chapelain et al., 2012; Bardo et al., 2015). Further, studies almost always involve solely captive populations of primates, which could possibly bias the results (McGrew and Marchant, 1997; Cashmore, 2008).

Despite these limitations, clear trends have emerged from these studies. Most studies found that task complexity influences hand preference, with more complex tasks more often eliciting manual lateralization. Studies employing the tube task have found it commonly elicits a preferred hand use, though not always to the same side (Meunier and Vauclair, 2007; Bardo et al., 2015). In a wide review of manual laterality in non-human primates, Fagot and Vauclair (1991) found that non-human primates were only lateralized for high-level complexity tasks; low-level tasks elicited symmetrical distribution of hand preferences across groups but did not support a population-wide bias for either side. When a preference for hand usage occurs, it most often favors the left hand, in contrast to the right-hand usage most often seen in modern humans (Meunier and Vauclair, 2007; Cashmore, 2008; Bardo et al., 2015). It is also important to note that even when primates preferentially use a hand for a given task, the frequency does not exceed 65%, far from the 90-95% right-hand bias seen in modern humans (Fitch and Braccini, 2013).

Meta-analyses of the literature have likewise failed to find a clear signal for primate hand-use preference. Papademetriou et al. (2005) performed a meta-analysis to evaluate current evidence supporting the postural origins theory (MacNeilage et al., 1987). They found more articles that reported no population-level bias than a directional bias and no difference between the number of studies that reported a left or right bias. However, using a review model that incorporated individual variability rather than error term, they found a left-hand bias for reaching tasks, most noticeably in cercopithecids. This finding contrasts with what is expected according to the task complexity theory from Fagot and Vauclair (1991). Marchant and McGrew (1997) conducted a meta-analysis of the literature regarding non-human primate hand preference and failed to find any evidence supporting human-like hand preference within non-human primates. They ranked handedness on a scale of 1-5, with level 1 being ambi-preferent and level 5 being population-level hand preference; level 1 results were most common for cercopithecids, while level 5 was reserved for "human-like handedness" (McGrew and Marchant, 1997: 201). However, these studies often found conflicting results even when considering hand use within populations. For instance, Japanese macaques (*Macaca fuscata*) on Koshima island were unlateralized when performing low-complexity tasks such as carrying sweet potatoes for washing or picking up objects from the ground (Watanbe and Kawai, 1993). However, the same study found level 2 (significantly lateralized, but the direction does not depart from randomness) lateralization with more complex tasks such as carrying handfuls of wheat grains and extractive foraging. Overall, the study found increased individual laterality with increased demands of the motor skills required to handle the objects, but population level results only emerged when a haptic, rather than visual, stimulation was imposed.

Finally, some studies proposed that posture influences hand preference and argued that a bipedal posture is more likely to elicit a lateralized hand preference. However, the results across studies are likewise ambiguous. Bipedal posture can enhance lateralization of hand preference relative to sitting or standing quadrupedally or tripedally for some studies, but this effect is not universal; rhesus monkeys were significantly lateralized to the left when standing quadrupedally but not when in a bipedal posture (Westergaard et al., 1998). The current literature suggests that handedness in non-human primates appears to be both population and task dependent, and it is not comparable to that of modern humans.

***Macaca* spp. Hand Use**

Despite decades of research (Helmkamp and Falk, 1990; Fagot and Vauclair, 1991; Fagot et al., 1991; Schmitt et al., 2008) on hand preference within *Macaca* spp., no study has found evidence for population or species-wide hand preference within the taxon (McGrew and Marchant, 1997). As mentioned previously, Fagot and Vauclair (1991) theorized that different levels of task complexity should elicit differential hand use within primates, with complex, high-level tasks triggering asymmetrical hand use, while simple, low-level tasks should not.

To this end, studies have mainly included experiments that force subjects to perform both types of tasks when studying hand preference within the non-human primates. Schmitt et al. (2008) studied hand preference in unimanual and bimanual tasks for 21 Barbary macaques (*Macaca sylvanus*). They found no hand preference for the low-complexity unimanual task (simple reaching) or for the high-complexity, bimanual task (opening a box/tube task, aka the “TUBE task”) at the population level, stating they did not find evidence that task complexity influences hand use preference. Likewise, Regaiolli et a. (2016) failed to find evidence for hand preference within a population of pig-tailed macaques (*Macaca nemestrina*) tasked with performing a series of high and low-level tasks, instead finding a nearly equal distribution of right and left-hand preferent individuals across both sets of tasks. In contrast, Fagot et al. (1991) investigated hand use preferences in a large group of rhesus monkeys (*Macaca mulatta*) using a haptic discrimination task that required subjects to adopt a hanging posture while reaching for items. This type of task is considered “high complexity” because one hand is used as a support while the other is used for reaching. Subjects maintained a three-point vertical posture while reaching into an opaque box to haptically discriminate between peanuts and rocks. The study found a left-hand preference for reaching and noted neither age nor sex significantly influenced hand use preferences. Finally, Westergaard et al. (2001) studied hand preference across three species of adult and juvenile macaques (*M. mulatta*, *M. nemestrina*, and *M. fascicularis*) by inducing quadrupedal reaching for food thrown into a corral. They found a left-hand bias for both adult and juvenile *M. mulatta*, no bias for either group of *M. fascicularis*, and no bias in juvenile *M. nemestrina*, but a left-hand bias within adults within that taxon.

***Gorilla* spp. hand use**

Researchers have extensively studied hand use preferences within both captive and wild populations of gorillas, but the data generated from these studies is far from conclusive. Early studies (Fischer et al., 1982) reported right-hand use bias in gorillas, but were constrained by small samples, limiting the power of the analysis. Shafer (1987) demonstrated a right-hand bias over a large range of tasks, while Heestand (1987) found a non-significant right-hand bias for pick-up food tasks and lead arm during terrestrial locomotion. In contrast, Fagot and Vauclair (1988) found a significant left-hand bias during a high-complexity food-retrieval task.

Hopkins et al. (2003) found a right-hand preference for the TUBE task in a sample of captive gorillas (*n*=33) but noted the number did not reach significance. Byrne and Byrne (1991) studied hand use during feeding in wild mountain gorillas (*n*=44) and found no population level preference across five sets of tasks, though they did note a slight preference (64%) for some of the tasks recorded (processing of three leafy foods [nettle, gallium, and thistle]), but ultimately found no preference when processing stem foods. They concluded that one must specify a leaf-hand preference and a stem-hand preference, rather than a simple overall hand preference. They did not find any evidence of population-level hand preference; though when a preference did exist, they note it is to hold the object (i.e., stem) in the left hand while using the right for finer manipulation movements.

Likewise, Byrne and Byrne (2001a) studied hand use at the population level in wild populations of gorillas and found a right-hand bias for fine manipulation and a left-hand bias for simple reaching tasks. This is in line with the task complexity theory proposed by Fagot and Vauclair (1991). In a meta-analysis of hand use within great apes, Hopkins et al. (2011) found gorillas had the highest handedness index (HI) score (indicating a hand preference) of any of the great apes. They defined HI as (R-L)/(R+L). Using this metric, they reported a significant number (p=0.002) of right-handed gorillas when performing the TUBE task based on both pooled data from Hopkins et al. (2003 and 2011[p=0.001]), with a stronger preference in the latter group. Finally, in a study of food processing in western lowland gorillas (*G. gorilla*) Parnell (2001) found that 11 of 33 gorillas showed a hand preference above chance when consuming two separate kinds of plants, but directionality did not deviate significantly from chance.

Some authors (Cashmore et al., 2008; Cashmore, 2009; Uomini, 2009) have proposed that any right-hand bias found within captive populations is simply an artifact of right-hand usage within the human caretakers present (which is in line with the theory proposed by Warren (1980) that hand preference is entirely ontogenetic). However, the highest number of captive-born apes within the study by Hopkins et al. (2011) were the orangutans (*Pongo* spp.), which exhibited the lowest levels of hand preference. This finding does not support the theory that hand preference within captive populations is only a learned behavior from right-handed caretakers.

Gorilla spp. Hand Anatomy

Gorilla spp. hands are very similar to modern humans in both hand proportions (Almecjia et al., 2015) and musculature (Diogo et al., 2012). Hand musculature within apes is phylogenetically conserved, meaning there is little variation within the muscles of the primate hand and forearm (Diogo et al., 2012). Like all primates (except for callitrichids, in which the muscle was secondarily lost), *Gorilla* spp. possess an opponens pollicis muscle and lack a separate muscle belly for the flexor pollicis longus (though, as previously mentioned, *Hylobates* also possess a distinct FPL) (Diogo and Wood, 2012; Lemelin and Diogo, 2016). Additionally, they lack the intrinsic muscle variably referred to as the "adductor pollicis accessorius" or the "interosseous/volar muscle of Henle" (Diogo and Wood, 2012), though it is important to note this muscle has been found in several primate taxa in varying frequencies; as Diogo et al. (2012) point out, it is not the muscles themselves that make human hands autapomorphic, but rather the combination of muscles that together constitute an autapomorphic state for *H. sapiens*.

Until recently, most scholars believed the last common ancestor (LCA) of humans and chimpanzees possessed a very "chimp-like" hand, i.e., long digits and a relatively short thumb, implying the longer thumb and shorter digits seen in humans and gorillas constitute a derived condition for hand proportions. However, recent research has shown that *Pan* hand proportions are in fact derived, and humans and *Gorilla* instead exhibit a more plesiomorphic condition relative to other extant primate taxa (Tocheri et al. 2008; Almecija et al., 2015). Like humans, gorillas possess relatively robust thumbs (Bowland et al., 2021) and shorter digits, in contrast to the longer digits and shorter thumbs seen in many other primates. This relationship holds when measuring hand proportion as either intrinsic (the ratio of the thumb to the fourth digit) or extrinsic (the ratio of thumb to digits standardized for body size) (Almecjia et al., 2015).

Within modern humans and *Gorilla* spp., the shift in hand proportions appears to be a result of digital length reduction, rather than a significant lengthening of the thumb, relative to the "moderate" digital length inferred for the LCA (Almecija et al., 2015: 6). Compared to other great apes, *Gorilla* possess longer thumbs relative to digit length, but this is more a consequence of their shortened digit lengths, rather than them possessing a truly long first digit. For instance, their thumbs are shorter than in *Pan*, but *Pan* possesses highly derived, likely specialized digits that result in their thumbs being relatively shorter.

While early work on primate hands (Napier, 1962) suggested the ability to form certain grip types was one of the things that "made us human" subsequent work has shown that most grip types employed by humans are also available to many other primate taxa (Marzke, 1997, 2013). This includes *Gorilla* spp., in which wild populations have been documented (Neufuss et al., 2019) employing multiple grip types, including the power grips once thought to be unique to humans. However, while the thumb of *Gorilla* spp. is relatively long compared to other great apes, it is not long enough to produce a powerful enough grip to resist opposing forces (Almecija et al., 2015; Neufuss et al., 2019), i.e., the power precision grip that is likely unique to *H. sapiens* (see Marzke, 2013 for more on this).

***Gorilla* Feeding Habits**

Gorilla spp. use their hands to process a wide variety of foods, but feeding preferences vary between species and even within populations of the same species, likely partially at least because of the environmental differences between populations (Neufuss et al., 2019).

Mountain Gorillas

Mountain gorillas (*Gorilla beringei*) engage in manual food processing more often than western lowland gorillas (*Gorilla gorilla*) because they are herbivorous (Doran and MacNeilage, 1998); their diet largely consists of stems, leaves, and pith, which require more manual processing than the food items typically consumed by lowland gorillas (Neufuss et al., 2019). In addition, their diet is relatively constant and less dependent on seasonality than lowland gorillas (Doran and MacNeilage, 1998).

The feeding preferences of *G. beringei* have been extensively documented for decades, particularly within the Virunga Mountain populations (Byrne and Byrne, 1991), and recent work has further documented feeding preferences within the Bwindi Mountain populations as well (Neufuss, 2017; Neufuss et al., 2019). Both Bwindi and Virunga Mountain gorilla populations commonly eat herbaceous foods such as leaves, thistles, and stems that require extensive processing before consumption, though it is important to note that plant diversity is high between the two populations due to altitude differences. Both populations regularly consume thistle plants (though the frequency is higher in the Virunga population) which require extensive processing to remove the physical defenses prior to consumption. Processing leaves of the thistle *Cardus nyassanus* by the Virunga population is considered the most complex feeding task and requires multiple stages using varying degrees of manual dexterity throughout (Byrne and Byrne, 1991; Neufuss et al., 2019). Likewise, Bwindi Mountain gorillas consume a large variety of fibrous foods such as vines and stems that are encased in woody or herbaceous coverings and that require complex processing for consumption (Neufuss et al., 2019). Both populations are known (Byrne and Byrne, 1991; Byrne et al., 2001b; Neufuss et al., 2019) to use a variety of grip types when processing foods, including the precision and power grips.

Lowland Gorillas

Lowland gorillas (*Gorilla gorilla*) have a much more varied and seasonal diet than mountain gorillas. Doran and MacNeilage (1998) report that, across six sites, multiple populations of lowland gorillas consumed more than 90 species of fruits at each site. Fruit is considered a primary resource consumed during times of resource abundance. In addition to fruit, lowland gorillas consume both terrestrial and aquatic herbaceous vegetation, though it is likely aquatic herbaceous vegetation makes up much less of the diet than does terrestrial vegetation. As noted previously, fruit consumption constitutes the largest proportion of lowland gorilla diets, and low-quality terrestrial herbaceous vegetation is mostly consumed during times of resource scarcity.

***Hylobates* spp. Hand Use**

Hylobatids are small-bodied Asian apes belonging to the genera *Hylobates, Symphalangus*, *Nomascus*, and *Hoolock.* Members of the family Hylobatidae inhabit rainforests of South and Southeast Asia. Hylobatids practice brachiation, a highly specialized form of suspensory locomotion in which the upper limbs are used to move beneath a substrate without the aid of the lower limbs (Prime, 2014). During brachiation they employ a hook grip, in which the middle phalanges contact the top of the horizontal support structure, and the metacarpophalangeal joint is flexed (Prime and Ford, 2016; Patel et al., 2020). They possess the second longest thumb, absolutely, among primates, though it is relatively short due to the elongation of the other digits (Almecija et al., 2015). They also have a ball and socket pollical carpometacarpal joint that allows for a very wide range of motion through the joint (e.g., they are able to fully oppose the palmar surface of the index finger) but which also limits the amount of stabilization possible through the trapeziometacarpal joint and which makes the joint, “inherently less stable” than the saddle-shaped trapeziometacarpal joint morphology present in most other primates (Van Leeuwen, 2022:141). Additionally, the thumb is set more proximally within the hand, creating a deep cleft within the first and second digit that, in combination with the joint morphology, for the large degree of abduction at the joint (Kivell et al., 2022), possibly limits interference of the thumb during brachiation (Van Leeuwen et al., 2022).

Diogo and Wood (2012) reported that hylobatids engage their thumb during locomotion, but this is not common, and generally only occurs when moving along vertical substrates (Prime and Ford, 2016). In addition, Patel et al. (2020) reported that the first metacarpal of hylobatids is relatively weaker than the first metatarsal in several dimensions of midshaft robusticity, implying it is not well adapted for bearing large loads, such as those incurred during locomotion. This would support previous research that reported that the first metacarpal is only rarely recruited during hylobatid locomotion (Prime, 2014; Prime and Ford, 2016). Hylobatids often use their thumbs for "sensory tactile actions" such as exploratory probing or picking up objects; this contrasts with other apes, that generally reserve the index finger for such tasks (Prime and Ford, 2016: 284). This is interesting considering that the skin on hylobatid thumbs is thinner than their other fingers (Lorenz, 1974) and that they possess a separate flexor pollicis longus muscle (Diogo and Wood, 2012), both of which suggest adaptations for fine precision grasping.

Despite the apparent morphological adaptations for enhanced manual dexterity within hylobatids, their hand usage outside of locomotion is understudied and poorly understood (Prime, 2014), but arboreal apes are a key group for lateralization studies because they often support their body mass with one or both hands, making them ideal to test the postural origins theory (MacNeilage et al., 1987; Morino, 2011). Most of the data on hylobatid hand usage comes from studies of captive populations, and the data from these studies does not offer a clear picture of hand preference. For instance, Stafford et al. (1990) studied lateralization within a group of captive gibbons looking at both leading limb during brachiation and food reaching. The study found a right-hand preference for both tasks within adult females, but no preference for either task for males, regardless of age. Conversely, Morino (2011) studied hand preference in a population of wild siamangs during a complex reaching task: participants were made to reach into a tree to cup water with one hand while supporting the body with the opposite hand. The study found a left-hand preference for reaching at the population level. In a later study of captive hylobatid (*Symphalangus syndatylus*, *Hylobates* spp., and *Nomascus leucogenys*) hand use during the TUBE task, Morino et al. (2017) found both an individual (78%) and population-level (69%) preference for left-hand use, though when further broken down by species, gibbon (*Hylobates* spp.) hand-use preference did not differ from simple chance. Finally, Prime and Ford (2016) studied hand manipulation preferences in two populations of captive hylobatids (*H. lar* and *N. leucogenys*) using a large variety of objects of different material properties to assess how the objects were handled by the individuals (finger-only, thumb-only, and thumb and finger). They reported that hylobatids might engage the thumb for grasping objects when engaged in brachiation, but there is no evidence this is done preferentially with regards to hand choice. Additionally, they reported no preference for hand usage at the population level, and only a very slight (possibly only an artifact of sampling bias) preference for left-hand use within individuals, but ultimately concluded there was no evidence for preference for hand use within hylobatids. The available literature on hylobatid hand use offers no compelling evidence that hylobatids engage in any level of preferential hand usage that would result in asymmetrical manual enthesis development.

***Hylobates* spp. Feeding Practices**

Hylobatids are terminal branch feeders, meaning they hang in the tree canopy and extend their reach to pluck food items from terminal branches, allowing them to exploit resources not available to larger apes and quadrupedal monkeys (Elder, 2009; Prime and Ford, 2016). Within wild populations, they are entirely arboreal feeders (Prime and Ford, 2016). In general, they are ripe-fruit specialists that use figs as fallback resources, though some populations of *H. lar* have been observed to consume figs even when there are other, more nutritionally superior fruits available (Elder, 2009). In addition, they often supplement their frugivorous diet with leaves, flowers, insects, and even unripe fruits at times. In a wide sample of hylobatids (*H. lar*, *Symphalangus*, and *Hoolock*), Elder (2009) found 60% of them were frugivorous, with leaves and figs comprising another 28 and 26%, respectively, and 7% insects.

The unique structure of the hylobatid thumb is likely a consequence of their terminal branch feeding, which involves reaching for food objects while suspended from the tree canopy. Hylobatid locomotion involves rapid hand-over-hand movements where the fingers grip and release branches in quickfire movements. As such, an adaptation to maintaining a hold on small objects during brachiation and foraging is essential. During foraging bouts, hylobatids use their thumbs to pluck food objects from terminal branches while keeping their long fingers wrapped around branches in a hook-like grip. The unique structure of the thumb (i.e., long, with a deep cleft between the first and second digits, and a carpometacarpal joint that allows for increased movement at the joint) allows hylobatids to hold a small food item firmly next to the palm, while keeping the long fingers free for travel (Prime and Ford, 2016).

METHODS REVIEW

Numeric Data Collection

Traditional bioarcheological studies generally favor qualitative methods, in which entheses are scored macroscopically on a presence/absence continuum, allowing for low-cost, easily accessible research projects (Weiss, 2015b). Hawkey and Merb's (1995) seminal method measured entheseal expression on a scale of 0-6, where 0 was absent and 6 was the most rugose or developed. Their method is still heavily used and cited within the literature (Mariotti et al., 2007; Weiss, 2007; Drapaeu, 2008; Milella et al., 2012; Niinimaki, 2012), though it does not differentiate between entheses and enthesopathies or between different types of entheses (fibrous or fibrocartilaginous). Other researchers have attempted to address these issues when developing further scalar recording methods. Mariotti et al. (2007:293) differentiated between enthesopathies (markers resulting from pathological abnormalities) and robusticity of the marker (resulting from muscle recruitment) when they divided enthesis robusticty into five classes, with 0 being "practically absent" and 4 being "strongly developed." However, they admitted this method is also not without limitations, as it attempts to place continuous variation within discrete categories, complicating inter-observer methods and rendering category placements "largely arbitrary" (Mariotti et al., 2007: 293). Subsequent studies (Villotte et al., 2010; Henderson et al., 2013) highlighted the need to consider the nature of entheses: whether the muscle in question has a fibrocartilaginous or fibrous attachment, as this influences the morphology of the site.

Villotte et al. (2010) noted that fibrous and fibrocartilaginous entheses present differently on bones and argued that measuring both types of entheses on the same ordinal scale obscured data and limited accuracy of the results. To combat this, they proposed measuring entheses on a binary scale denoting presence or absence of change. Under this method, researchers are most concerned with whether a change in enthesis expression has occurred, rather than the direction or magnitude of change. However, this binary method tends to obscure subtleties in enthesis expression. Additionally, both types of data analysis rely on non-parametric tests that generally have lower statistical power than parametric tests (Weiss, 2015b), and both have very high rates of inter-observer error (Davis, 2013); in some cases, the chances of two researchers scoring an enthesis as the same category was little better than chance (0.45) (Henderson et al., 2013).

Studies have recently moved away from these subjective studies, but there is still a lack of consensus as to the best methodology for quantifying entheseal size and morphology (Villotte et al., 2010; Davis, 2013; Weiss, 2015b).

Various researchers have attempted to develop more quantitative methods for studying entheseal expression considering the limitations of qualitative data collection methods. Henderson (2013) placed chords across the x and y axis of an enthesis and measured its size along the chords using calipers. Several authors (Wilczak, 1998; Nolte and Wilczak, 2013) have also used chalk to outline the enthesis to better delineate its boundaries before taking linear caliper measurements. Maki and Trinkaus (2011) and Williams-Hatala et al. (2016) measured enthesis size in the first metacarpal by regressing the maximum length of the metacarpal against radial breadth taken at 65% of maximum length, which they argued captured the broadest portion of the opponens pollicis enthesis. While these methods are more reliable than scalar or binary methods (with intra-observer error rates ranging from only 15-33%), they still have relatively high inter- and intra-observer error rates, and critics (i.e., Weiss, 2015b) note they do not account for the 3-dimensional (3D) nature of entheseal morphology.

3D Data Collection

Recently, studies have attempted to develop 3D methods for measuring enthesis morphology to address previous concerns. Zumwalt (2006) used GIS software to measure the change from a flat surface on 3D scans of the area in question. Wallace et al. (2017) isolated enthesis area from micro-CT scans before using topographic surface analyses to holistically measure the enthesis area. Most pertinent to this dissertation, Karakostis and Lorenzo (2016) developed a system specifically for measuring manual enthesis morphology. Their method consisted of scanning the bones and using software to delineate the enthesis of interest before isolating it from the rest of the model, leaving only the enthesis for subsequent measurements. This method was further used in Karakostis et al. (2017; 2019) to quantify what they termed "synergistic" muscle groups which they analyzed using multivariate statistical analyses. These methods tend to have much lower error rates than qualitative methods since they do not rely on subjective observations of enthesis expression (Mariotti et al., 2007) or on being accurately able to teach the methods to future researchers (Weiss, 2015b).

Confounding Factors

However, while there is no debate that entheses are present at soft tissue attachment sites and that they likely are at least in part formed as a response to mechanical loading, there is debate as to how much of their etiology and formation is the result of soft tissue recruitment and how much is a result of systemic factors such as age, activity level, and sex (Foster et al., 2014). Indeed, it is accepted that not all strains induce bone remodeling equally (Ruff et al., 2006). Bone is more adaptive to dynamic than static loads and the remodeling response of bone is not constant but instead varies according to skeletal location. Sex and body size also influence the rate of bone remodeling and subsequent levels of bone deposition. Subadult bone is more adaptive to strain than bone in older individuals (Ruff et al., 2006), because subadult bone deposition occurs via periosteal bone remodeling, while later in life, bone resorption occurs via endosteal bone deposition. Endosteal bone is not as efficient at counteracting loads as is periosteal bone, and it takes a relatively larger amount of endosteal bone than periosteal bone to counteract strains. The slower rate at which endosteal bone remodels in older individuals could possibly induce a negative relationship between muscle recruitment and bone remodeling in older samples (Ruff et al., 2006).

There are also sex-based differences in bone remodeling caused by different levels of estrogen and androgen, which differentially affect bone remodeling rates. Estrogen maintains bone homeostasis by inhibiting osteoblast and osteocyte apoptosis, thus limiting the rate of bone remodeling in individuals with increased estrogen levels (Florencio-Silva et al., 2015). Pre-pubescent females exhibit greater endosteal apposition and lower periosteal bone apposition, but following menopause, this trend reverses, and females instead exhibit greater rates of endosteal deposition and increased rates of periosteal deposition (Foster et al., 2014). Additionally, multiple studies (Wilczak, 1998; Weiss, 2007; Lieverse et al., 2009; Santana-Cabrera et al., 2015) have examined the relationship between sex and enthesis formation and generally agree that sex influences enthesis development in some way. However, these influences could be due to differences in activity patterns between men and women (Steen and Lane, 1998; Lieverse et al., 2009; Santana-Cabrera et al., 2015), body size (Weiss, 2007; Godde and Taylor, 2011), or possibly to hormonal differences through ontogeny (Wilczak, 1998; Wiess, 2007; Foster et al., 2014).

Lieverse et al. (2009) scored upper limb enthesis development between populations in the Cis-Baikal region of Siberia and found differences between sexes, but also noted these populations likely practiced sexual divisions of labor. Wiess (2007) proposed body size was responsible for differences in enthesis development between sexes, and so regressed enthesis development against body size by aggregating several measurements from the humerus and found that controlling for body size yielded more accurate results. On the other hand, Godde and Taylor (2011) tested the relationship between body size and enthesis development in obese individuals, proposing overweight individuals would use “sit and stand” muscles more frequently than non-obese ones, and so should exhibit more marked enthesis development in those muscles.

Their study found no relationship between muscle recruitment and enthesis size for the "sit and stand" muscles, but did note greater remodeling of the tibia, consistent with greater strain in that region because of increased body mass.

CURRENT STUDY

The *m. opponens pollicis* inserts onto the first metacarpal and is responsible for moving the thumb away from and towards the hand and is important in grip (Figure 1.3).

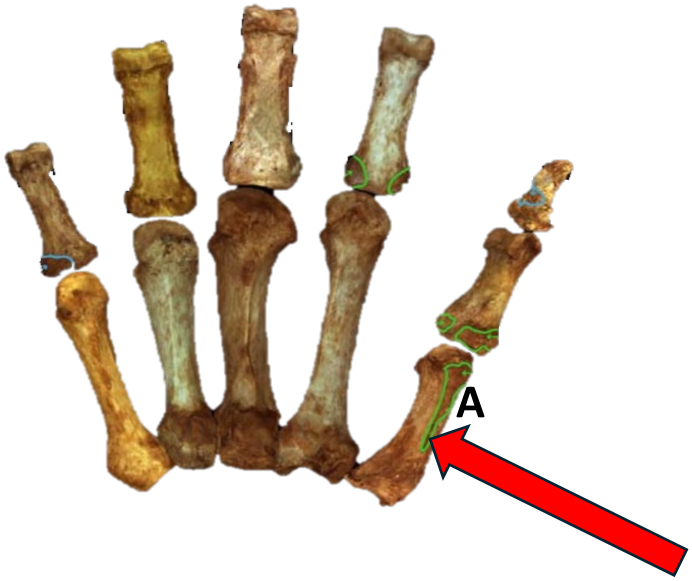

Figure 1.3. A human hand showing the palmar surface of the bones. The opponens pollicis muscle enthesis (A) is located on the first (thumb) metacarpal and denoted by the red arrow. Figure taken from Karakostis and Lorenzo (2016) and modified to emphasize the opponens pollicis attachment.

The muscle is heavily used during activities in which the dominant hand is more likely to be preferentially employed, making it an ideal site for testing if enthesis development is reflective of repetitive muscle recruitment. If entheseal development is a function of muscle force and muscle recruitment, then the enthesis associated with the opponens pollicis should be better developed on the dominant hand, leading to asymmetry in entheseal development. The proposed study will test the hypothesis that bony morphology is reflective of repetitive muscle recruitment using non-handed primates as a control group for bilateral asymmetry in the opponens pollicis caused by handedness, with non-handed primates acting as a control group for comparison with handed humans. Evaluation of this hypothesis will provide a way to control for confounding factors because the fundamental comparison will involve entheseal development within individuals. This issue is extremely important because if entheseal development is not related to workload or behavior, a large body of existing literature, in bioarcheology especially, would be potentially undercut. In addition, this study presents a new methodology for quantifying enthesis morphology across primate taxa, allowing for more broad, comparative studies of the issue outside of anthropoid primates. This study will test the following hypotheses to evaluate if enthesis development is reflective of muscle recruitment in handed humans, with comparisons of other, non-handed primates as a baseline.

HYPOTHESES

Q1: Does enthesis morphology reflect repetitive muscle recruitment?

If enthesis size is in fact reflective of repetitive lifetime muscle recruitment, humans should show asymmetrical development of the opponens pollicis enthesis due to the species-wide preference for right-hand dominance (Fitch and Braccini, 2013). Conversely, since species-wide hand preference is limited to humans, non-human primates should not exhibit asymmetrical development of the opponens pollicis enthesis. If entheseal development is not asymmetrical, then proportional entheseal size should be similar on both right and left hands, with no bias to one side or the other. However, if enthesis development is associated with repetitive muscle use, then entheseal development should be strongly biased to the right metacarpal in the human sample, while the non-human primate sample should show no bias.

H$_1$: Modern humans (*H. sapiens*) will show right-directional asymmetrical development of the opponens pollicis enthesis.

H$_2$: Non-human primates (*Macaca*, *Hylobates*, and *Gorilla* spp.) will show non-significant asymmetrical development of the opponens pollicis enthesis.

Q2: Do larger primates exhibit larger enthesis size than smaller-bodied individuals?

Previous research on modern humans has demonstrated that larger bodied individuals have both absolutely and relatively larger enthesis size in multiple regions of the body (Weiss, 2007; Nolte and Wilczak, 2013; Weiss, 2014; Bowland et al., 2019). I expect the results from this study to provide further support for these findings, with the smaller-bodied population from Merida having smaller relative and absolute enthesis size. Based on previous findings that body size correlates with enthesis size in humans, I expect the relationship to also be true for non-human primates. If the relationship seen in humans continues in the non-human primates included here, larger individuals will exhibit both absolutely and relatively larger entheses.

H1: Larger-bodied humans will exhibit larger enthesis size than smaller-bodied individuals.

H2: If nonhuman primates follow the human pattern, then larger individuals will have both larger absolute and relative entheseal size.

Q3: Does asymmetry of the Mc1 shaft predict similar asymmetry in the Mc1 proximal articular surface?

Studies have shown the differential manipulative behaviors of living and fossil hominins are reflected in the shape and bony architecture of the proximal articular surface (Niewoehner, 2000; Tocheri et al., 2003; Marzke et al., 2010; Stephens et al., 2016). These studies demonstrate that differential use of the thumb is reflected in the proximal articular surface of the first metacarpal across primate taxa. It can therefore be hypothesized that the proximal articular surface of the first metacarpal would also reflect differential hand use due to handedness by exhibiting right-directional asymmetry in humans, while non-human primates should not exhibit asymmetry of the first metacarpal proximal articular surface.

H_1: If humans display right-directional asymmetry of the Mc1 shaft due to handedness, then they will also exhibit right-directional asymmetry in the proximal articular surface reflective of right-handedness.

H_2: If non-human primates do not exhibit asymmetry of the Mc1 shaft, then they will not exhibit asymmetry in the proximal articular surface.

Q4: **Does asymmetry of the Mc1 shaft predict similar asymmetry in the metacarpal head?**

Stephens et al. (2016) found right-directional asymmetry in the trabeculae of the first metacarpal head in modern humans, which they hypothesized reflected the species-wide preference for right-handedness. The radial and ulnar collateral ligaments attach on the palmar condyles on the first metacarpal and are the main stabilizers of the metacarpophalangeal joint against ulnar and radial stress during flexion and extension (Tang, 2011). It is therefore expected that modern humans will show right-directional asymmetry at the insertion sites for the collateral ligaments as they are routinely recruited during flexion and extension by the dominant hand. Conversely, since non-human primates do not exhibit handedness, they should not exhibit any asymmetry in the metacarpal due to differential hand-use patterns.

H_1: If humans display right-directional asymmetry of the Mc1 shaft due to handedness, then they will also exhibit right-directional asymmetry in the metacarpal head.

H_2: If non-human primates do not exhibit asymmetry of the Mc1 shaft, then they will not exhibit asymmetry in the metacarpal head.

CHAPTER 2: OPPONENS POLLICIS ENTHESIS ASYMMETRY

INTRODUCTION

Muscle attachment sites (entheses) are often used to infer soft tissue anatomy and reconstruct behaviors within skeletal populations (Lieverse et al., 2009; Villotte et al., 2010; Schlecht, 2012), but there remains a significant debate about whether and to what degree muscle use is accurately reflected in bony morphology (Williams-Hatala et al., 2016). One of the most difficult problems in establishing the relationship between variation in muscle use and entheseal development is the inability to exclude a variety of external factors thought to influence enthesis development, including age, sex, body mass, and activity patterns. One way around this is to take advantage of the fact that humans are handed and consistently use one hand over the other when performing skilled manipulative tasks. If a direct relationship between bony morphology and muscle recruitment does exist, one would expect to find strong asymmetry in entheseal development within human hands. Conversely, non-human primates do not exhibit species or even population level handedness (McGrew and Marchant, 1997; Stephens et al., 2016) and so should not show asymmetrical manual entheseal development. Previous research (Karakostis et al., 2017) indicates lifetime activity patterns are likely reflected in the bony morphology of the first (thumb) metacarpal, with asymmetrical loading patterns favoring the right side in humans (Stephens et al., 2016). The opponens pollicis inserts onto the first metacarpal and is largely active during flexion and abduction of the thumb, as well as adduction when the thumb is in early stages of opposition (Maki and Trinkhaus, 2011). As such, the muscle is heavily used in many key grips employed during precision manipulation (Markze et al., 2010), thus making it an ideal site for testing if enthesis development is reflective of repetitive muscle recruitment.

Handedness Outside of Modern Humans

Outside of modern humans, the expression of handedness is poorly understood, but observational studies have failed to find evidence for hand preference above the individual level within non-human primates (Stephens et al., 2016). Most studies on non-human primates suggest that while a hand preference might exist for an individual, it is not species-wide, and is dependent upon multiple factors, including the task at hand, complexity of the task, and posture, among others (McGrew and Marchant, 1997; Meunier and Vauclair, 2007; Fitch and Braccini, 2013; Bardo et al., 2015). Some authors (Cashmore et al., 2008; Cashmore, 2009; Uomini, 2009) have proposed that any right-hand bias found within captive populations is simply an artifact of right-hand usage within the human caretakers present (i.e., [Warren (1980)]). However, in a review paper by Hopkins et al. (2011), they found that orangutans (*Pongo* spp.) exhibited the lowest levels of hand preference, despite comprising the group with the highest number of captive-born apes across studies. This finding does not support the theory that hand preference within captive populations is only a learned behavior from right-handed caretakers and instead implies it must be derived, at least in part, from something other than learned behavior during ontogeny.

Understanding the evolutionary origins of human handedness has likewise proved difficult, though the available evidence does provide some insight into handedness prior to *H. sapiens*. Archeological studies often rely on accurately inferring striking preference during stone tool flake production (Stephens, et al., 2016; Bargallo et al., 2017) but there is debate as to how informative lithic remains are in assessing handedness, as even experienced knappers tend to produce flakes differently across experiments (Cashmore, 2009). Fossil evidence for handedness is scarce, as most fossil assemblages simply do not have enough postcranial remains from which to accurately infer handedness (Cashmore, 2009; Stephens et al., 2016). However, evidence from labial striations on the anterior dentition of Neanderthals has been employed to infer handedness in fossil populations. Several studies (Volpato et al., 2012; Lozano et al., 2017) found right-directional bias within Neanderthal assemblages across sites. Volpato et al. (2012) stated the Regourdou 1 Neanderthal was likely right-handed based on oblique striations on the anterior dentition. Likewise, Lozano et al. (2017) determined 14 of the 18 Neanderthal specimens in their study were right-handed based on labial striations, while only one showed evidence for left-directional bias.

HAND USE IN DIFFERENT TAXA WITHIN STUDY

Apart from humans, all extant primates primarily use their hands for locomotion, though they also use them in varying degrees for food processing, tool use, and object manipulation. As a result of these different use patterns, primate hand proportions are highly variable (Almecija et al., 2015), as are the ways in which they manipulate objects and the grip types employed to do so across taxa. Differences in primate hand use, proportion, and muscle recruitment are discussed briefly here, but further summarized in Table 2.1, along with the resulting directional asymmetry predictions based on these factors.

Homo sapiens

Humans perform a variety of complex grips in which the thumb is in opposition to the fingers, allowing for forceful precision handling of objects. These grips are facilitated in part by derived thenar musculature, including the opponens pollicis, which has a larger physiological cross-sectional area (PCSA) than other apes and so can produce larger forces through the joint (Marzke, 1997). During flexion and opposition, the first metacarpal is loaded by a combination of joint reaction forces and muscular tension (Stephens et al., 2016), meaning variation in loading pattens should be reflected based on the tenets of the mechanostat model (Frost, 1987; Stephens et al., 2016). Since humans display a species-wide preference for right-handedness across populations (Fitch and Braccini, 2013), we predict asymmetrical loading patterns in the first metacarpal will reflect this behavior, regardless of geographic region of origin.

Hylobates

Arboreal apes are important for lateralization studies because they often support their body mass with one or both hands, making them ideal to test the postural origins theory (MacNeilage et al., 1987; Morino, 2011). In particular, the unique nature of the hylobatid thumb (see Table 2.1) makes it an ideal test for how possible adaptations for fine precision grasping, independent of handedness, influence asymmetry within the first metacarpal. It is likely that the structure of the hylobatid thumb is a consequence of their terminal branch feeding behavior, which involves reaching for food objects while suspended from the tree canopy. During foraging bouts, hylobatids use their thumbs to pluck food objects from terminal branches while keeping their long fingers wrapped around branches in a hook-like grip. The unique structure of the thumb allows hylobatids to hold a small food item firmly next to the palm, while keeping the long fingers free for travel (Prime and Ford, 2016). However, hylobatid hand usage outside of locomotion is still largely understudied and poorly understood (Prime, 2014), but there is no evidence that hylobatids engage in any level of preferential hand usage that would result in asymmetrical manual enthesis development.

Gorilla

Gorilla spp. use their hands to process a wide variety of foods, but feeding preferences vary between species and even within populations of the same species, partially at least because of the environmental differences between populations (Neufuss et al., 2019). *Gorilla beringei* often engage both hands, with one hand acting as a support while the other is processing the food (Byrne and Byrne, 1991), as opposed to lowland gorillas, which consume mostly fruits (Doran and MacNeilage, 1998) that do not require much as much manual processing to consume. During feeding, *G. beringei beringei* engage the first digit across several different grip types in which the thumb is strongly flexed, meaning the opponens pollicis is heavily recruited during feeding and foraging bouts, though empirical data on this is still lacking (Bardo et al., 2017; Neufuss et al., 2019). Previous research (Knigge et al., 2015) has documented interspecific morphological variation in the postcranial skeleton of *Gorilla* spp*.,* and we expect these morphological differences to be reflected in our sample, though it is important to note that small sample size of this study limits the statistical power of the analysis.

Macaca

Macaca fascicularis practice arboreal palmigrade locomotion, in which pressure is evenly distributed over the entire palm (Patel, 2010), meaning locomotor habits should not induce asymmetry within *M. fascicularis* metacarpals. Outside of locomotion, decades of research (Helmkamp and Falk, 1990; Fagot and Vauclair, 1991; Fagot et al., 1991; Schmitt et al., 2008) on hand preference within *Macaca spp*. failed to find evidence for population or species-wide hand preference (McGrew and Marchant, 1997). Studies focusing on “task complexity” (Fagot and Vauclair, 1991) have found that high-complexity, bimanual tasks tend to elicit a more asymmetrical hand use within the taxon (Fagot et al., 1991), though this finding is not universal, and many studies have found that, regardless of task complexity, *Macaca* spp. does not show any evidence for significant right-and-left-hand usage across *Macaca* species (Schmitt et al., 2008).

Table 2.1 Predictions for hand use and muscle recruitment in humans and non-human primates.

Taxon	Relevant Anatomy	Thumb Use	Grip Types Used	Opponens Pollicis Recruitment	Directional Prediction
Gorilla	Hand proportions most like modern humans (Almecija et al., 2015)	Food processing for both species. *Gorilla beringei* use thumbs for vertical climbing (Stephens et al., 2017, Nuefuss et al., 2019) but do not engage in much tool use (Neufuss et al., 2019	No forceful precision grip but use others such as the V-pocket grip, thumb wrap (both precision grips), and the two-jaw chuck. *G. beringei* engage in a greater number of grips than lowland gorillas (*G. gorilla*) (Neufuss et al., 2019)	Unknown when grasping tools (Bardo et al., 2017) but could assume opponens pollicis is used as in humans when the thumb is in flexion/opposition (Stephens et al., 2016)	Would not exceed predictions for neutral (50/50) because past studies have found conflicting hand use patterns (right (Hopkins et al., 2003, 2011; Parnell, 2001) Fischer et al., (1982) and Shafer (1987) (non-significant left bias (Fagot and Vauclair (1988)
Homo sapiens	Longer thumb and shorter fingers (Almecija et al., 2015) Opponens pollicis constitutes (23%) of the physiological cross sectional (PCSA) area (Marzke et al., 1999)	Thumbs are used exclusively for manipulation and free from locomotor uses (Kivell et al., 2022)	Opponens pollicis is recruited during precision grip (Marzke, 1997)	Mc1 is loaded by both joint reaction forces and from muscular tension during both flexion and opposition (Stephens et al., 2016)	Right (Fitch and Braccini, 2013; Stephens et al., 2016, 2018; Karakostis et al., 2017)

Taxon	**Relevant Anatomy**	**Thumb Use**	**Grip Types Used**	**Opponens Pollicis Recruitment**	**Directional Prediction**
Hylobates	Lack any of the six wrist features associated with the power grip (Marzke, 1992); second longest Mc1 relative to digit length (Almecija et al., 2015); ball and socket pollical carpometacarpal joint, and have a second digit that is separated from the first by a deep cleft, all of which make its first digit potentially adapted for fine manipulation (Prime, 2014; Patel et al., 2020) Separate muscle for the flexor pollicis longus (Susman, 1998)	Only rarely use the thumb when climbing vertical substrates rare (Prime and Ford, 2016).	Hook-like grip when grasping branches (Prime and Ford, 2016).	Opponens pollicis is not recruited during the hook grip (Bardo et al., 2018)	Would not exceed predictions for neutral (50/50) (Prime and Ford, 2016)
Macaca	Short thumb compared to digit length (Almecija et al., 2015)	Simple tasks like carrying objects in one hand but unlateralized when doing so (McGrew and Marchant, 1997)	Precision pinching by long-tailed macaques while processing shellfish (Gumert et al., 2009)	Potentially during limited precision grip handling of tools	Would not exceed predictions for neutral (50/50) because there is no evidence for lateralized hand use across populations (McGrew and Marchant, 1997)

MATERIALS AND METHODS

Study Sample

Table 2.2 shows the sample used within this study. All specimens within this study are adults. For all individuals in this study, the right and left sides were scanned. The *H. sapiens* sample in this study is composed of 43 individuals from the site of Merida (Tiesler et al., 2020), a late 18-19th century cemetery sample from the Yucatan, Mexico, and 42 individuals from Mistihalj (Cowgill, 2010), a 14th-15th century site from modern-day Montenegro, all housed at the Peabody Museum in Cambridge, Massachusetts. The *Gorilla* spp. sample is composed of two wild-shot *G. beringei* from the Republic of Cameroon and six wild-shot *G. gorilla* individuals, all housed at the Museum of Comparative Zoology at Harvard University. The *M. fascicularis* sample is composed of 59 individuals from a captive breeding population at Wake Forest University in Winston-Salem, North Carolina. The *H. lar* sample is composed of 45 wild-shot individuals from Thailand, housed at the Museum of Comparative Zoology at Harvard University.

Table 2.2. Showing the breakdown by sex of each taxon.

Taxon	**Male**	**Female**	**Sex Unknown**	**Total**
Macaca fascicularis	24	21	14	59
Hylobates lar	25	20	0	45
Homo sapiens				
Merida	19	23	1	43
Mistihalj	23	16	3	42
G. gorilla	4	2		8
G. beringei	2	0		
Total number of specimens				197

Method One: Linear Caliper Measurements

Linear measurements were taken in millimeters using digital calipers and include (1) maximum length of the metacarpal; (2) metacarpal base breadth; (3) metacarpal head breadth following previously published methods (Maki and Trinkhaus, 2011; Bowland et al., 2019). The mean of the maximum length of the metacarpal was calculated using Microsoft Excel (Microsoft, 2023) and was used to control for body size when assessing relative entheseal size across samples. While this method was developed for human and hominin samples (Maki and Trinkhaus, 2011), the *m. opponens pollicis* attaches to the same area of the bone across primates (Diogo and Wood, 2012) (the muscle sometimes joins with the adductor pollicis brevis (APB) in *Hylobates* spp. and attaches to the proximal phalange of the thumb, but this condition is variable and was only noted within some specimens of *Hylobates*), meaning the attachment area on the radial portion of the bone should be the same across species used within this study (Vanhoof et al., 2020). This method is a more localized view of asymmetry, focusing mainly on the opponens pollicis enthesis.

Method Two: 3D Overlays

Scanning procedure

Three dimensional (3D) models of the specimens were constructed from textured light scans captured using a mounted textured light scanner (Einscan HD Pro). Specimens were placed on a turntable connected to the scanner which was allowed to rotate between 20-30 times per specimen and, depending on the size of the specimen, repeated twice to capture both the proximal and distal ends of the metacarpal. *Macaca* spp., being the smallest of the specimens, required 30 scans per side, while the larger-sized *H. sapiens*, *Gorilla* spp., and *Hylobates* spp. specimens only required 20 scans per side. Specimens were anchored to the turntable using a small amount of Blu-Tack putty placed on the center of the table occluding with either the proximal or distal end of the bone. Specimens were first placed with the proximal end of the bone attached to the putty, allowing for the shaft and distal end of the bone to be captured by the scanner. The bone was then flipped so that the distal end of the bone (the metacarpal head) was down, allowing for the capture of the proximal end. After capturing both sides of the bone, the scans were then cleaned and merged using the Einscan Pro proprietary software. Any further cleaning of the meshes (removing triangles, filling holes, etc.) was done using Geomagic software [https://oqton.com/geomagic-designx/]. Enthesis area was calculated using two methods to test for accuracy against one another and to evaluate asymmetry on both a local (method one) and more holistic (method two) basis.

The open-source program CloudCompare [https://www.danielgm.net/cc/] was used to evaluate enthesis asymmetry within the 3D models creating heat maps illustrating distances between the two meshes using the "Cloud/Mesh Distance" feature. A specimen is designated as the "reference" specimen, and the difference is measured between the reference and the specimen in question. For this study, left sides were always designated as the reference specimen and measurements generated from CloudCompare reflect the difference between sides. After importing meshes, normals are computed per vertex for each specimen and the non-reference specimen (in this case, always the right) is mirrored to the geometry of the reference (the left side). Next, the bounding box of the two meshes is matched using the principal dimension of the two meshes and the meshes are registered using the iterative closest point (ICP) algorithm without adjusting the scale of the meshes. Finally, the difference between the two meshes is computed by using the "measure distances" tool and selecting the "Cloud/Mesh" function. Since the left side is always used as the reference, positive values indicate larger values from the right side, while negative values indicate larger values from the left side. This method also produces a color scalar overlay to show areas of least to greatest difference between the two meshes. For this project, the “blue>green>yellow>red” color scale was selected, with blue indicating negative (left-directional) values, green indicating values around 0 (no difference between sides) to red indicating positive (right-directional) values. This method evaluates if asymmetry is uniform across the bone and examines degree of variation across segments of the bone to see if entheseal asymmetry is reflected in other portions of the bone.

Model Segmentation

After following the workflow described above to align the meshes through the ICP alignment step, meshes were then segmented using the segmentation tool in CloudCompare. Aligned meshes were segmented using the “segment out” function in CloudCompare to isolate the metacarpal shaft from the proximal and distal epiphyses following homologous points (Figure 2.8). Distances between the isolated metacarpal shaft were then computed using the same procedure as outlined in the previous section.

Caliper Measurements

Linear caliper measurements were taken in millimeters using digital calipers and include (1) maximum length of the metacarpal; (2) metacarpal base breadth; (3) metacarpal head breadth following previously published methods (Maki and Trinkhaus, 2011; Bowland et al., 2019). The mean of the maximum length of the metacarpal was calculated using Microsoft Excel (Microsoft, 2023) and was used to control for body size when assessing relative entheseal size across samples.

Statistical Analyses

(Q1) Calculation of asymmetry was determined first using linear caliper data from the entire metacarpal. To determine if there were statistically significant differences between the means for right and left sides in the linear measurements, paired t-tests were conducted using the RStudio base package (Rstudio, 2020). When significant differences were found for the radial breadth measurement, a Cohen's d test was used to determine the magnitude of the variation. Calculation of asymmetry followed the handedness index of Mays (2002) for directional asymmetry (DIRA): DIRA= (r-l)/((r+l)/2) *100, with a positive number indicating right directional asymmetry and a negative number indicating left directional asymmetry (Stephens et al., 2016). DIRA values were calculated using Microsoft Excel (Microsoft, 2023). Within-group binomial exact tests were used to determine if the frequencies differed from the expected 50/50 right-versus-left distribution.

Asymmetry was also evaluated using 3D models of the bones derived from laser scans. The metacarpal was first analyzed as a whole and then again after segmenting the shaft to isolate variation driven by the opponens pollicis enthesis site. After isolating the metacarpal shaft, paired t-test of the shaft values versus the whole bone were performed to see if the means between whole and segmented shaft values differed after attempting to isolate the entheseal variation in the shaft segment. After isolating the shaft, weighted mean averages (asymmetry scores) of the distances between right and left sides were calculated per specimen based on the distances obtained from CloudCompare overlays. Per specimen distances are output from CloudCompare into eight "bins" based on number of times the observation fell within a given bin. For each bin, (1a) multiply the number of individuals by the median of each bin and (1b) repeat the calculation for each bin; (2) sum the values calculated in 1b for all bins, and (3) divide the result from step two by the total number of observations for each bin. After calculating asymmetry scores for all individuals, a one-way ANOVA was performed to determine the magnitude of asymmetry between taxa. When significant differences were found, a Tukey's post-hoc test was used to determine pairwise differences between taxa. Males and females were analyzed together as no significant differences in asymmetry were found between sexes.

(Q2)

To determine if there were differences in asymmetry between populations of modern humans, unpaired t-test were used to look for significant differences between the mean values for human populations. The geometric mean of maximum length, head breadth, and base breadth was then calculated to use as a proxy for body size to see if enthesis size is correlated with a larger body size. The geometric mean of these three values was regression against radial breadth using least squares regression. A Pearson's correlation coefficient was then calculated to see if there was a correlation between geometric mean and enthesis size.

RESULTS: METHOD ONE

H_1: Modern humans (*H. sapiens*) will show right-directional asymmetrical development of the opponens pollicis enthesis.

H_2: Non-human primates (*Macaca*, *Hylobates*, and *Gorilla* spp.) will show non-significant asymmetrical development of the opponens pollicis enthesis.

Linear Caliper Measurements

Table 2.3 presents the mean, minimum, and maximum for the caliper measurements (Maki and Trinkhaus, 2011) for both right and left sides. Asymmetry between taxa was analyzed using paired t-tests of lefts versus rights for each of the four caliper measurements. The results of these tests are listed in Table 2.4 and further visualized in Figure 2.1.

Table 2.3 Descriptive Statistics of Caliper Measurements. Showing the mean, minimum, and maximum for the linear caliper measurements. All measurements are in millimeters (mm).

Taxon		**Maximum length**	**Head Breadth**	**Base Breadth**	**Enthesis Breadth**
Macaca fascicularis	Mean	17.59	4.29	5.33	2.05
	Minimum	14.7	3.19	4.35	1.41
	Maximum	22.2	5.7	6.28	2.69
Hylobates lar	Mean	33.51	5.47	6.7	2.67
	Minimum	29.68	4.27	5.54	1.94
	Maximum	37.43	6.42	7.64	3.42
Homo sapiens	Mean	42	15.13	14.81	7.7
	Minimum	35.8	11.8	10.6	5.2
	Maximum	49.99	19.4	19.9	10.2
Gorilla spp.	Mean	48.89	15.87	15.87	9.21
	Minimum	40.11	12.63	12.53	5.24
	Maximum	60.18	19.39	21.42	14.26

These raw data largely follow expectations for all groups based on both size and activity patterns. *Gorilla* spp. are the largest of the groups and have the largest measurements for all variables, with *Ho. sapiens* the next largest, followed by *Hylobates* and *Macaca*, respectively. *Gorilla* are known to extensively process foods before consumption (Byrne and Byrne, 2001a; Neufuss et al., 2019), so it is not surprising their entheses are prominent based on radial projection measurements. It has also been demonstrated (Bowland et al., 2019) that larger individuals have larger opponens pollicis entheses, which is likely to contribute to overall enthesis size differences between taxa. On the other end of the spectrum, *M. fascicularis* entheseal breadth measurements are much smaller, even when accounting for body size differences (Figure 2.1) and reflect much less development at the attachment site. This is expected, as they are quadrupedal primates that use both hands when locomoting and are not known for fine precision manipulation (Marzke et al., 2013 [but see Gumert et al., 2009 for possible discrepancies]).

The results of the paired t-tests (Table 2.3) show significant differences between sides for *Ho. sapiens* for all measurements, while *Macaca* did not exhibit significant differences between sides for any of the four measurements included within this study. However, *Hylobates* and *Gorilla* both show significant differences between sides for the radial breadth measurement, which does not support hypothesis 1, that stated non-human primates would not show significant differences between sides. These results are further visualized in Figure 2.1 and will be discussed later.

Radial breadth size should reflect opponens pollicis enthesis development (Maki and Trinkhaus, 2011), as it captures the most radially projected aspect of the muscle flange. Figure 2.1 shows a graph of the right versus left measurements for the radial breadth for each of the taxon. There are clear differences between taxa based on the radial projection measurement, even when accounting for size differences. *Homo sapiens* and *Gorilla* have absolutely larger radial projection size than *Macaca* or *Hylobates*, though this is to be expected based on the size differences between the taxa. As expected, *Macaca* measurements fall mostly along the line and do not show any evidence of asymmetry between right and left sides. *Hylobates* measurements deviate from the regression line and show left-directional asymmetry for the radial projection measurements, in line with other results discussed further on. *Gorilla* shows the largest range of variation in terms of left versus right enthesis size and does not appear to differ from chance when considering directionality of the radial projection measurement (Table 2.4). This result is in line with the results of the binomial exact test shown in Table 2.4.

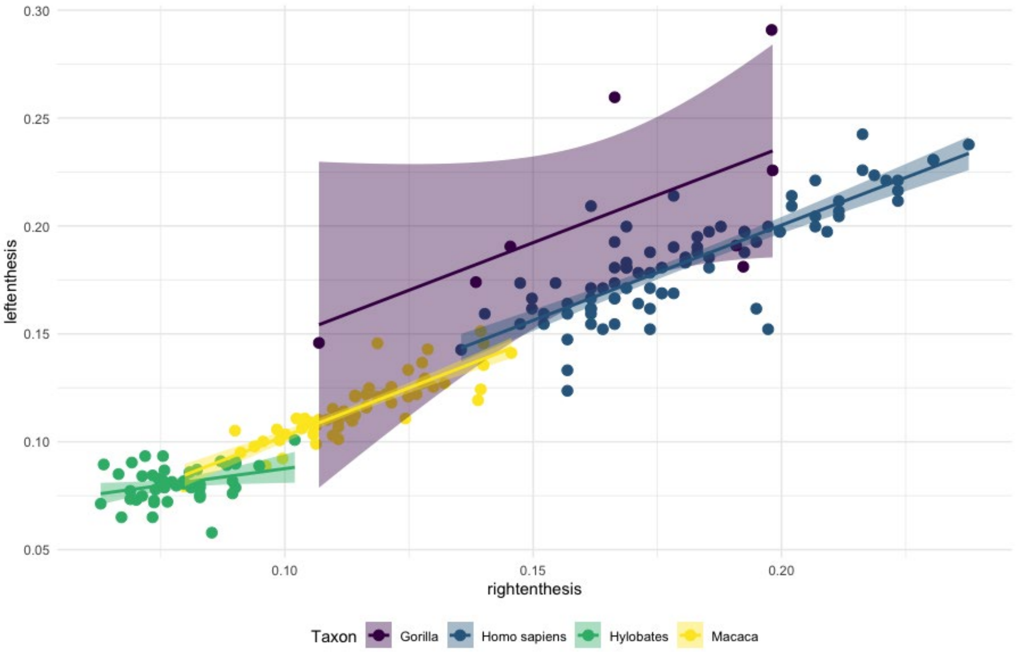

Figure 2.1 Bivariate plot of the right (x axis) and left (y axis) of Mc1 relative radial breadth. All measurements listed are in millimeters. The line fitted shows a linear regression model. Measurements for both sides have been divided by the mean length of the metacarpal for each taxon to correct for size differences between taxa.

Table 2.4. Results of a paired t-test of left versus right caliper measurements.

Taxon	**Max Length**	**Base Breadth**	**Head Breadth**	**Radial Breadth**
Macaca	not sig.	not sig.	not sig.	not sig.
Hylobates	not sig.	not sig.	not sig.	**.002**
Homo sapiens	**.02**	**.00**	**.00**	**.03**
Gorilla	not sig.	not sig.	not sig.	**.00**

DIRA Asymmetry

Table 2.5 presents the results of DIRA and right-directional asymmetry counts, along with the results of the within-group binomial test (Mays, 2002; Stephens et al., 2016). *Homo sapiens* exhibit right-directional asymmetry for all caliper measurements, while *Macaca* and *Gorilla* do not show asymmetry for any of the measurements. *Hylobates* shows left-directional asymmetry for the radial breadth measurement. The boxplot showing radial breadth measurements for all taxa (Figure 2.2) shows the radial breadth measurements for *Gorilla* as being left-directional, though the results of the binomial exact test (Table 2.5) shows these results do not reach statistical significance. The non-significant results for *Gorilla* are likely due to the small sample size used within this study, which limits statistical power of the test.

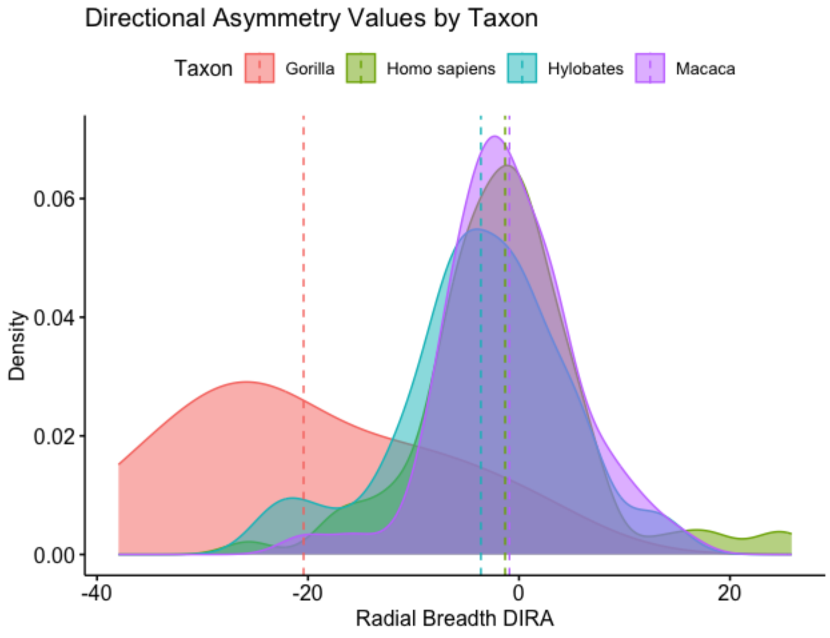

Figure 2.2 Density plot of the DIRA asymmetry values by taxon. Dashed lines indicate the mean value for each taxon. Negative values indicate larger left side values, while positive indicate larger right values.

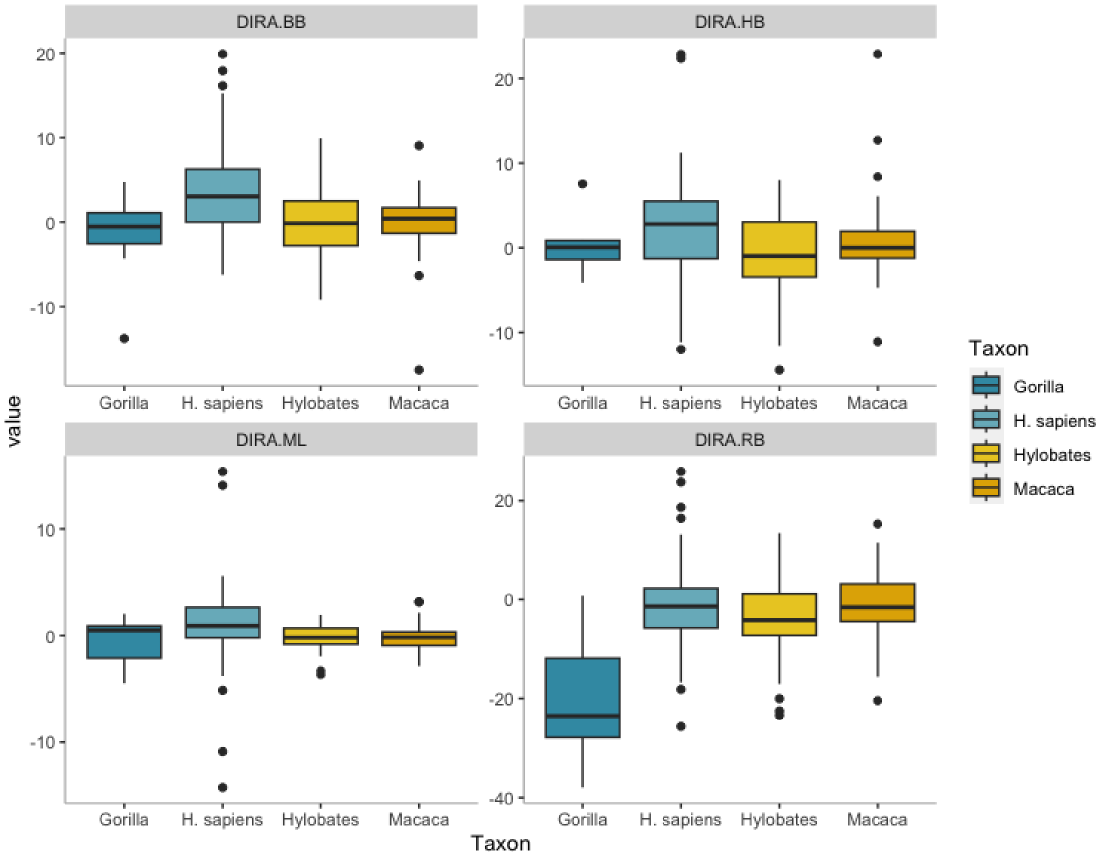

Figure 2.3. Boxplot showing distribution of right (negative) and left (positive) directionality for the four caliper variables across taxa.

Table 2.5. Results of binomial exact test for caliper data of the entire shaft by taxa. Significant differences are indicated in bold. *p*-value for binomial exact test with the expected distribution of 50/50 distribution.

	***Gorilla* spp.**		***Homo sapiens***		***Hylobates***		***Macaca***	
Variable	R>L	*p*-value	R>L	*p*-value	R>L	*p-value*	*R>L*	*p*-value
Max Length	5/8	Non-sig	57/85	**0.00**	19/45	Non-sig	23/59	Non-sig
Head Breadth	4/8	Non-sig	57/85	**0.00**	20/45	Non-sig	29/59	Non-sig
Base Breadth	3/8	Non-sig	60/85	**0.00**	20/45	Non-sig	34/59	Non-sig
Radial Breadth	1/8	Non-sig	29/85	Non-sig	14/45	Non-sig	24/59	Non-sig

DISCUSSION: METHOD ONE

Homo sapiens are significantly different between sides for all measurements gathered. They exhibit right-directional asymmetry for the radial breadth measurement, which should capture the development of the opponens pollicis muscle flange (Maki and Trinkhaus, 2011). *Macaca* do not show any significant differences for any of the measurements, and do not exhibit any degree of asymmetry. *Hylobates* show significant differences between sides for the radial breadth projection measurement, which is shown to be left-directional in both Figure 2.1 and Figure 2.2. *Gorilla* is significantly different regarding the radial breadth measurement, though the differences are likely due to outliers in the small sample size, which reduces statistical power.

Results from the DIRA analysis are listed in Table 2.5 and further visualized in in Figures 2.2 and 2.3. Humans display right-directional asymmetry for all measurements except radial breadth, which is unexpected given the species-level preference for right-hand dominance and the theoretical higher levels of muscle recruitment of the opponens pollicis. Neither *Macaca* nor *Hylobates* display significantly different results for any of the variables listed, which supports hypothesis 2b. This finding is expected, as they both use their hands for locomotion and any manipulative activities performed are not likely to override the signal from locomotion (Stephens et al., 2016). Further, many decades of studies have failed to find any kind of population or species wide signal for hand preference within either taxon (McGrew and Marchant, 1997; Prime and Ford, 2016).

RESULTS: METHOD TWO

CloudCompare Measurements

Descriptive statistics of the results from the CloudCompare analyses looking at the entire metacarpal are summarized in Table 2.6 and further visualized in Figure 2.4. These data are a synthesized comparison of right versus left values, showing the difference between both sides. Taxa can clearly be distinguished on the degree of asymmetry for each of the variables. As shown in Figure 2.3, *Ho. sapiens* and *Gorilla* exhibit much higher levels of asymmetry for the entire metacarpal than do *Hylobates* or *Macaca* (Figure 2.3). However, *Ho. sapiens* and *Gorilla* largely overlap in their levels of asymmetry for each of the variables, particularly for standard deviation, in which their mean values are almost identical (Table 2.6). *Macaca* shows the smallest amount of variation for each of the four variables listed, followed by *Hylobates*. These results are not surprising, as these two taxa use both hands for locomotion, and are not known for the high levels of manual manipulation seen in wild populations of *Gorilla* (Byrne and Byrne, 2001b; Neufuss et al., 2019) or for the fine precision grasps often employed by humans.

Table 2.6. Showing descriptive statistics of mean, maximum, and minimum values for the entire metacarpal from the CloudCompare variables by taxon.

Taxon		Maximum distance	Average distance	Standard Deviation	RMS value
Macaca fascicularis	Mean	0.41	0.06	0.08	0.10
	Minimum	0.22	0.03	0.05	0.05
	Maximum	0.82	0.18	0.14	0.27
Hylobates lar	Mean	0.68	0.09	0.12	0.16
	Minimum	0.41	0.04	0.09	0.10
	Maximum	1.73	0.25	0.23	0.39
Homo sapiens	Mean	1.74	0.24	0.25	0.41
	Minimum	0.69	0.10	0.15	0.19
	Maximum	5.78	0.88	0.89	1.34
Gorilla spp.	Mean	1.42	0.2	0.24	0.36
	Minimum	0.87	0.10	0.15	0.20
	Maximum	2.5	0.42	0.42	0.71

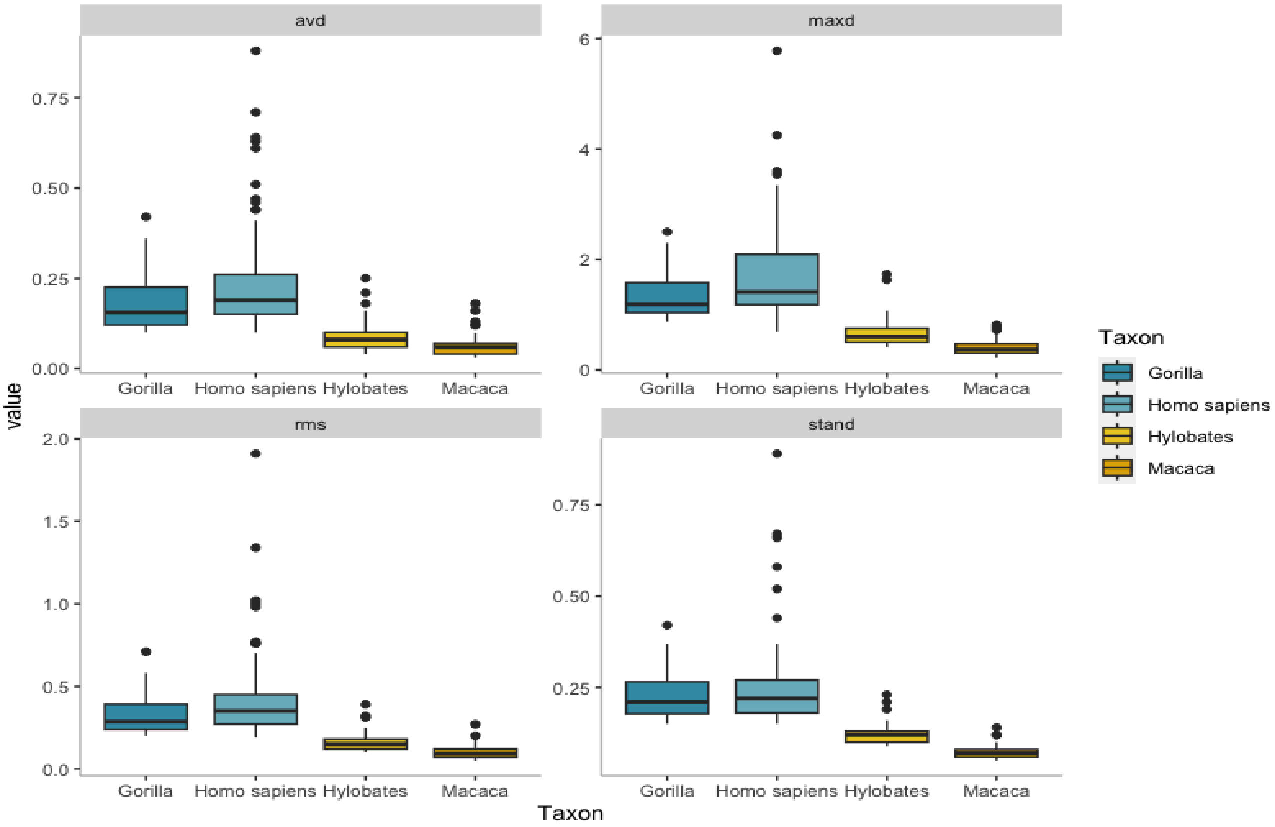

Figure 2.4. A boxplot comparing the range of values between right and left sides for the entire metacarpal shaft by taxon. Avd=average distance, maxd=max distance, rms=rms value, stand=standard deviation.

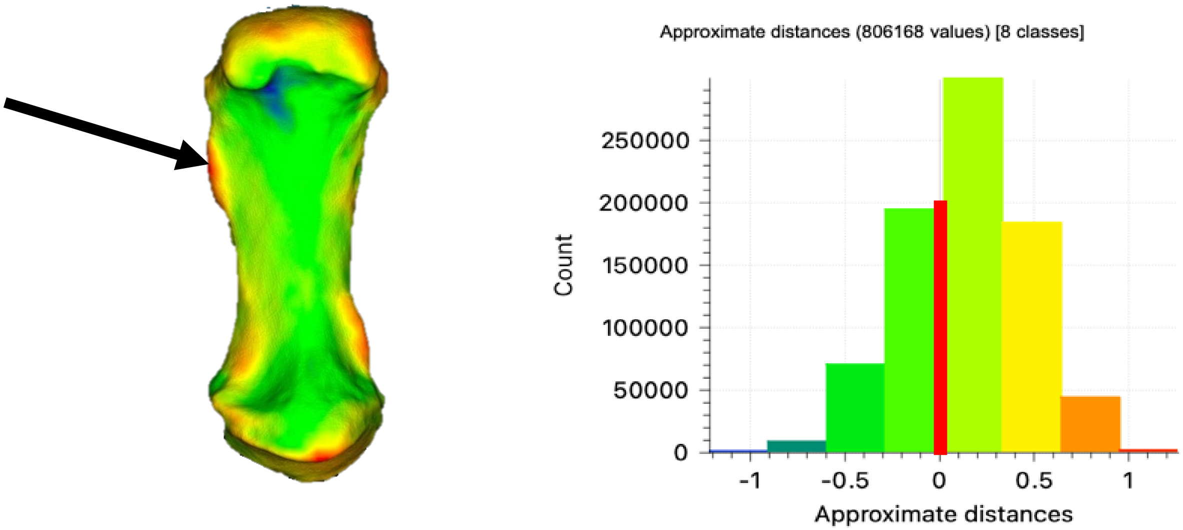

Figure 2.5 A and B. Heat map (A) of *H. sapiens* Mc1 (HPM 61048), showing the variation from the OP enthesis, denoted by the black arrow. Green indicates minimal variation (~0), while red indicates large amounts of variation (~1). Figure 2.5 (B) shows the accompanying histogram showing the values of the root mean square (RMS) in millimeters. Positive values indicate right-directional asymmetry, while negative values indicate left-directional asymmetry. The black arrow indicates the areas with the greatest right-directional asymmetry. RMS value=0.39.

Segmenting the Metacarpal

The entire metacarpal was first analyzed to determine if variation in symmetry exists between the right and left sides of primates with handedness (*Ho. sapiens*) versus those without (*Gorilla*, *Hylobates*, *Macaca*). However, this obscures the asymmetry signal from the opponens pollicis muscle insertion site, as it also incorporates variation from other portions of the metacarpal. For example, larger values for the right side are sometimes due to asymmetry in as the metacarpal head and base, as shown in Figure 2.6 A and B. To better determine if the asymmetry seen within these groups is indeed driven by the muscle flange and no other portions of the bone, the metacarpal shaft was segmented to remove the proximal and distal articular portions. The metacarpal proximal and distal ends will be analyzed and discussed in a further chapter of this manuscript.

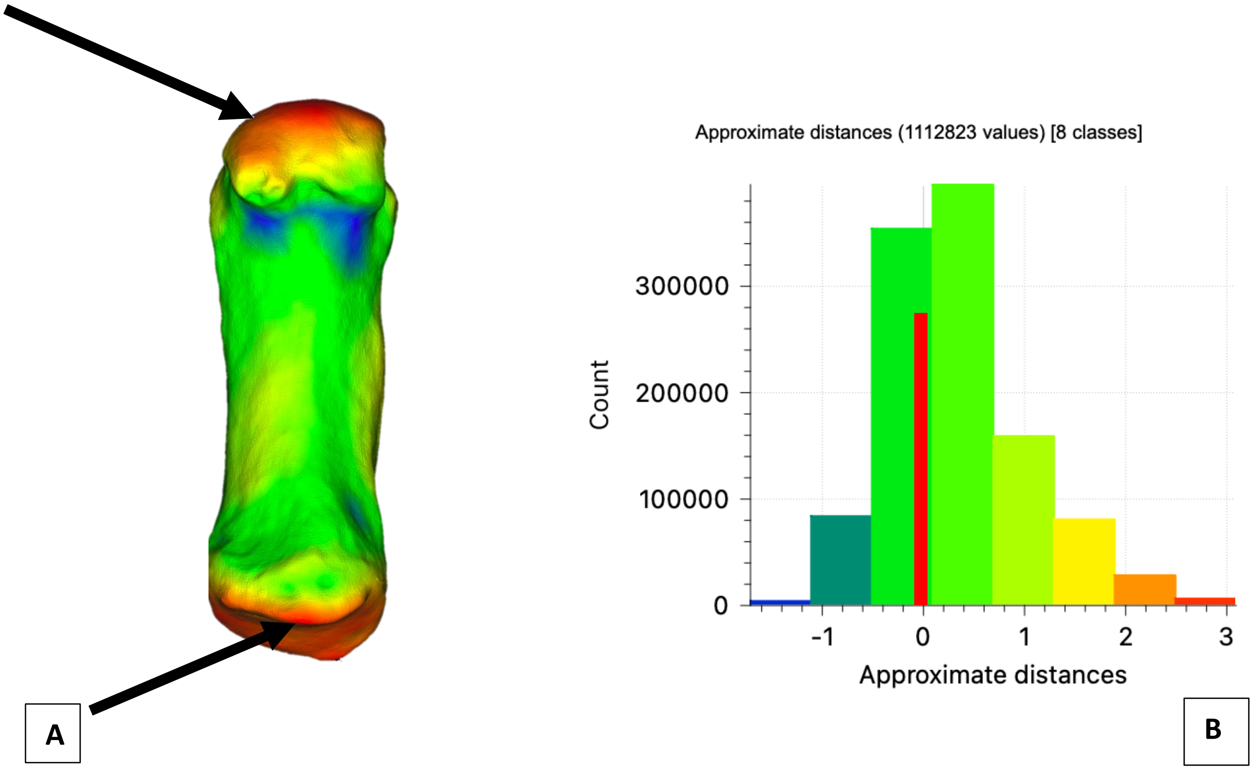

Figure 2.6 A and B. Heat map (A) of *H. sapiens* Mc1 (HPM 6048), showing the variation within the metacarpal, denoted by the black arrows. Green indicates minimal variation (~0), while red indicates large amounts of variation (~1). (B) shows the accompanying histogram showing the values of the root mean square (RMS) in millimeters with a red line indicating 0. Positive values indicate right-directional asymmetry, while negative values indicate left-directional asymmetry. Black arrows indicate the areas with the greatest right-directional asymmetry shown in red.

Does Segmenting the Shaft Better Isolate the Signal from the Enthesis?

The results of paired t-test comparing the measurements of the entire bone versus the segmented shaft portion are shown in Table 2.7. All taxa show significantly different results for maximum distance and standard deviation, while all taxa except *Gorilla* show significant differences for RMS value. Figure 2.7 further visualizes these results. There is a smaller range of variation for all taxa for all variables when the shaft is segmented out from the proximal and distal ends. In particular, the maximum distance between the two sides is greatly reduced when the proximal and distal ends of the bone are removed, suggesting this metric is heavily driven by those areas of the bone. In contrast, the average distance between the two sides does not vary much for any of the taxa, except for *Macaca,* in which there is a statistically significant difference between the two values, though it is unclear what is driving this. These results imply that much of the variation present when analyzing the entire bone is not driven by the shaft, and that isolating the shaft removes variation potentially coming from the proximal and distal ends, thus obscuring the signal from the opponens pollicis enthesis. The results also raise the question of how much variation is present within the proximal and distal ends of the metacarpal; this will be addressed in chapters 3 and 4 of this manuscript.

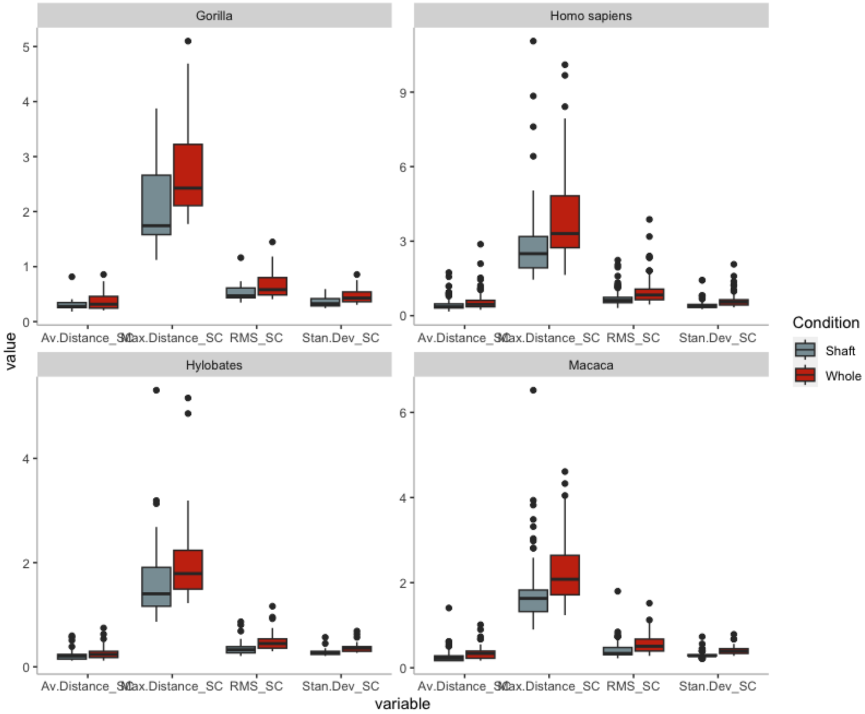

Figure 2.7. Boxplot of CloudCompare data for the shaft from each taxon. Data are size corrected (each value is divided by the mean of maximum metacarpal length). Av. Distance=average distance, Max distance= maximum distance, RMS=root mean square value, Stan. Dev=standard deviation.

Table 2.7. Results of a paired t-test comparing the measurements from the whole metacarpal to those of the segmented shaft portion. Data are size corrected (each value is divided by the mean of maximum metacarpal length). RMS= root mean square.

Taxon	**RMS**	**Average Distance**	**Maximum Distance**	**Standard Deviation**
Gorilla	.1	.3	**0.01**	**0.00**
Homo sapiens	**0.00**	**0.00**	**0.00**	**0.00**
Hylobates	**0.00**	.13	**0.00**	**0.00**
Macaca	**0.00**	**0.00**	**0.00**	**0.00**

Figure 2.8 (A and B) show heatmaps comparing a single specimen from *Ho*. *sapiens* (HPM 61048) both with the entire metacarpal (left) and after segmenting the bone to isolate entheseal variation (right). After isolating the shaft, the amount of variation driven by the opponens pollicis attachment site (A) is much more pronounced than when analyzing the metacarpal as a whole. The range of maximum distance between the two sides is decreased overall (Figure 6), and the greatest area of variation is now concentrated on the muscle attachment site, demonstrating that when the shaft is isolated from the proximal and distal ends, the opponens pollicis enthesis is the main driver of variation between sides. After establishing that variation in the shaft is driven by the opponens pollicis enthesis, the question arises of whether this asymmetry is right-directional in humans, and if the opponens pollicis enthesis is asymmetrical in non-human primates **(Q1)**.

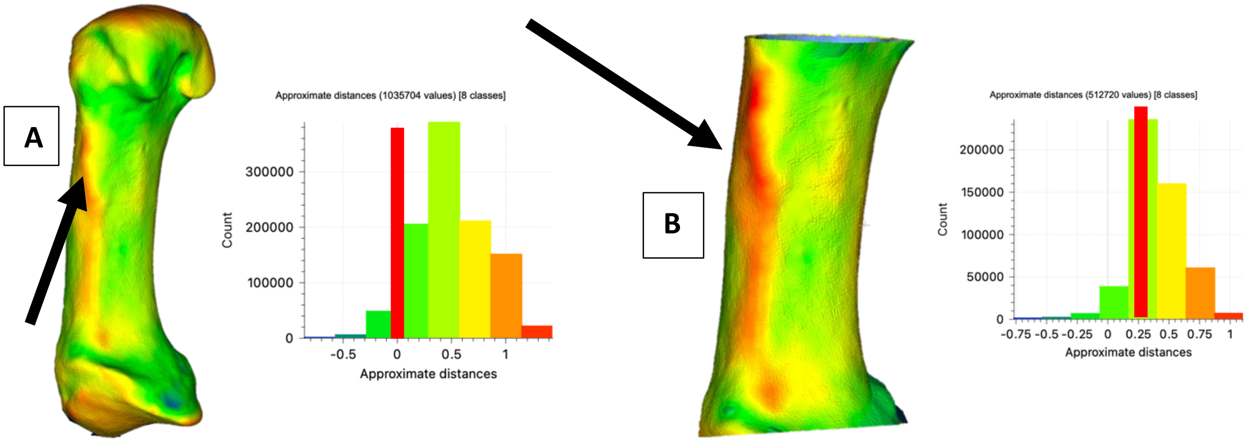

Figure 2.8. Left: 2.8 (A) CloudCompare heatmap of a *Ho. sapiens* specimen (HPM 60156) showing variation between sides before (left) and after (right) segmenting the shaft to isolate enthesis variation. Figure 2.8 (B) shows the accompanying histogram for each specimen showing the values of the root mean square (RMS) in millimeters, with a red line indicating 0. Positive values indicate right-directional asymmetry, while negative values indicate left-directional asymmetry. Black arrows indicate the areas with the greatest right-directional asymmetry shown in red and indicated by A.

Asymmetry Levels Between Taxa

The results of a one-way ANOVA comparing the weighted average (asymmetry score) per specimen across taxa are shown in Table 2.8. The results suggest that there are statistically significant differences in weighted averages between *Ho. sapiens* and each of the other three taxa (*Gorilla*, *Hylobates*, and *Macaca*), but there are no statistically significant differences between *Gorilla*, *Hylobates*, and *Macaca* when compared to each other. These results show that magnitudes of asymmetry between taxa can be distinguished based on levels of asymmetry for the opponens pollicis enthesis. Species averages for the weighted asymmetry scores are shown in Table 2.9, and further underscore these results, showing that, on average, *Macaca* show no evidence of asymmetry and *Hylobates* shows very minor right-directional asymmetry. In line with previous results from the caliper measurements, *Gorilla* shows slight left-directional asymmetry, while *Ho. sapiens* are the most asymmetric, and the direction of asymmetry is right.

Table 2.8. Results of an ANOVA with a Tukey's post-hoc and a Bonferroni correction. Data is from the specimen shaft averages from the CloudCompare data. Significant differences are shown in bold.

Homo sapiens - Gorilla	*Hylobates - Gorilla*	*Macaca- Gorilla*	*Hylobates- Homo sapiens*	*Macaca- Homo sapiens*	*Macaca- Hylobates*
0.03	Not sig.	Not sig.	**0.01**	**0.00**	Not sig.

Table 2.9. Species weighed averages for the CloudCompare shaft data. Negative values indicate left-directional asymmetry while positive values indicate left-directional asymmetry.

Homo sapiens	*Gorilla*	*Macaca*	*Hylobates*
0.20	-0.04	0.00	0.02

Does Opponens Pollicis Asymmetry Distinguish Between Taxa?

Results from the one-way ANOVA for specimen differences, as well as the species averages from based on asymmetry scores by taxon, demonstrate that humans are more asymmetrical than other primates in their opponens pollicis enthesis. The species average for *Ho. sapiens* is much higher than the other taxa (Figure 2.9), indicating the asymmetry within the taxon is right-directional, but the values do not address the question of whether the asymmetry within the taxon is significantly right-directional, only that some degree of asymmetry exists. To determine whether the values seen in *Ho. sapiens* (and *Gorilla* to a lesser extent) are significantly asymmetrical, the mean of weighted asymmetry scores per individual was calculated and plotted with a 95% confidence interval to determine if values fall outside of the expected range of variation (Figure 2.10). *Hylobates* and *Macaca* have a mean of 0 or nearly 0, and the values for both taxa are largely concentrated on 0. *Gorilla* shows more variation than the other two non-human primate taxa, but this is likely an effect of sample size (*n*=8) and is mainly driven by outliers. *Homo sapiens* shows the most variation of any taxa, and while the data are right-directional, it is not significantly so. In addition, the large amount of variation in either direction is unexpected given the high prevalence of right-handedness within modern humans (85-95%) (Papademetriou et al., 2005; Fitch and Braccini, 2013; Papadatou-Pastou et al., 2020).

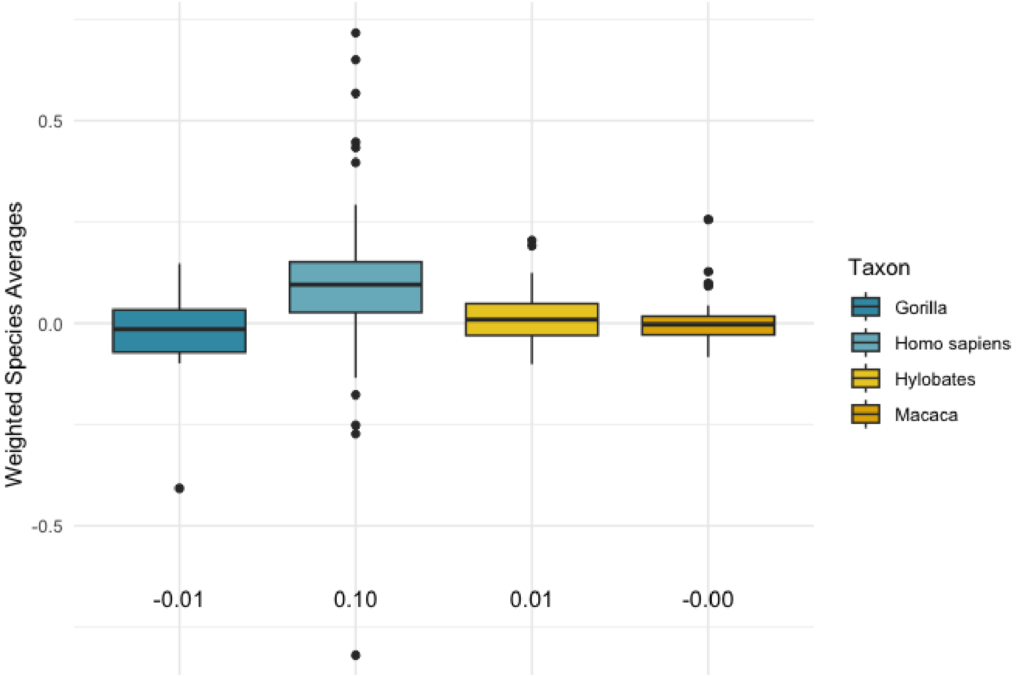

Figure 2.9. Boxplot with median weighted asymmetry score listed below each taxon. Positive values indicate right-directional asymmetry, negative values indicate left-directional asymmetry, and 0 indicates symmetry.

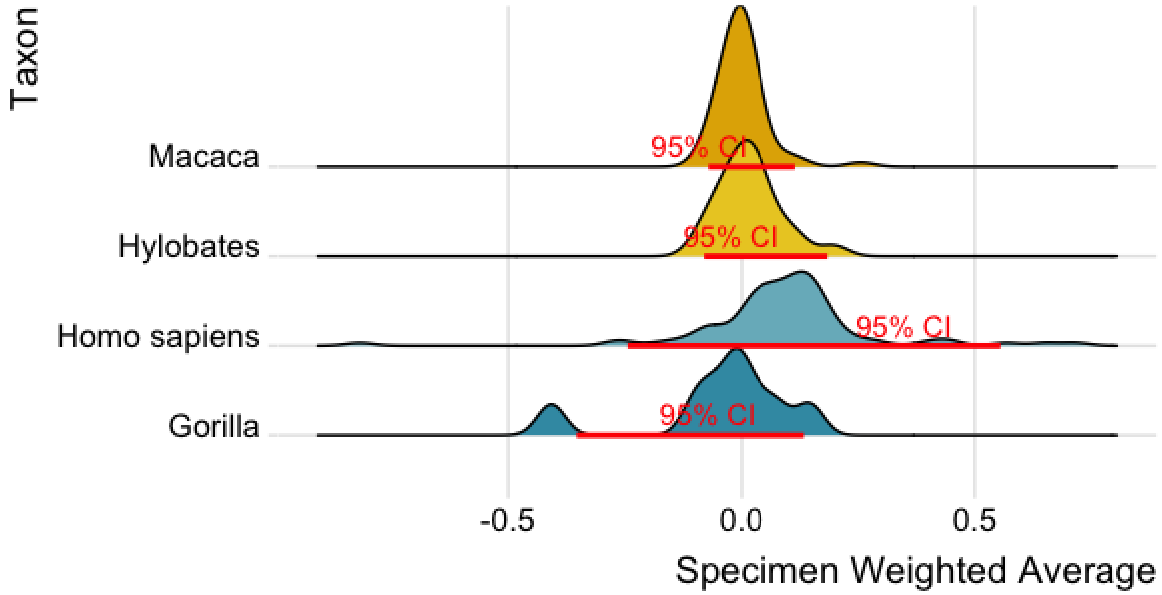

Figure 2.10. Density plots of asymmetry scores per specimen. 95% confidence intervals are labeled and indicated in red. Negative values indicate left-directional asymmetry, while positive values indicate right-directional asymmetry.

Figure 2.10 shows the asymmetry scores per specimen for the isolated shaft distances between sides. As previously stated, most of the *Ho. sapiens* values fall within the range of variation seen in *Macaca* and *Hylobates*, though it is clear the mean, median, and mode of the data skew to the right, and that the data require further analysis to fully understand the functional signal seen here. To isolate the variation that is outside the range of symmetry (the ranges seen in *Macaca* and *Hylobates*) specimens from *Ho. sapiens* that exceeded this range were isolated and the range of those values was plotted to assess directionality of the outliers within the *Ho. sapiens* sample.

Figure 2.11 shows the *Ho. sapiens* specimens that lie outside the range of values for *Macaca* and *Hylobates* (aka outside the null hypothesis of symmetry) minus the one extreme left-directional outlier. When these specimens are isolated, there is a clear right-directional signal within *Ho. sapiens* at the opponens pollicis enthesis. The emergent pattern follows the known frequencies of right-handedness within modern humans (85-90%) right-handed (Papademetriou et al., 2005; Fitch and Braccini, 2013; Papadatou-Pastou et al., 2020). These results suggest that most humans will not differ significantly from the null hypothesis of symmetry between right and left sides. This is likely because there is a muscle recruitment threshold to induce osteogenic changes that most individuals will not exceed, and therefore will not show evidence of asymmetrical bone remodeling.

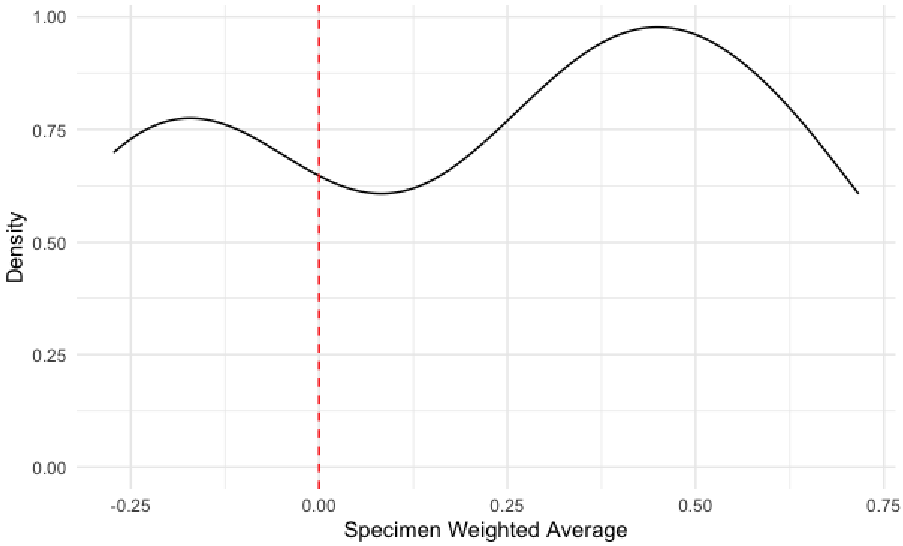

Figure 2.11. Specimen weighted averages for the *Ho. sapiens* specimens without the left outlier. The red line denotes 0. Positive values indicate right-directional asymmetry, while negative values indicate left-directional asymmetry.

Q2: Do larger primates exhibit larger entheses than smaller-bodied individuals?

Inter-Population Differences

The differences between the two populations of modern humans are visualized in Figures 2.12 and 2.13. All measurements are significantly different between the two populations. These results are most likely due to overall body mass differences between the two populations. Larger individuals tend to have large entheseal areas (Bowland et al., 2019), as visualized in Figure 2.8.

Disentangling muscle use from body size in terms of enthesis development has long been a problem when attempting to discern their relationship with muscle recruitment, as is evident here. However, when comparing the right versus left directionality of the enthesis between the populations (Figure 2.13) there appears to be little difference in terms of directional asymmetry between the two populations. Further, there is little asymmetry present within either population, as the mean of the DIRA values for radial breadth is centered on 0 for both populations.

Table 2.10. Showing descriptive statistics of mean, maximum, and minimum values of the caliper measurements for the two populations of modern humans.

Population		**Max Length**	**Base Breadth**	**Head Breadth**	**Radial Breadth**
Merida	Mean	40.7	13.9	14.1	7.2
	Minimum	35.8	10.6	11.8	5.2
	Maximum	48.3	19.9	17.1	10.2
Mistihalj	Mean	43.4	15.8	16.2	8.2
	Minimum	35.8	12.6	13.2	6.2
	Maximum	49.9	19.5	19.4	10.0
T-test		**0.00**	**0.00**	**0.00**	**0.00**

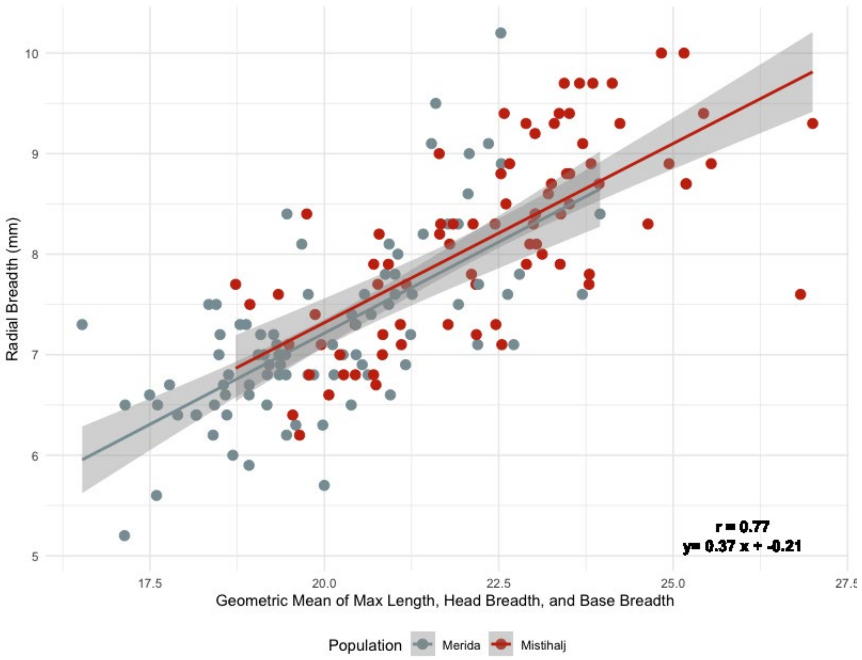

Figure 2.12. Bivariate plot of least squares regression of geometric mean of maximum length, head breadth, and base breadth against radial projection for the two populations of modern humans. Radial projection and maximum length are both pooled samples with both left- and right-side values.

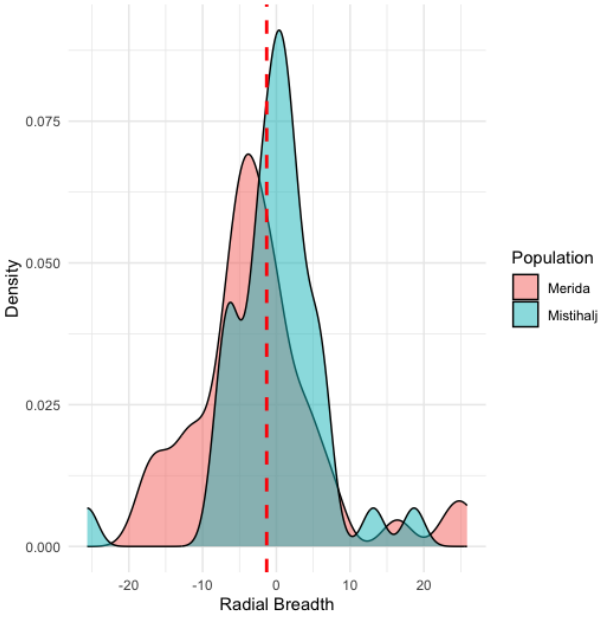

Figure 2.13. Density plot of DIRA values for the two populations of modern humans. Positive values indicate right-directional asymmetry and negative values indicate left-directional. The dotted red line indicates the mean for the two populations.

Body Size and Enthesis Size in Non-Human Primates

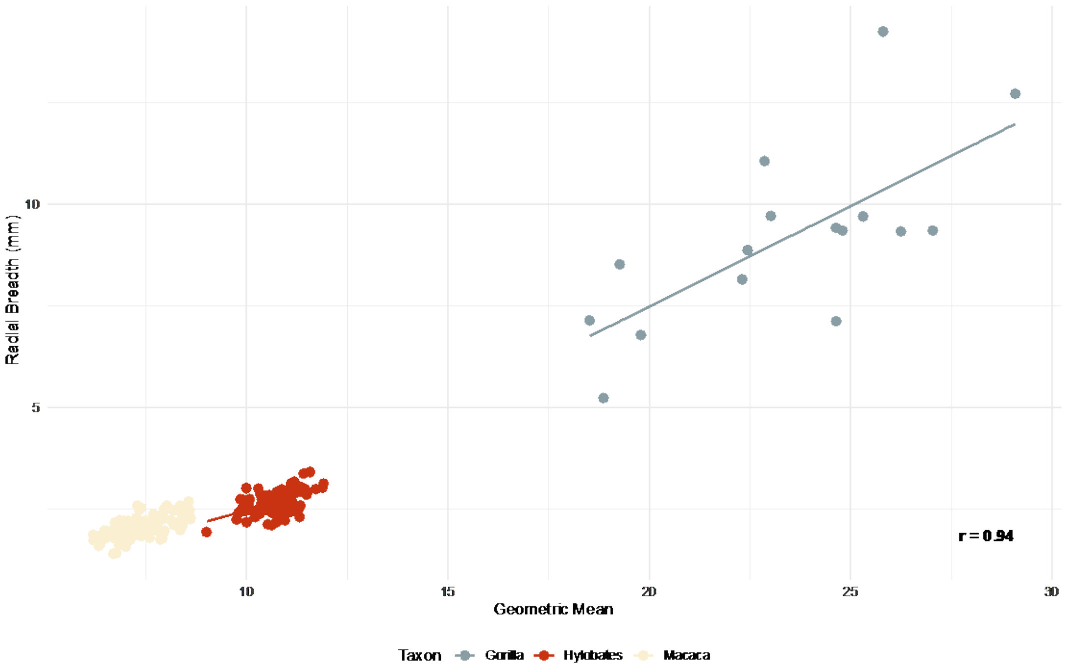

Figure 2.14. Bivariate plot of geometric mean of maximum metacarpal length, head breadth, and base breadth against radial breadth for the non-human primate sample.

There is a strong correlation (*r*=.94) between geometric mean of the maximum length of the metacarpal length, head breadth, and base breadth and radial breadth within the nonhuman primate sample (Figure 2.14). These results indicate that, even when accounting for body size differences, larger primates have both relatively and absolutely larger enthesis size. This is in line with previous studies (Drapeau, 2008; Milella, 2014) that have examined enthesis and body size within great apes, but it is the first study (to my knowledge) to examine the relationship outside of humans and great apes.

DISCUSSION: METHOD TWO

This study sought to test whether primates with handedness (*Ho*. *sapiens*) were more asymmetrical than primates without handedness (*Gorilla, Macaca,* and *Hylobates*) in the expression of the opponens pollicis muscle enthesis because of differential loading of the dominant versus non-dominant hand. This hypothesis is based on the mechanostat model (Frost, 1987) of bone functional adaptation, which states that areas of bone under increased strain will remodel at greater rates than those under relatively smaller amounts of strain. Overall, this study found right-directional asymmetry for humans, as expected, but the degree of asymmetry is slight and driven by outliers, suggesting the right-directional asymmetry seen is the result of complex hand use patterns and not reflective of a straightforward, linear relationship between dominant hand use and muscle recruitment.

The variation found was largely concentrated on the opponens pollicis enthesis site, demonstrating that the asymmetry present is driven by the muscle insertion and no other areas of the bone and that the asymmetry found within the paired first metacarpals of modern humans is highly localized and site-specific. However, it is also clear that repeated muscle recruitment alone does not explain the asymmetry results seen here; while humans can be distinguished from other non-human primates based on opponens pollicis enthesis asymmetry, the degree of asymmetry is slight, and does not appear to match known frequencies of human right handedness. Rather, the results imply there is a basic minimum of enthesis development across taxa, which is greater in taxa that exhibit handedness than in those that do not, but that enthesis size is the result of both systemic and functional factors (Ruff et al., 2006) and cannot be attributed to hand use patterns alone. This study also found that *Gorilla* exhibited left-directional asymmetry of the opponens pollicis enthesis, though it did not deviate significantly from chance, likely due to the small sample size in this study. As predicted, *Macaca* and *Hylobates* did not exhibit any significant degree of enthesis asymmetry.

This study also utilized a new method for measuring the opponens pollicis enthesis across primate taxa. Heat maps generated from 3D mesh overlays (Figure 2.6) captured variation at the insertion site for the opponens pollicis and highlighted how this area drives asymmetry within the metacarpal shaft in modern humans. These results are in line with previous research (Karakostis et al., 2017), which found that muscle loading is reflected in the size of the opponens pollicis enthesis and that handedness drives right-directional asymmetry in the first metacarpal of modern humans (Stephens et al., 2016). This method can be applied to additional areas of the body for future studies analyzing asymmetry.

Hypothesis 1 predicted that modern humans would show right-directional asymmetry of the opponens pollicis enthesis because of differential hand use related to species-wide right-handedness. The results from this study found evidence for population-level asymmetry between the right and left side opponens pollicis enthesis for modern humans, and so can reject the null hypothesis of symmetry for this taxon. The finding of right-directional asymmetry of the opponens pollicis held when using both linear caliper measurements and heat maps generated from 3D renderings of the bone, reinforcing the results. Further, after segmenting the metacarpal to isolate the insertion area of the muscle (Figure 2.6), the degree of right-directional asymmetry present at the insertion site increased within these individuals (Figure 2.8), demonstrating that the enthesis is driving asymmetry in the shaft portion of the bone. However, the results also highlight the complex nature of enthesis studies. For instance, the amount of asymmetry present even within the isolated shaft segment is not enough to drive overall variation away from a mean of 0 for many of the individuals included here (Figure 2.10). These findings indicate that while modern humans do display right-directional asymmetry of the insertion site on the population level, is it not significantly different from 0 for many individuals. This finding suggests there is a "threshold" for enthesis size within modern humans, below which sides do not deviate significantly from the null hypothesis of symmetry, but above which asymmetry is present (Ruff et al., 2006). This threshold is enough to distinguish humans from other primate taxa (Figure 2.9) but does not necessarily distinguish between sides within modern humans.

Customary Strain Level and Bone Responses Explain the Confusing Signals

The idea that bone is continually acting to maintain an "optimum or customary strain level" is likely to explain why most of the human individuals within this study do not differ significantly between sides (Figure 2.10). Bone modeling and remodeling is a complex process that can be simplified as a feedback loop between stress (applied force) and strain (deformation or displacement). Increased strain level (through higher activity levels) induces increased bone remodeling, which then decreases the level of strain present at the site to a "customary strain level." Decreased strain (through inactivity) leads to bone resorption, which also acts to restore the original strain levels (Ruff et al., 2006). Since bodies are continually striving to maintain a "customary strain level," above which bone deposition is stimulated, but below which remodeling is unlikely to occur, osteogenic changes are largely the result of high strain rates due to increases in either strain magnitude, frequency, or both. As Ruff et al. (2006: 489) states, "Strains developed during less vigorous (but more common)" activities, such as everyday hand use, would be "residual" and "not sufficient to stimulate modeling/remodeling." This means that, while humans might be routinely engaging their dominant hand over the non-dominant hand, it does not mean the activities performed by the dominant hand are enough to exceed the customary strain level and thus induce remodeling events, and by extension, significant external bony changes at the muscle insertion site.

In context of the results found here, this would imply that the individuals that pull significantly right (away from the mean of symmetry) would be the ones frequently exceeding the optimum strain level and thus significantly remodeling the bone at the muscle insertion site. This could also explain the somewhat conflicting results of the study. While the mean/median/mode between sides are not centered on zero clearly pull to the right, there are enough modern humans that do not show significant levels of asymmetry to make the results non-significant for the whole sample. This could explain why the binomial exact test from the DIRA asymmetry measurements failed to find significant differences between sides, as most of the sample showed little to no variation between right and left side measurements. Further, when you isolate the humans that fall outside the threshold, a very clear distribution of values emerges that largely follows the literature on hand preference studies in humans: a roughly 80/20 split for right/left directionality (Figure 2.11).

Handedness is Not a Discrete Variable

It is likely some of the difficulty in interpreting the results of this study are due to the binary classification of handedness used here. Handedness was presented as a discrete variable with no consideration given for the nuance of hand usage seen within modern humans, which likely obscured some of the functional signal arising from hand use. This study followed values often reported in the literature for handedness within modern humans (85-95% right-handedness), but it is important to note handedness studies are not without complications of their own.

Hand preference data are largely based on self-reported values gathered via questionnaires (Cashmore, 2009), whose methods and parameters vary widely. Often, subjects are asked to specify hand preference for a series of tasks such as writing, drawing, and using scissors, and tasks are often given equal weighting (Cashmore, 2009), which likely obscures the nuances of hand use. A meta-analysis of handedness studies (Papadatou-Pastou et al., 2020) that included data from over 2 million participants of mixed race and sex highlighted many of the issues of handedness studies. A major issue raised was that handedness and hand use were not uniformly defined across studies and the number of categories given for handedness ranged from 2 to more than 7 options. For instance, mixed handedness and ambidexterity are sometimes given as third options, but the terms are used interchangeably and can cause confusion. Ambidexterity refers to equal competency with either hand, while the term mixed handedness seems to be poorly defined across studies and its meaning is not clear.

Another complication is how handedness data are collected and analyzed, which varies widely across studies. The most used hand preference questionnaire is the Edinburgh Handedness Inventory (EHI), in which participants answer 10 questions about everyday hand use and then a laterality quotient is assigned to the participant based on self-reported answers. Laterality quotient classifications range from consistent left-handedness (-100) to consistent right-handedness (100), though the assigned categorical values are not themselves consistent across studies (for instance, a score of -90 might mean consistent left-handedness in one study but mixed handedness in another). While tasks are sometimes given equal weight (Cashmore, 2009, this is not always and the case, and some studies consider writing hand to be the most important factor in determining handedness values. One study assigned participants as "left-handed" based on self-reported writing hand, regardless of if the same participants indicated they used the left hand "for any" or "for all" (Papadatou-Pastou et al., 2020).

The meta-analysis further found that left-handedness values across studies ranged anywhere from 9.3 to 18.1%, with an overall estimate of 10.4% prevalence of left-handedness.

Frequency of left-handedness varied by sex (higher in males than females) and ancestry (values were higher in European populations than in East Asian or Sub-Saharan African populations), among other variables. Earlier studies also reported lower frequencies of left-handedness than more recent studies, which could possibly reflect changing cultural views of left-handedness through time. Left-handedness was previously viewed as a social stigma and use of the left hand for tasks such as writing was discouraged, possibly leading some individuals to change their dominant hand. Fear of social stigma could possibly also have led participants to falsely report hand use, which would artificially inflate the frequency of reported right-handedness (Papadatou-Pastou et al., 2020).

While the results found here do agree with a species-wide preference for right handedness in modern humans, the degree of right-directional asymmetry is slight and not in line with the high values regularly reported in the literature for handedness (90% on average) (Papadatou-Pastou et al., 2020). Handedness is often presented as a discrete variable, when instead, handedness and hand use fall along a continuum, though hand preference studies often fail to account for this. This study highlights (and falls victim to) the dangers of presenting handedness as a binary metric, when the reality is likely something more fluid and not as black and white as researchers often present it to be. Future studies on handedness and asymmetry resulting from handedness would benefit from taking these issues into account when categorizing variation based on hand or upper limb use.

Hypothesis 1 also postulated that non-human primates would not show asymmetry in the opponens pollicis enthesis because they do not have species-wide handedness and therefore would not habitually engage one hand over the other. The results from this study supported this hypothesis, with the caveat that a larger sample size would likely alter the results for *Gorilla*.

Because of the small sample size included within this study, differences between sides failed to reach statistical significance for the binomial exact test, though looking at the graphs of the DIRA data (Figures 2.12 & 2.13), it is clear there is left-directional asymmetry within the radial projection measurements for this taxon.

It is also important to note that due to small sample size, this study grouped *G. gorilla* and *G. beringei* at the genus level and did not evaluate possible species differences in enthesis expression for the taxon. Most (if not all) of the work on hand use within *Gorilla* has focused on *G. beringei* (Byrne and Byrne, 2001b; Neufuss, 2017; Neufuss et al., 2019), and not much is known about the hand use of lowland gorillas (*G. gorilla*). *Gorilla beringei* are known to extensively process their food prior to consumption and to engage in a wide variety of hand grips (Neufuss et al., 2019), and while there is currently no data to support species-wide hand preference within the genus (McGrew and Marchant, 1997), hand use data on wild populations is still scarce and more studies are needed to better understand behavioral patterns in wild populations. *G. beringei* have a more varied diet that includes more pith and other items that require more pre-consumption processing than lowland gorillas (Doran and MacNeilage, 1998; Parnell, 2001; Neufuss et al., 2019), so it is reasonable to assume they could use their hands more extensively than *Gorilla gorilla,* though more studies are needed to confirm this. Additionally, there is evidence that muscle recruitment patterns are reflected in both the forelimbs and hindlimbs of *Gorilla gorilla* (Drapeau, 2008), so it is possible these trends would extend to hand use patterns within the species. Finally, Knigge et al. (2015) found morphological differences between the postcrania of the two species related to different locomotor and ecological factors, meaning it is not unreasonable to assume that there could be differences in the enthesis expression of the two species as well based on different muscle usage between the species. Small sample size prevented species-specific analyses for this study, but future studies investigating enthesis differences between the two would benefit from analyzing entheseal expression on the species level for *Gorilla.*

Inter-Population Asymmetry in Modern Humans

Overall, the Mistihalj population has larger entheses than the Merida population. This is most likely an artifact of body size differences. The mean body size (as inferred from the geometric mean of head breadth, base breadth, and maximum metacarpal length) for the Mistihalj population is larger, and this sample also contains more males than the Merida population. These results demonstrate a strong correlation between body size (based on geometric mean) and enthesis size, which is in line with previous research (Bowland et al., 2019) that larger-bodied individuals have correspondingly larger entheses, and that males often have larger entheses than females (Milella et al., 2012), both of which could explain the size differences between the two populations. Further, while there is little demographic data available for ether population, some information is known which could shed further on the issue. The Mistihalj sample is composed of Vlahks, an indigenous Balkan ethnic group which regularly engaged in pastoral activities and who were "highly active, robust people" (Cowgill, 2010: 81). In contrast, while little information is available for the historical Merida sample, it is composed of individuals from the Yucatan, which have historically been of shorter stature and known to suffer from stunted growth patterns (Tiesler et al., 2020). Finally, while there do appear to be entheseal size differences between the two populations, neither population is more right- or left-directional than the other, and both populations exhibit overall right-directional asymmetry for the opponens pollicis enthesis.

Does Enthesis Size Scale with Body Size in Human and Non-human Primates?

Hypothesis 2 proposed that enthesis size would scale with body size in both human and non-human primates. The data from this study support this hypothesis for both populations of modern humans as well as the non-human primates. Based on both the maximum metacarpal length and the geometric mean of the base breadth, head breadth, and maximum length proportions, the Mistihalj population had overall larger body size than the Merida population. Body size (based on geometric mean) was regressed against the enthesis size using a least square's regression and a Pearson's correlation was performed to look for correlations between body size and enthesis for the modern human populations. The Pearson's correlation (r=0.77) demonstrates a strong correlation between enthesis size and body size for modern humans. These findings are in line with previous research regarding enthesis development and body size (Bowland et al., 2019), which found a link between the two in modern human populations.

While there is not much data regarding enthesis size and body size in non-human primates, Milella et al. (2014) did find that enthesis development correlates with sexual dimorphism in both *Gorilla* and modern humans, and specifically that *Gorilla* showed more pronounced differences between sexes based on qualitative assessments of enthesis development. While they did not directly correlate enthesis size with body size in their study, the results suggest that larger-bodied primates (in this case, males) would have correspondingly larger entheses due to body size differences resulting from body mass dimorphism. The results from this study found that larger individuals do have larger entheses, even when adjusting for body size differences between taxa (Figure 2.14). The results from the Pearson's correlation of geometric mean and radial projection found a strong correlation (r=0.94) for the two measurements, meaning that, across primate taxa, larger-bodied individuals have relatively larger enthesis attachment sites.

CHAPTER 3: ASYMMETRY IN THE SHAFT MODERATELY PREDICTS ASYMMETRY IN THE PROXIMAL END

INTRODUCTION

While most other primates use their thumbs mainly for locomotion, humans employ a wide variety of complex grip types required for precision manipulation (Marzke, 1997), and previous studies demonstrate that differential use of the thumb is reflected in the proximal articular surface of the first metacarpal across primate taxa (Niewoehner, 2000; Tocheri et al., 2003, 2005; Marzke et al., 2010; Marchi et al., 2017). In humans, the joint surface is distinguished by a wide trapeziometacarpal articular surface, compared with a smaller and more radioulnarly and dorsoplantarly curved surface in non-human primates (Marchi et al., 2017). The wider joint seen in humans is necessary to accommodate the larger forces passing through the joint surface during forceful precision grasping activities (Marzke, 2013). In addition to shape of the joint acting to accommodate the larger joint reaction forces, the human trapeziometacarpal joint (tmcj) is held relatively stable during opposition by many ligaments that cross the joint and protect against subluxation of the joint (Bettinger et al., 1999; Ladd et al., 2012).

Joint Shape and Stability

Stability of a joint is its ability to resist displacement in each direction. As such, a larger contact surface area (such as that seen in modern humans) contributes to an overall more stable joint (Hamrick, 1996; Marzke et al., 2010). Stability of the joint depends largely on the ligaments which cross the joint and help to hold the structures in place. In humans, these ligaments are essential to maintaining joint stability because surface contact of the joint surface is reduced during pinch movements of the thumb and index finger, leaving the joint susceptible to dorsal subluxation (Marzke et al., 2010).

As previously stated, the tmcj is a complex joint capable of movement in multiple planes of motion (Komatsu and Lubahn, 2018) that represents a constant tradeoff between joint motion and stability (Ladd et al., 2012; Kawanishi et al., 2018). There are several soft tissue structures which cross the joint and act to stabilize it against opposing muscle forces. Historically, as many as 16 ligaments have been identified to act on this joint; though more recent research has demonstrated much of the joint's stability is achieved through the action of just a few key ligaments (Bettinger et al., 1999; Edmunds, 2011; Ladd, 2012). The dorsal ligament complex (Figure 3.1), which consists of the dorsal radial ligament (DRL), the dorsal central ligament (DCL), and the posterior oblique ligament (POL), runs from the dorsal tubercle on the trapezium to the inferior aspect of the dorsal surface of the first metacarpal and fan out to insert in a deltoid-shaped appearance. The dorsal ligament complex is the strongest of the ligaments that surround the joint and plays a major role in stabilizing the joint against subluxation (Bettinger al., 1999; Kawanishi et al., 2018), which commonly occurs later in life, particularly in older females (Bettinger et al., 1999). The importance of the dorsal ligament complex is further unscored by the greater innervation of this structure compared to the volar ligaments that insert on the opposite aspect of the bone (Ladd et al., 2012).

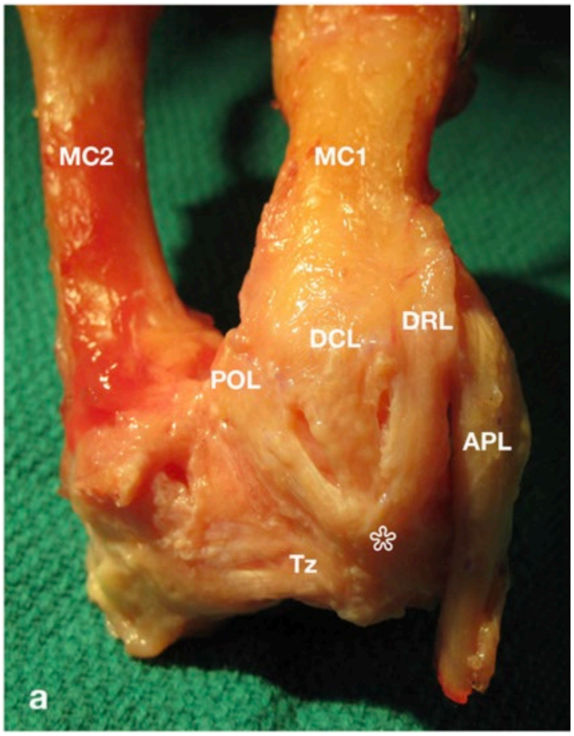

Figure 3.1. The dorsal thumb carpometacarpal ligaments as seen from the dorsal aspect of the thumb (Fig. a), illustrating the three ligaments of the stout dorsal deltoid ligament complex, including the dorsal radial ligament (DRL), the dorsal central ligament (DCL), and the posterior oblique ligament (POL). Also seen is the insertion of the abductor pollicis longus (APL) and the dorsal aspect of the second metacarpal (MC2). Figure from Ladd et al., 2012.

During opposition, the first metacarpal flexes and pronates around the dorsal portion of the bone, which acts as the center of the movement. Movement in both the palmar-radial and palmar-distal directions occurs during the sequence from radial abduction to opposition (Figure 3.2), during which time the dorsal ligaments are pulled taut, and as previously stated, serve as the major stabilizing complex for the joint through the power and precision grips (Kawanishi et al., 2012; Komatsu and Lubahn, 2018).

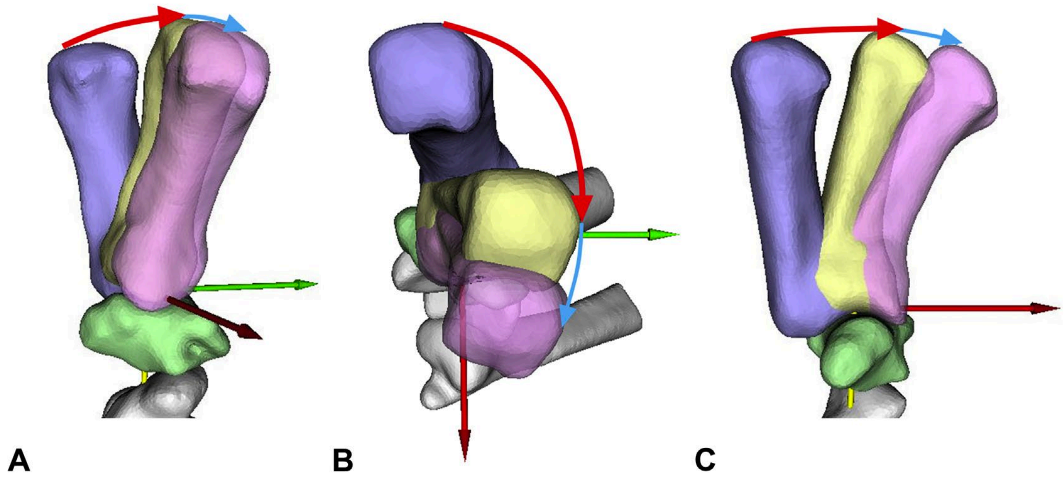

Figure 3.2. Motion of the first metacarpal during thumb opposition. The first metacarpal A abducted, B internally rotated, and C flexed on the trapezium. Curved red arrows show the motion from radial abduction (blue bone) to palmar abduction (yellow bone), and the curved blue arrows show the motion from palmar abduction to opposition (pink bone). Figure from Kawanishi et al., 2018.

Joint Shape Across Primates

The tmcj is typically saddle-shaped in humans and other catarrhine primates, which helps to facilitate opposition of the thumb to the other fingers of the hand (Marzke et al., 2010). While the shape of the joint is consistent across most catarrhine primates, curvature and mobility of the joint surface vary widely across taxa. African apes have overall more curved tmcj surfaces than *Ho. sapiens*, which aids in stability, but which limits the amount of force that can be transferred through the joint. *Gorilla* exhibit high dorsovolar curvature in the tmcj, which Marzke et al. (2010) argues is part of a suite of features that work to increase stability through the joint, but which could also be linked to documented behavior of forceful pulling and processing of vegetation within the genus (Neufuss et al., 2019). The tmcj of macaques (*M. mulatta*) is more curved at the saddle point of the joint surface compared to gibbons, bonobos, and humans, but the curvature does not extend through the entire joint surface, which becomes flatter toward the periphery of the joint surface. Overall, the joint in macaques exhibits high congruence and is relatively flat, which results in restricted mobility of the joint (Van Leeuwen et al., 2022). In contrast, humans have less curved joint surfaces, which allows for greater transmission of force, but leaves them susceptible to dorsal subluxation of the joint, particularly in older females with higher instances of degenerative bone diseases (Marzke et al., 2010).

Unlike the saddle-shaped joint present in most catarrhine primates, the trapeziometacarpal joint in hylobatids is a ball-and-socket joint (Van Leeuwen et al., 2022) that is rarely loaded during locomotion (Van Horn, 1972). The joint's range of motion is comparable to that seen in modern humans, but because the shape of the joint limits axial stabilization, it is much less stable than the saddle-shaped joint seen in other catarrhine primates. Hylobatids also do not have any reinforcement of the joint through either stronger ligaments or thenar muscles, as might be suspected to compensate for the high degree of joint mobility (VanHoof et al., 2020). Gibbons also have less soft tissue structures that pass through the joint (Van Horn, 1972; Van Leeuwen et al., 2022), which means that although they tend to match modern humans in terms of overall joint mobility, it is unlikely they can match the grip strength produced by the well-developed thenar musculature seen in modern humans (Marzke et al., 1992; Van Leeuwen et al., 2022).

Previous Work Quantifying TMC Joint Shape

Studies have shown the shape of the first metacarpal proximal articular surface reflects differential manipulative behaviors across both living and fossil hominins (Niewoehner, 2000; Tocheri et al., 2003,2005; Marzke et al., 2010). Tocheri et al. (2003) quantified the shape of the joint by generating least squares planes on the trapezial articular surfaces in humans, great apes, and fossil hominins and found distinct patterns which distinguished the living taxa from one another. Likewise, Tocheri et al. (2005) showed that humans have larger relative first metacarpal and scaphoid surfaces on the trapezium, which they explained is likely due to the regular recruitment of the thumb during forceful manipulative activities. Finally, Marzke et al. (2010) quantified curvature of the trapeziometacarpal joint surface across living primates and found that the curvature of the surface differed between humans and other living primates relative to the axial joint loads being transferred across the surface. The internal architecture of the joint surface has also been shown to reflect differential hand use across primate taxa. Stephens et al. (2016) assessed trabecular structure within the first metacarpal in humans and *Pan* and found that humans demonstrated right-directional asymmetry in the base of the bone, consistent with the species-wide preference for right-hand use.

Grip Types

Studies of hand use within primates have long focused on the different grip types employed across taxa (Marzke et al., 1992; Marzke, 1997), as they are linked to the ability to manufacture stone tools and the rise of manual dexterity (Markze, 2013). Primates employ a wide range of grip types when manipulating objects which are broadly categorized as either "precision" or "power" grips (Napier, 1956; Marzke, 1997). A precision grip is one in which the object is held between the thumb and one or more fingers, with or without the use of the palm acting to further prop the object (Marzke, 1997). Power grips are those in which the object is "strongly squeezed by the fingers, thumb, and actively by the palm" (Marzke, 1997: 92). While the ability to use precision grips was originally and erroneously attributed to only humans, it is now clear that precision grips are regularly employed across primate taxa, and what makes human distinct is their ability to produce "forceful precision grips" using a single hand to hold an object against an opposing force, such as when striking a core during stone tool manufacture (but see Gumert et al., 2009 for possible evidence of forceful precision grips in macaques) (Marzke, 2013).

Humans use a variety of forceful precision grips during stone tool manufacture and other activities requiring manual dexterity. The 3-jaw chuck grip, in which an object is held between against the index finger and the thumb and during which the thumb is abducted and opposed to the second digit (aka the "baseball grip") is commonly used to wield hammerstones during stone tool production. During this grip, the thumb is abducted and rotated to oppose the second and third digits (Marzke, 1997). Humans also use pad-to-side and cradle grips when working with flakes, all of which both oppose the thumb to the other fingers and recruit the opponens pollicis muscle (Key et al., 2018; Rolian et al., 2011; Dunmore et al., 2020).

Accommodation to loads depends on both the extent to which the orientation of the surface is normal to the loads and the degree of congruence across the joint surface during grips. In humans, the applied load during pinch grasp in humans is 12x greater than the contact load, such that if the contact load is 1kg, the applied load would be 12kg (Marzke et al., 2010). Further, contact area has been shown to be largest in opposition, with 53% of the mutual trapezium and metacarpal surfaces in contact when the thumb is loaded in opposition (Momose et al., 1999), meaning these grips would elicit the greatest bony response to applied loads through the joint. Compared to other hominins, the joint surface in humans is radially extended to better accommodate larger loads being transferred through the joint during forceful precision grasping, when the thumb is highly abducted (Marzke et al., 2010; Marchi et al., 2017). The radial extension of the proximal facet provides a larger contact area during abduction and contributes to greater stability of the joint during forceful precision grasping (Marchi et al., 2017). This is not the case in other catarrhine primates, which have lower degrees of axial loading during manipulative behavior, and which lack the radially extended facet seen in *Homo* (Marzke et al., 2010). This is especially true for hylobatids, whose ball-and-socket configuration joint shape and limited soft tissue reinforcement of the joint result in less contact surface area and less grip strength generated through the joint, respectively (Van Leeuwen et al., 2022).

Based on this information, it is predicted that (1) *Macaca* will not exhibit asymmetry of the joint surface because of the low degree of mobility through the joint as it is loaded during locomotion and because they do not regularly recruit one hand over the other when performing manipulative tasks; (2) Likewise, hylobatids should not exhibit asymmetry of the joint surface because they do not possess thenar musculature capable of exhibiting the large muscular loads needed to induce remodeling of the joint; and (3) while gorillas are known to engage their hands in a large variety of tasks that elicit multiple grip types (Neufuss et al., 2019), there is no evidence to support manual lateralization within the genus. Further, it is unlikely any manipulative activities would override the signal (or lack thereof) from routinely uniformly loading the joint during locomotion, when it is held relatively immobile. It is further predicted that humans will exhibit asymmetry of the joint surface due to differential use of the hands during high intensity activities that will unilaterally work the joint surfaces. As most joint forces incurred during forceful precision pass through the radial aspect of the tmcj (Stephens et al., 2018), it is predicted this area of the joint will exhibit the greatest levels of asymmetry. This is supported by previous work quantifying the trabecular structure of the Mc1, which found evidence of higher bone volume levels at the palmar aspect of the radial margin of the joint (Stephens et al., 2018). Finally, it is predicted the asymmetry within modern humans will be greater within the Mistihalj hunter/gatherer population than the Merida population, as previous studies have found evidence that bony architecture of the joint surface is more anisotropic in hunter/gatherer populations compared to villagers due to possible differences in loading during manipulation; it is expected this pattern of asymmetry will hold for the cortical bone (Stephens et al., 2018).

Predictions

Since humans display a species-wide pattern of right-hand dominance, and therefore recruit the muscles of the right hands more often, there should be greater joint forces passing through the joint on the right side than on the left. Conversely, non-human primates are not handed and generally use their hands for locomotion, in which both hands are placed in contact with a substrate, and during which the thumb is rarely engaged (Matarazzo, 2013). It can therefore be hypothesized that the proximal articular surface of the first metacarpal would reflect differential hand use due to hand use. Specifically, I hypothesize that (1) humans will show right-directional asymmetry in the proximal surface of the trapeziometacarpal joint, particularly on the radial aspect of the joint surface as this area is subject to the highest loads while the thumb is abducted during fine precision grasping activities; (2) non-human primates will not show asymmetry of the tmcj joint surface, as they predominantly load the thumb bilaterally during locomotion and do not regularly engage in fine precision grasping activities; and (3) the attachment site for the dorsal ligament complex (Figure 3.1) in modern humans will show evidence of asymmetrical loading as it is recruited during opposition of the dominant hand when engaged in power and precision grips.

METHODS

Meshes were segmented after alignment using the CloudCompare software. The alignment process is described in more detail in a previous chapter. The proximal end was segmented from the rest of the metacarpal bone by placing a line across the bone at the widest margin of the shaft on the radial and ulnar sides of the palmar shaft using the segmentation tool. Distances between the left and right meshes were then calculated using the methods detailed in the previous chapter. This process is further visualized in Figure 3.3 A and B.

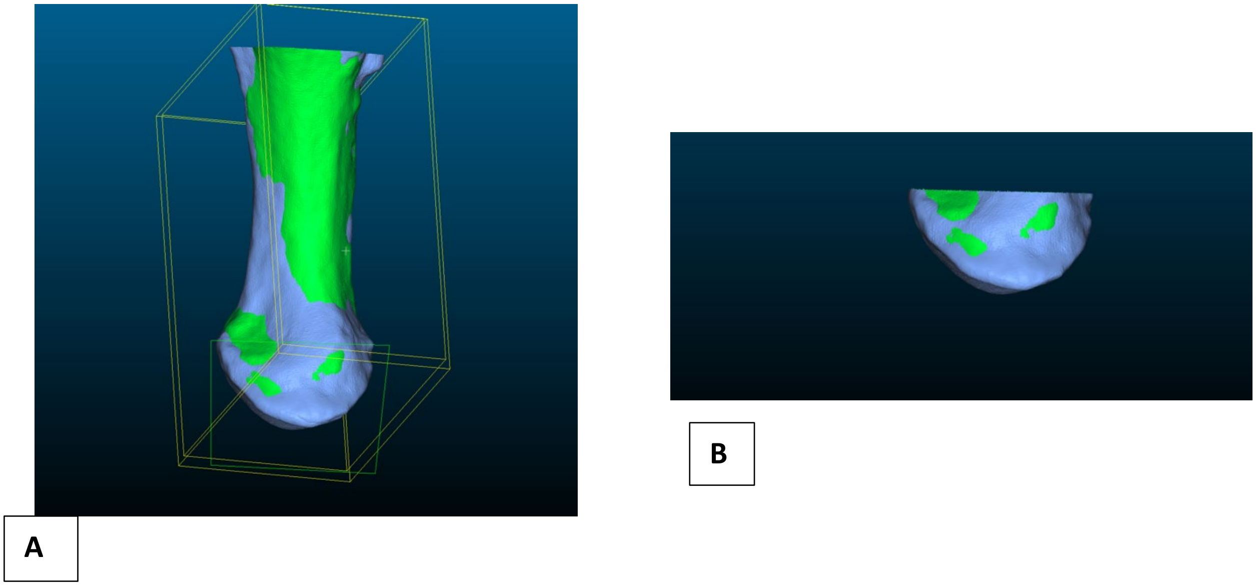

Figure 3.3. The metacarpal before proximal end segmentation. B) The distal end after segmentation.

After isolating the shaft, weighted mean averages (asymmetry scores) of the distances between right and left sides were calculated per specimen based on the distances obtained from CloudCompare overlays. Per specimen distances are output from CloudCompare into 8 categories or “bins” based on number of times the observation fell within a given bin. For each bin, (1a) multiply the number of individuals by the median of each bin and (1b) repeat the calculation for each bin; (2) sum the values calculated in 1b for all bins, and (3) divide the result from step two by the total number of observations for each bin.

RESULTS

Asymmetry in the Mc1 Proximal End in Humans

Figure 3.4 visualizes the differences between taxa in the weighted asymmetry scores for the proximal end of the first metacarpal. Median asymmetry scores for each taxon are listed above the boxplot in the figure. These results are further summarized in Tables 3.1 and 3.2. As with the shaft asymmetry scores, taxa are readily distinguished based on asymmetry in the proximal end of the bone, and the results from this segmented portion largely follow those from the shaft. *Macaca* and *Gorilla* exhibit no asymmetry for this portion of the bone, while *Hylobates* is slightly more right-directional than in the shaft, though not significantly different from 0. As with the shaft, *Ho. sapiens* are right-directional, though the magnitude of right-directional asymmetry is less than in the shaft. Table 3.2 displays the result of a one-way ANOVA with a Tukey's post-hoc pairwise comparison for proximal end asymmetry scores between taxa. As with the shaft segment, the non-human primates are significantly different from *Ho. sapiens* but are not significantly different from each other.

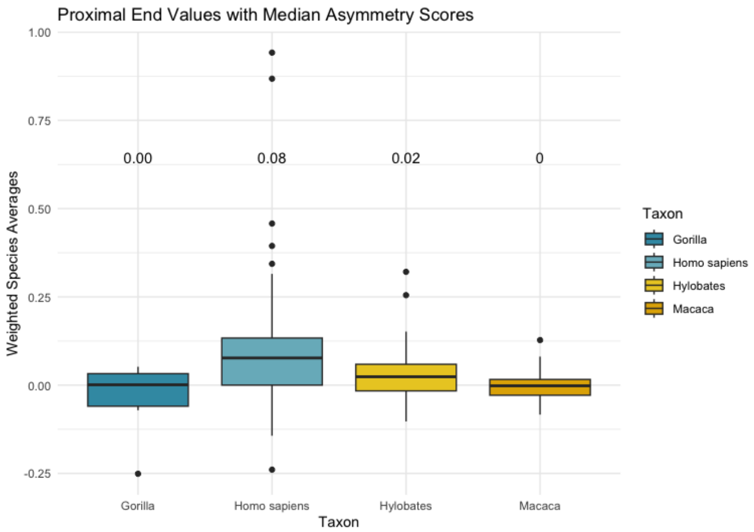

Figure 3.4. Boxplot showing the range of values with the species weighted average median values displayed above each taxon.

Table 3.1. Species weighed averages for the CloudCompare shaft data. Negative values indicate left-directional asymmetry while positive values indicate left-directional asymmetry.

Human	*Gorilla*	*Macaca*	*Hylobates*
0.1	-0.02	0.00	0.03

Table 3.2. Results of a one-way ANOVA with Tukey's post-hoc pairwise comparison. Significant values are in bold. Significance is based on *p*=0.05.

Homo sapiens - Gorilla	*Hylobates - Gorilla*	*Macaca - Gorilla*	*Hylobates - Homo sapiens*	*Macaca - Homo sapiens*	*Macaca - Hylobates*
0.0266	Not sig.	Not sig.	**0.026**	**<0.001**	Not sig.

Figure 3.5 shows the result of a ridge plot of asymmetry scores per taxon for the proximal end of the metacarpal. As with the shaft segment, there is a large range of variation for the *Ho. sapiens* values, which stretches the confidence interval and causes the distribution for *Ho. sapiens* to be flatter than in the non-human primates. However, the median and mode are clearly positive, indicating right-directional asymmetry for *Ho. sapiens*. Additionally, after isolating the values from *Ho. sapiens* that lie outside the range of values for the symmetrical *Hylobates* and *Macaca (*Figure 3.6*),* there is once again a clear right-directional signal that largely follows the

right/left hand dominance frequency data for modern humans seen in the shaft portion of the bone (Papadatou-Pastou et al., 2020).

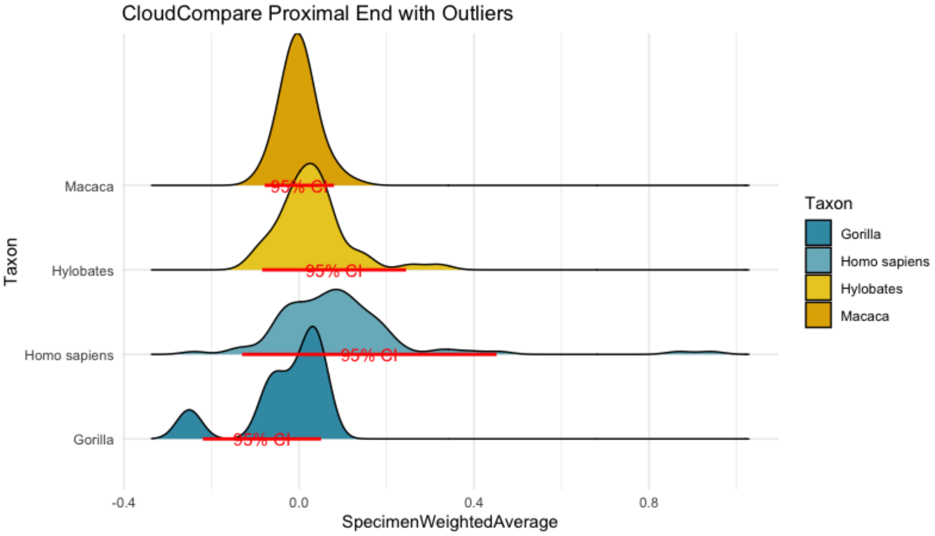

Figure 3.5. Density plots of the weighted asymmetry scores per taxon. 95% confidence intervals are labeled and indicated in red. Negative values indicate left-directional asymmetry, while positive values indicate right-directional asymmetry.

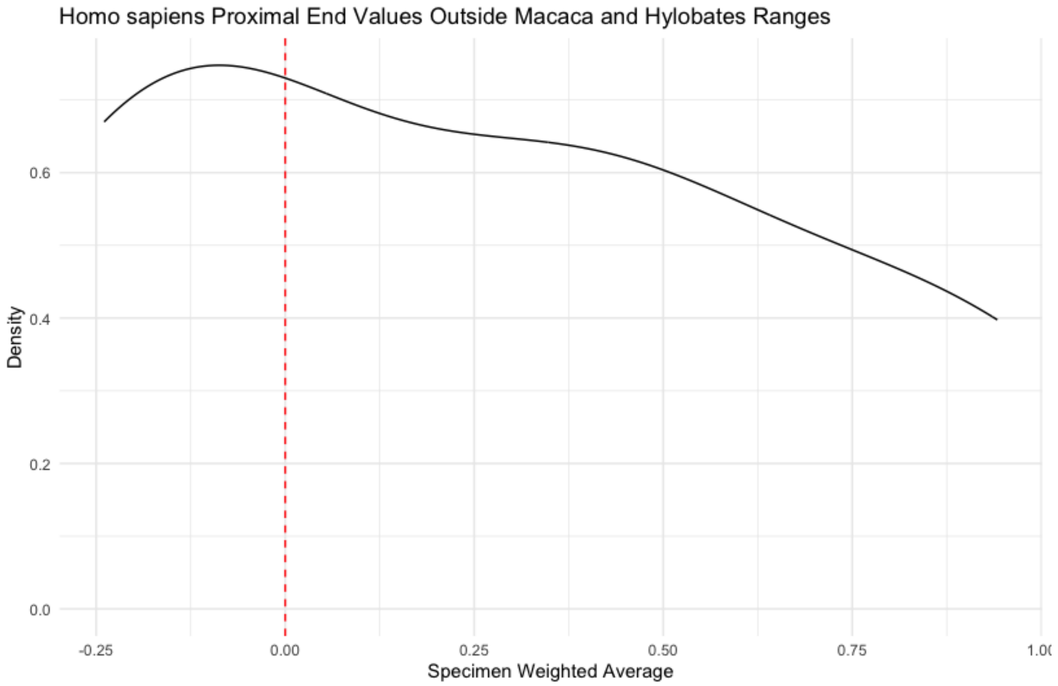

Figure 3.6. Specimen weighted averages for the *Ho. sapiens* specimens that lie outside the range of values for *Macaca* and *Hylobates*. The red line denotes 0. Positive values indicate right-directional asymmetry, while negative values indicate left-directional asymmetry.

Interpopulation Differences in Modern Humans

There is not much demographic data available for either population included here, but the Mistihalj population is composed of hunter/gatherers (Cowgill, 2010), who would have been highly mobile and regularly engaged in varied loading regimes that required a diverse set of grip types during daily tasks (Stephens et al., 2016). While information on the Merida population is largely absent, there is nothing to suggest they also engaged in a hunter/gatherer lifestyle (Tiesler et al., 2020). Previous work (Stephens et al., 2018) found that forager populations showed evidence of more varied loading patterns compared to post-agricultural groups in multiple dimensions of first metacarpal trabecular bone. It is therefore expected similar trends would be found in these two samples if the Mistihalj population was regularly engaging in more strenuous and varied loading patterns throughout the lifetime because of their hunter/gatherer lifestyle.

The results of this study do not support this prediction, as there is no difference in the means of the weighted asymmetry scores for the two populations of modern humans, and both populations show evidence of right-directional asymmetry in the proximal portion of the bone (Figure 3.7). It is important to note, however, that the lack of demographic data available for either population, especially the Merida population, makes drawing any conclusions about the behavioral differences of the populations problematic. More research is needed on populations with precise demographic data to more accurately assess if different lifetime activity patterns are reflected in the proximal articular surface of the first metacarpal between populations of modern humans.

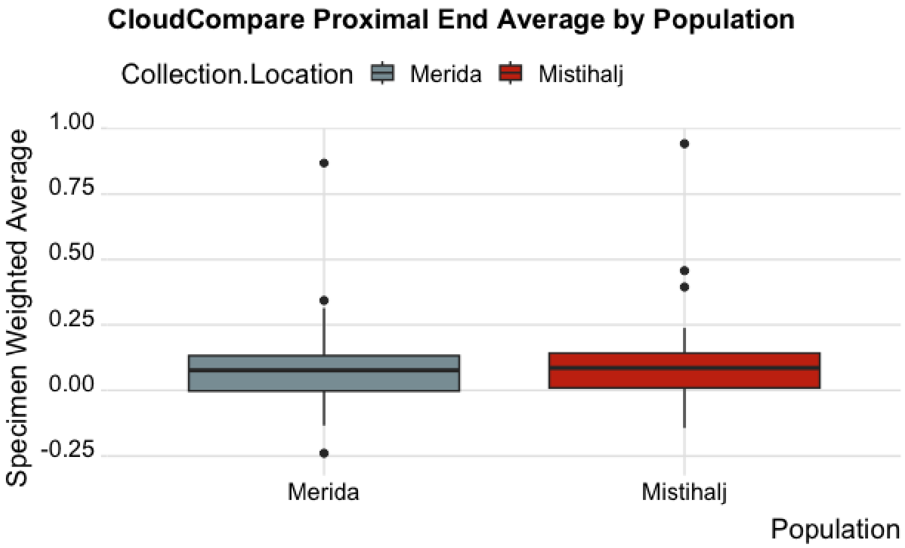

Figure 3.7. Boxplot of the proximal end specimen averages for each population of modern humans.

Correlation Between Shaft and Proximal End Asymmetry

It was predicted that asymmetry within the shaft portion of the bone would predict asymmetry in the proximal portion, as recruitment of the powerful intrinsic thenar muscles, including the opponens pollicis muscle, results in large joint reaction forces being passed through the joint. There is a moderate correlation (*r*=0.66) (Figure 3.8) between the shaft and proximal end weighted asymmetry values, indicating a moderate amount of the asymmetry present in the proximal segment of the bone is predicted by asymmetry in the shaft. This provides support for the hypothesis that the joint is at least partially adapted to accommodate the large joint reaction forces produced by powerful intrinsic thenar muscles seen in later *Ho. sapiens* (Bowland et al., 2021).

Previous research has demonstrated the shape of the joint and proximal Mc1 shaft is correlated with hand use patterns in hominins (Tocheri et al., 2003; 2005; Marchi et al., 2017). Specifically, the expanded proximal base of the Mc1 in recent *Ho. sapiens* has been hypothesized to be adaptive for dissipating stress from repeated recruitment of powerful intrinsic pollical muscles (Bowland et al., 2021). Asymmetry in the proximal portion of the bone is therefore to be expected if the expanded base is indeed adapted to dissipating powerful muscle forces; though further research is needed to fully understand the functional significance of the asymmetry results seen here. However, it is important to note that this analysis incorporates more than just the proximal articular surface, and so any explanation of the asymmetry seen here must consider the other portions of the bone that could be driving asymmetry, such as the soft tissue structures that surround the joint (Ladd et al., 2012).

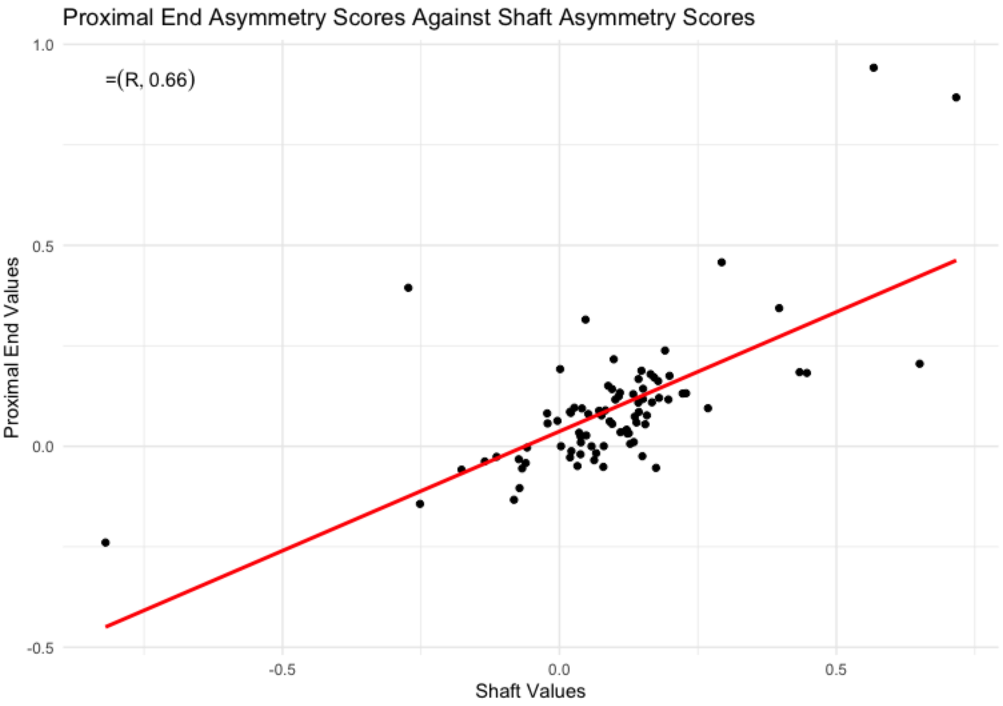

Figure 3.8. Linear regression of proximal end asymmetry scores against shaft asymmetry scores in humans.

Location of Asymmetry in the Proximal Facet

It was predicted that the greatest levels of asymmetry in the proximal articular facet would be on the radial portion of the articular surface, as the joint reaction forces incurred during stable grips (high-force, power grips, etc.) are mostly displaced through the radial side of the hand (Stephens et al., 2018). This study failed to find evidence to support this prediction, as the specimens which show the greatest levels of asymmetry in the proximal facet do not exhibit it in the predicted region of the articular surface. Instead, asymmetry in the proximal facet seems to be concentrated either on the dorsal aspect on the ulnar side (Figure 3.9) or spread uniformly across the entire surface of the facet (Figure 3.10). Further, as predicted, when asymmetry at the dorsal margin of the facet is present, it is generally right-directional, as visualized by the red color scale on the heat maps displayed in Figure 3.9. However, as shown in the case of HPM

61056 (Figure 3.9), the pattern of asymmetry is sometimes left-directional, as indicated by the blue color scale of the heat map.

Variation is also driven by differences across the entire joint surface, as shown in specimens HPM 9122 and HPM 61010 in Figures 3.9 and 3.10. In the case of HPM 61010, the variation driving the high asymmetry score comes from the right articular surface being larger overall, rather than in one area of concentrated variation. This is also somewhat true for HPM 9122, which does exhibit high levels of concentrated asymmetry at the dorsal region, but also appears to be overall right directional across the entire joint surface, as shown by the yellow color scale of the heat map.

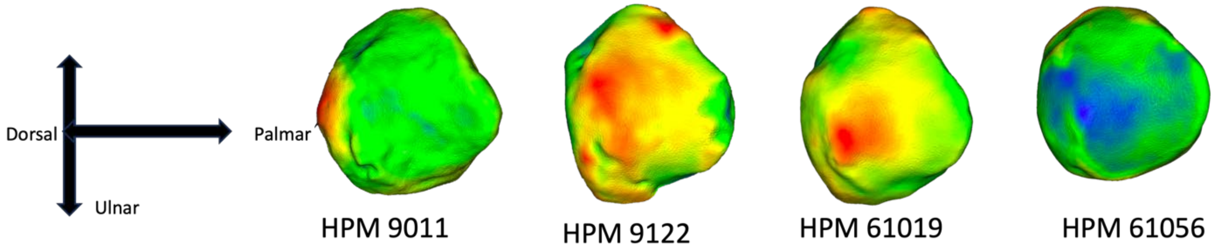

Figure 3.9. The proximal articular facet in individuals that exhibit high concentrations of asymmetry at the contact area for the trapezium during radial abduction.

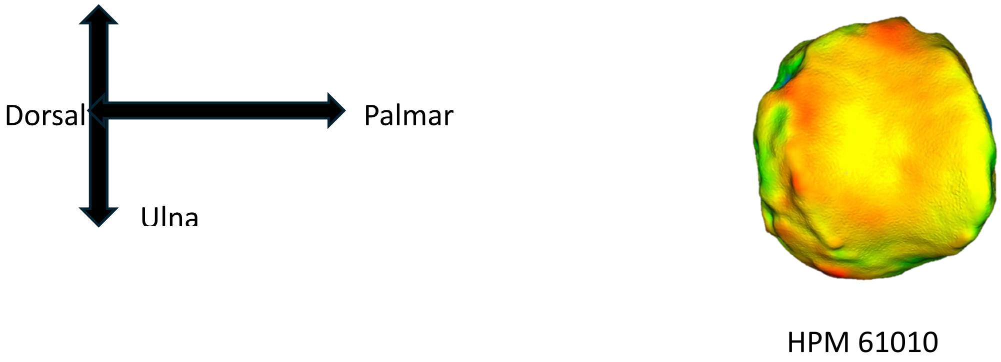

Figure 3.10. Showing the proximal articular facet in which the increased right-directional is spread across the joint surface, rather than concentrated on a specific area.

Asymmetry at the Dorsal Ligament Complex Attachment Site

The right-directional asymmetry seen in the proximal portion of the bone is complex, and likely attributable to multiple factors that can induce bony change. Results from the heat maps generated on the proximal portion of the bone (Figure 3.11) indicate that at least some degree of asymmetry seen within the proximal portion is likely due to recruitment of the dorsal ligament complex (Figure 3.1), which, as previously stated, is largely responsible for stabilizing the trapeziometacarpal joint during flexion (Bettinger al., 1999; Kawanishi et al., 2016). The dorsal ligament complex is regularly recruited by the dominant hand during precision and power grips (Bettinger et al., 1999) and is active during manual precision grasping. The ligaments tighten during flexion and act in concert with other muscles during the last phase of opposition to stabilize the joint (Edmunds, 2011; D'Agostino et al., 2017), meaning it is recruited in addition to the opponens pollicis muscle during opposition of the thumb (D'Agostino et al., 2017).

While there is a growing body of research into the soft tissue attachment sites of the hand and their relationship to bony morphology (Marzke et al., 2007; Cashmore and Zakrzewski, 2013; Karakostis and Lorenzo, 2016), little focus has been placed on the ligamentous contribution to flexion and opposition. It is beyond the scope of the current project to further investigate the functional signal of this ligamentous attachment and its contribution to pollical metacarpal asymmetry, though further work focusing on this attachment area would enable researchers to better understand the role it plays in contributing to precision and power grips, and ultimately, its contribution to asymmetry in the first metacarpal.

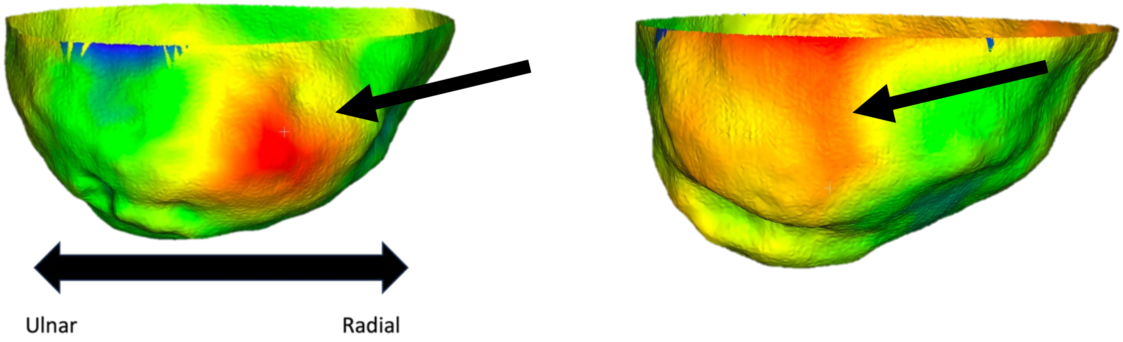

Figure 3.11. HPM9011 and HPM 9160, respectively, proximal ends shown in dorsal view. The black arrows indicate the concentrated area of right-directional asymmetry at the insertion site for the dorsal ligament complex.

DISCUSSION

Asymmetry in the Proximal Portion is Partially Explained through Radial Abduction and Flexion

The combination of asymmetry concentrated at both the DLC attachment site, and the dorsal margin of the proximal articular facet could indicate a pattern of repeated radial abduction and flexion through the trapeziometacarpal joint, as in the case of grasping a baseball (the 3-jaw chuck grip). During the 3-jaw chuck grip, the thumb is flexed, radially abducted, and opposed (Marzke, 1997), which recruits the opponens pollicis muscle and the dorsal ligament complex (Bettinger et al., 1999). During opposition of the thumb, the first metacarpal base rotates and the dorsoradial ligament tightens, causing the palmar beak to lock against the palmoulnar region of the trapezium to stabilize the joint (D’Agostino et al., 2017; Stephens et al., 2018). Further, as shown in Figure 3.12 , the area of contact between the trapezium and first metacarpal during radial abduction is greatest at the dorsal margin of the articular facet (Momose et al., 1999), which would explain why this is the area of greatest asymmetrical variation is found within the proximal facets included here (Figure 3.12).

This interpretation would be consistent with a similar transfer of kinetic energy through the joint during power or precision grips (Tocheri et al., 2003, 2005; Stephens et al., 2018). This could also partially account for the correlation in the weighted asymmetry scores between the shaft and the proximal segment, as forces through the joint are highest during opposition of the thumb (Momose et al., 1999) when the opponens pollicis muscle is recruited and the joint reaction forces are passed through the joint surface. However, it is beyond the scope of this project to fully evaluate the compressive loads passed through the joint surface during opposition, and future research is needed to fully understand the role the dorsal ligament complex plays in stabilization of the joint and how it affects asymmetry of the metacarpal.

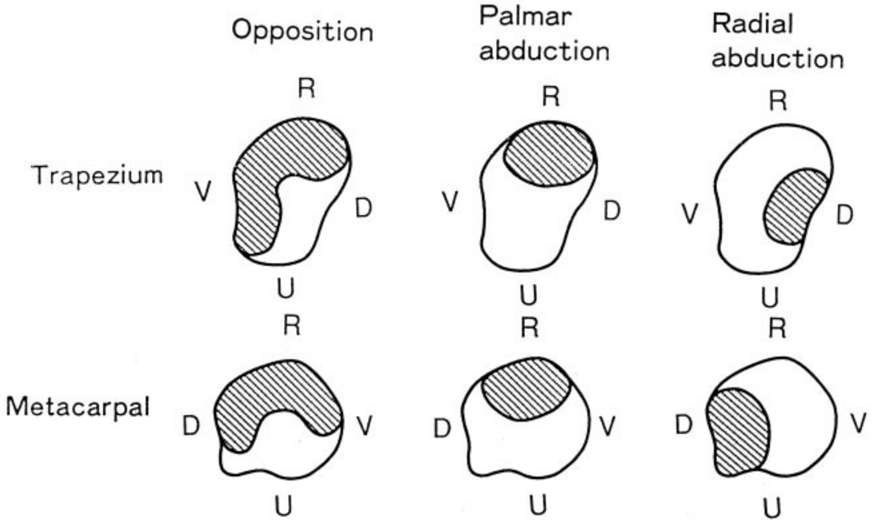

Figure 3.12. Contact area of the trapezium on the proximal articular surface of the first metacarpal. D, dorsal; V, volar; U, ulnar. Figure from Momose et al., 1999.

Proximal Segment Asymmetry is Partially Explained through Upper Limb Asymmetry

The right-directional asymmetry present in the proximal end of the bone is likely complex and attributed to multiple factors, one of which is fluctuating asymmetry present in the upper limbs. Fluctuating asymmetry refers to random variation in metric properties between the right and left sides of the body and can account for up to 1% of observable asymmetry. It is caused by developmental and environmental factors influencing bone growth, and while it does not generally override the signal from functional, directional asymmetry, it is important to note the possibility of its influence here (Cashmore, 2009).

In addition to fluctuating asymmetry, multiple studies have found the dominant limb is usually larger, which likely contributes to some degree of whole-bone asymmetry, in addition to the localized asymmetry noted in the metacarpal shaft. Bilateral asymmetry of the entire upper limb is well-documented within humans (Ruff and Jones, 1981) and is usually attributed to the high levels of right-limb dominance seen in modern humans (Roy et al., 1994). The pattern of right-limb dominance asymmetry extends to the hands, where research has shown that the dominant-side hand was larger in both cross-sectional area and bone strength, regardless of hand preference (i.e., left handers also larger measurements on the left side). This finding led Roy et al. (1994:203) to state, "handedness leads to periosteal and endosteal expansion of the [second] metacarpal cortex on the dominant side," which would explain why there is asymmetry that extends beyond the muscle attachment site on the dominant hand. Lazenby et al. (2008) also found right-directional asymmetry in measures of strength for midshaft geometry of the trabecular bone in the second metacarpal, which they attributed to right-hand dominance causing increased muscle recruitment and remodeling on the dominant side hand.

Finally, while limb asymmetry is not as extensively studied in non-human primates, Sarringhaus et al. (2005) found significant left-directional asymmetry in the subperiosteal bone of chimpanzee humeri, which they argued could provide evidence of limb laterality within chimpanzees. This previous research supports the hypothesis that at least some degree of the asymmetry seen within the proximal portion of the pollical metacarpal is explained by whole-bone asymmetry that, while functionally important, is not as straightforward as the signal seen in the more localized asymmetry of the muscle insertion site. Further research is needed to better understand how dominant limb asymmetry influences asymmetry in the proximal portion of the first metacarpal, as seen here.

CONCLUSION

The goal of this study was to determine if asymmetry in the shaft portion of the bone predicted asymmetry in the proximal portion, and the results confirm proximal end asymmetry is correlated with asymmetry in the shaft portion of the bone (r=0.66). As with the Mc1 shaft, modern humans exhibit right-directional asymmetry in the proximal portion as well, while the non-human primates exhibit little to no asymmetry. These results further support the hypothesis that handedness influences bone shape within modern humans, while non-human primates, who do not exhibit handedness and mainly use their hands for locomotion, are not loading the joint asymmetrically and therefore do not show evidence of asymmetrical muscle recruitment.

However, shaft asymmetry cannot fully account for the asymmetry seen within the proximal segment of the bone and it is likely the results seen here are driven by multiple functional signals. Another source of asymmetry appears to be the attachment site for the dorsal ligament complex, which acts to stabilize the joint during flexion (Bettinger et al., 1999). The ligament complex acts in conjunction with the thenar musculature at the end phase of opposition to flex and rotate the joint (Edmunds, 2011; D'Agostino et al., 2017), which would explain the evidence of asymmetrical recruitment in modern humans at the dorsal ligament complex attachment site as it is recruited during many key grips, including the 3-jaw chuck grip. Repeated use of the 3-jaw chuck grip, in which the thumb is radially abducted (Marzke, 1997), could also explain pattern of asymmetry at the dorsal margin of the bone, as this is the area of the facet which is contact with the trapezium during radial abduction (Momose et al., 1999).

The anthropological literature frequently neglects the significance of the dorsal ligament complex in stabilizing the joint during flexion. However, it comes into play during essential grips and could be one of the structures contributing to the large forces that necessitated the proximal joint expansion observed in later *Ho. sapiens* (Marchi et al., 2017). This complex plays a pivotal role in stabilizing the joint during flexion, but its importance is often overshadowed by the predominant focus on the hard tissue of the proximal facet (Tocheri et al., 2003; Marchi et al., 2017). In contrast, the clinical literature extensively recognizes the importance of these soft tissue structures because of the role they play in contributing to arthritis and joint degradation later in life (Bettinger et al., 1999; Edmunds, 2011; Kawanishi et al., 2018). To better understand the potential role these ligaments play in the observed proximal end asymmetry, it is essential for future research to delve into the biomechanical influence and remodeling aspects associated with them.

CHAPTER 4: ASYMMETRY IN THE METACARPAL SHAFT AND DISTAL END

INTRODUCTION

The high degree of mobility present in the human thumb stems largely from the proximal trapeziometacarpal joint, and much of the literature (Marzke, 1997; Tocheri et al., 2003; Marchi et al., 2017) on the manipulative ability of the humans has focused on this area, largely ignoring the other joints that also comprise the thumb. However, the thumb also includes the metacarpophalangeal (MCP) and interphalangeal joints (IP), and all three joints work in concert during thumb opposition (Imaeda et al., 1992; Li and Tang, 2007; Galletta et al., 2019). As such, kinematic movements during thumb opposition include movement in multiple directions across the three joints, and the joints are highly coordinated in flexion (Li and Tang, 2007; Galletta et al., 2019). Previous studies of human first metacarpals (Mc1) (Stephens et al., 2016; 2018; Dunmore et al., 2020) found the MCP joint trabeculae is more responsive to loading patterns than the proximal end and found right-directional asymmetry in the Mc1 head in humans (Stephens et al., 2018), which corresponds to the right-hand dominance within modern humans. It is therefore expected that modern humans will show right-directional asymmetry within the distal portion of the first metacarpal because of right-handedness, while non-human primates will not exhibit asymmetry, as they do not display any level of species-level handedness. Further, it is expected the asymmetry present within the modern humans will be largely where the ulnar and radial collateral ligaments insert, as they work to stabilize the MCP joint during flexion used in power and precision grips (Galletta et al., 2019).

Joint Shape and Stability

The human MCP joint has been described as a ball-and-socket joint with three degrees of freedom (Imaeda et al., 1992). Movement at the joint occurs mainly in the sagittal plane (flexion/extension), though it is capable of a limited range of abduction and adduction (Barmakian, 1992; Tang, 2011). It is relatively flat in humans compared to other great apes, which provides stability for precision and pinch grasping by limiting dorsopalmar motion and preventing nearly all radiopalmar motion at the joint (Galletta et al., 2019). However, the shape does vary considerably even within humans, and range of motion at the joint has been shown to vary depending on the shape of the joint. For example, flatter Mc1 heads have a smaller range of motion than more rounded heads (106 degree versus 77 degrees), and women have a more rounded first metacarpal head than men, resulting in a higher average range of motion through the joint in women compared to men (Yoshida et al., 2003).

Joint Shape in Non-Human Primates

There is little quantitative research on the morphology of the Mc1 head in *Gorilla*, and it is unclear how exactly the morphology of the joint correlates with range of motion in the genus. The MCP head breadth is comparable to humans (Susman, 1998), which could indicate a similar range of motion through the joint. Also, like humans, *Gorilla* have large epicondyles, which could imply the presence of large, well-developed collateral ligaments to aid in stabilizing the joint. However, the *Gorilla* Mc1 head is more rounded compared to humans, which could mean the joint is more mobile and less adapted for large joint reaction forces, relative to the flatter articular surface present in humans. *Gorilla* also lack the larger radial palmar condyle seen in humans, which is thought to correlate with a larger radial collateral ligament to cope with greater forces passed through the joint during forceful manipulation, though this is currently untested (Galletta et al., 2019). Finally, while the abductor pollicis longus does not differentiate into a distinct extensor pollicis brevis as in humans, (Diogo et al., 2012) it does insert onto the proximal phalanx, which could indicate increased thumb dexterity within the genus (Dunmore et al., 2020).

While there is little quantitative literature on the MCP joint in humans, (Galletta et al., 2019), even less literature exists on the joint in hylobatids or macaques. Tuttle (1969) stated the joint has an extremely limited range of motion in hyperextension and side-to-side deviation while grasping objects, and that movement in these planes in further limited by the capsular ligaments of the joint. However, he did note that flexion in the joint is “very permissive” and allows the thumb to oppose many objects, such as seen when climbing vertical substrates (Tuttle, 1969:165). Even less has been written about the joint in macaques. Though as in other primates, the joint is primarily a hinge joint that is mainly capable of flexion and extension, permitting some degree of abduction and adduction through the joint (Thompson, 2020; Van Leeuwen et al., 2022). In contrast to many other primates, however, the MCP joint of macaques is more mobile than the trapeziometacarpal joint and is recruited when thumb mobility is needed for complicated manual tasks, while the trapeziometacarpal joint remains relatively restricted (Van Leeuwen et al., 2022).

Soft Tissue Anatomy of the Joint

The MCP joint functions mainly as a hinge joint in most primates (Tuttle, 1969) and in humans, is crossed by radial and ulnar collateral ligaments that become taut during flexion and help stabilize the joint during precision and power grips (Barmakian, 1992; Stephens et al., 2018). These ligaments originate on the epicondyles of the metacarpal head and extend toward the volar (palmar) aspect of the proximal phalanx (Barmakian, 1992; Imaeda et al., 1992; Galletta et al., 2019). The ulnar and radial collateral ligaments act as the primary stabilizers of the MCP joint (Figure 4.1), though the ulnar collateral ligament is the stronger of the two ligaments (Barmakian, 1992; Tang, 2011). Both ligaments include a proper and accessory portion and range from 4-8 mm wide and 8-12 mm long. The proper ulnar collateral ligament (UCL) arises from the metacarpal head and extend to the proximal volar aspect of the proximal phalanx, while the accessory UCL arises on the palmar aspect and is contiguous with the proper UCL and attaches to the phalanx and volar plate. The radial collateral ligament (RCL) is similar except that is arises more dorsally on the metacarpal condyle (Barmakian, 1992). During flexion and extension, the ligaments become taught and provide lateral stability to the joint against radial and ulnar stress, accentuating the hinge-like motion of the joint (Tang, 2011; Galletta et al., 2019).

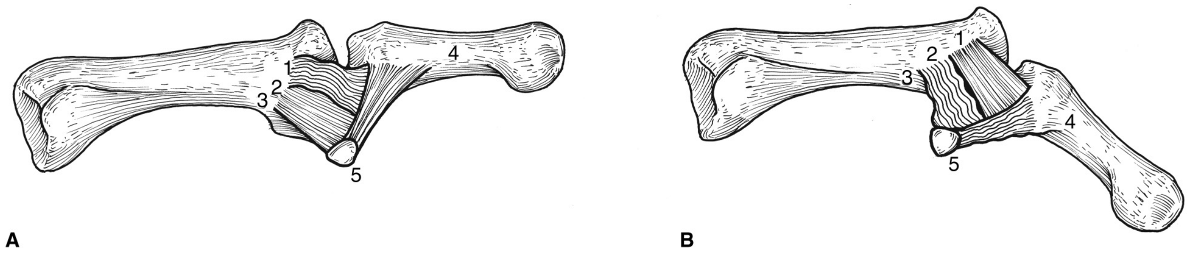

Figure 4.1. The collateral ligaments of the thumb metacarpophalangeal joint. A, In extension, the accessory collateral ligament (2) and volar plate (3) are taut, whereas the proper collateral ligament (1) is lax. B, In flexion, the proper collateral ligament is taut, and the accessory collateral ligament and volar plate are lax. 4 = proximal phalanx, 5 = sesamoid bone. In both images, left is proximal, and right is distal. Modified from Tang, 2011.

In addition to the collateral ligaments, the joint is also stabilized by intrinsic and extrinsic muscles that cross the joint. The extrinsic muscles crossing the joint provide dynamic stabilization during flexion and include the extensor pollicis longus, the flexor pollicis longus, and the extensor pollicis brevis. Humans are unique among great apes in possessing a flexor pollicis longus and an extensor pollicis brevis, which are part of the flexor digitorum profundus and the abductor pollicis longus, respectively in most other primates (both muscles are present in hylobatids, though they attach to the Mc1 base and adjacent carpals instead of the proximal pollical phalanx as in humans) (Diogo et al., 2012; Lemelin and Diogo, 2016). Intrinsic muscles that stabilize the joint include the abductor pollicis brevis, the flexor pollicis brevis, and the adductor pollicis, which provides dynamic resistance to pinch and grasp activities (Tang, 2011). The predominant role of the intrinsic muscles is closely related to the generation of low forces but involved in a predominant role in precision grip, making them important for everyday activities (Maier and Raymond, 1995).

Predictions

Humans display right-hand dominance, and therefore, recruit the muscles of the right hand more often. Therefore, they should induce greater joint forces through the distal Mc1 joint on the right side than on the left. Conversely, non-human primates are not handed and use their hands mainly during locomotion, in which both hands are placed in contact with a substrate, and during which the thumb is rarely engaged (Matarazzo, 2013). It is therefore hypothesized that the distal portion of the first metacarpal will reflect differential hand use due to handedness within modern humans. Specifically, I hypothesize that (1) humans will show right-directional asymmetry in the distal articular portion of the metacarpal, particularly on palmar epicondyles, as this is where the radial and ulnar collateral ligaments attach that are recruited to stabilize the joint during flexion, as in many pinch and precision grasps; (2) non-human primates will not show asymmetry distal segment, as they predominantly load the thumb bilaterally during locomotion and do not regularly engage in fine precision grasping activities.

METHODS

Meshes were segmented after alignment using the CloudCompare software. The alignment process is described in more detail in a previous chapter. The proximal end was segmented from the rest of the metacarpal bone by placing a line across the bone at the widest margin of the shaft on the radial and ulnar sides of the palmar shaft using the segmentation tool. Distances between the left and right meshes were then calculated using the methods detailed in the previous chapter. This process is further visualized in Figure 4.2 A and B.

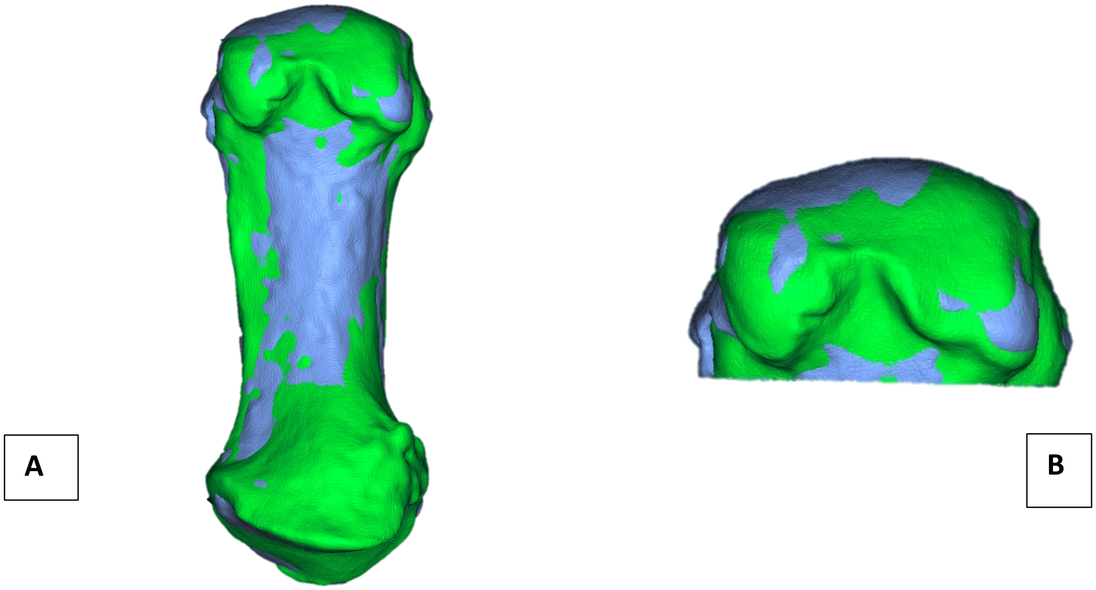

Figure 4.2 A and B. A) The metacarpal before segmentation; B) The distal end after segmentation.

After isolating the shaft, weighted mean averages (asymmetry scores) of the distances between right and left sides were calculated per specimen based on the distances obtained from CloudCompare overlays. Per specimen distances are output from CloudCompare into eight categories or "bins" based on number of times the observation fell within a given bin. For each bin, (1a) multiply the number of individuals by the median of each bin and (1b) repeat the calculation for each bin; (2) sum the values calculated in 1b for all bins, and (3) divide the result from step two by the total number of observations for each bin. A one-way ANOVA with a Tukey's post-hoc pairwise comparison was used to compare the magnitude of differences for asymmetry between taxa. To determine if distal end asymmetry is predicted by asymmetry in the shaft, proximal end weighted asymmetry scores were regressed against the weighted asymmetry values from the shaft and a Pearson's correlation coefficient was calculated to capture the association between the two sets of scores. Males and females were analyzed together as no significant differences in asymmetry were found between sexes.

RESULTS

Interpopulation Differences in Modern Humans

There is not much demographic data available for either population included here, but the Mistihalj population is composed of hunter/gatherers (Cowgill, 2010), who would have been highly mobile and regularly engaged in varied loading regimes that required a diverse set of grip types during daily tasks (Stephens et al., 2016). While information on the Merida population is largely absent, there is nothing to suggest they also engaged in a hunter/gatherer lifestyle (Tiesler et al., 2020). Previous work (Stephens et al., 2018) found that forager populations showed evidence of more varied loading patterns compared to post-agricultural groups in multiple dimensions of first metacarpal trabecular bone. It is therefore expected that similar trends would be found in these two samples if the Mistihalj population was regularly engaging in more strenuous and varied loading patterns throughout the lifetime because of their hunter/gatherer lifestyle.

The results of this study do not support this prediction, as there is no significant difference in the means (p=.84) of the weighted asymmetry scores for the two populations of modern humans, and both populations show evidence of right-directional asymmetry in the proximal portion of the bone (Figure 4.3). It is important to note, however, that the lack of demographic data available for either population, especially the Merida population, makes drawing any conclusions about the behavioral differences of the populations problematic. More research is needed on populations with precise demographic data to more accurately assess if different lifetime activity patterns are reflected in the proximal articular surface of the first metacarpal between populations of modern humans.

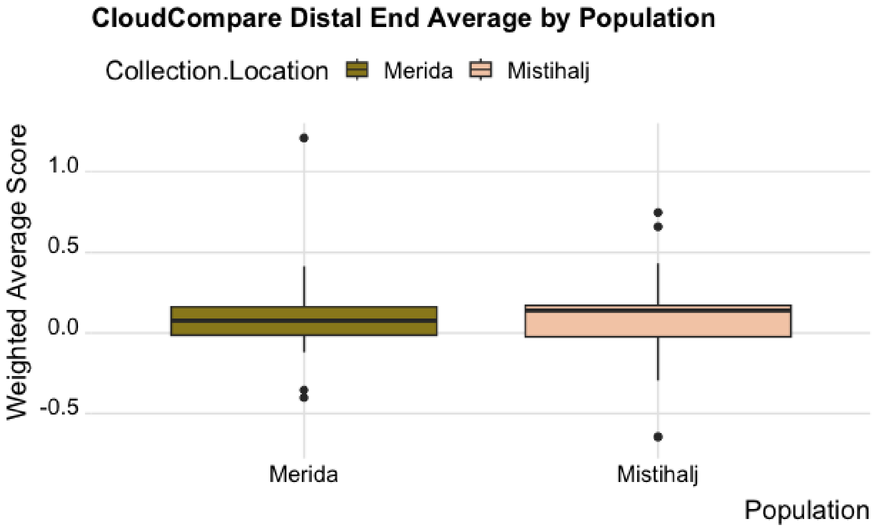

Figure 4.3. Specimen weighted averages for both populations of modern humans. Negative values indicate left-directional asymmetry, while positive values indicate right-directional asymmetry.

Asymmetry Across Taxa

Figure 4.4 visualizes the differences between taxa in the weighted asymmetry scores for the distal end of the first metacarpal. These results are further summarized in Table 4.1. Taxa are easily distinguished based on levels of asymmetry for the distal segment. *Hylobates* and *Macaca* once again show very limited levels of asymmetry and barely deviate from the null hypothesis of symmetry (0 variation). *Gorilla* shows left-directional asymmetry that is slightly more pronounced than in the proximal end or the shaft segment. *Homo sapiens* again exhibit right-directional asymmetry values that are much higher than the other taxa, as with both the proximal portion and the shaft segment. Table 4.2 displays the results of a one-way ANOVA with Tukey's post-hoc pairwise comparison for all taxa. *Homo sapiens* are significantly different from all non-human primates, while none of the non-human primates are significantly different from each other.

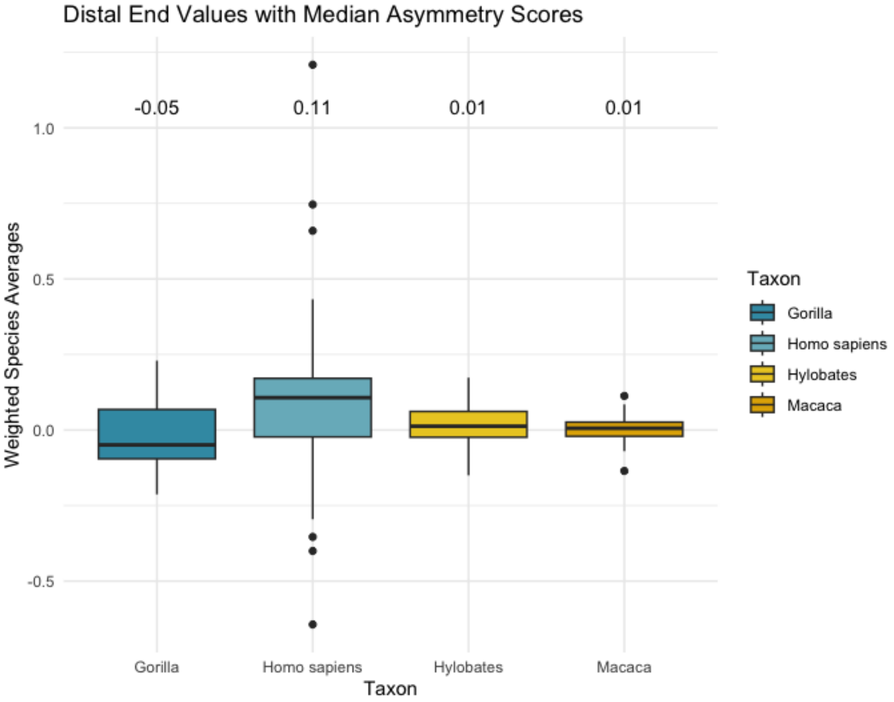

Figure 4.4. A boxplot showing the range of values with the species weighted average median values displayed above each taxon.

Table 4.1. Descriptive statistics for the specimen weighted averages for each taxon.

Taxon	**Minimum**	**Maximum**	**Mean**
Macaca	0.14	0.11	0.00
Hylobates	0.15	0.17	0.02
Homo sapiens	0.64	1.21	0.10
Gorilla	0.21	0.23	0.02

Table 4.2. Results of a one-way ANOVA with Tukey's post-hoc pairwise comparison. Significant values are bolded.

Homo sapiens - Gorilla	*Hylobates - Gorilla*	*Macaca - Gorilla*	*Hylobates - Homo sapiens*	*Macaca - Homo sapiens*	*Macaca - Hylobates*
0.027	Not sig.	Not sig.	**0.026**	**<0.001**	Not sig.

Even though the spread of values for *Ho. sapiens* is quite broad for the distal segment (Figure 4.5), the mean of the values is clearly positive and right directional. The *Ho. sapiens* individuals that fall outside the range of the symmetrical *Macaca* and *Hylobates* were isolated to better understand the asymmetry values for modern humans and the values plotted to show the distribution of these individuals (Figure 4.6). When the *Ho. sapiens* individuals that fall outside the range of the symmetrical *Hylobates* and *Macaca* are isolated, there is a clear trend towards right-directional asymmetry (69/31% right to left). These results also largely follow the expected right/left distribution of handedness within modern humans.

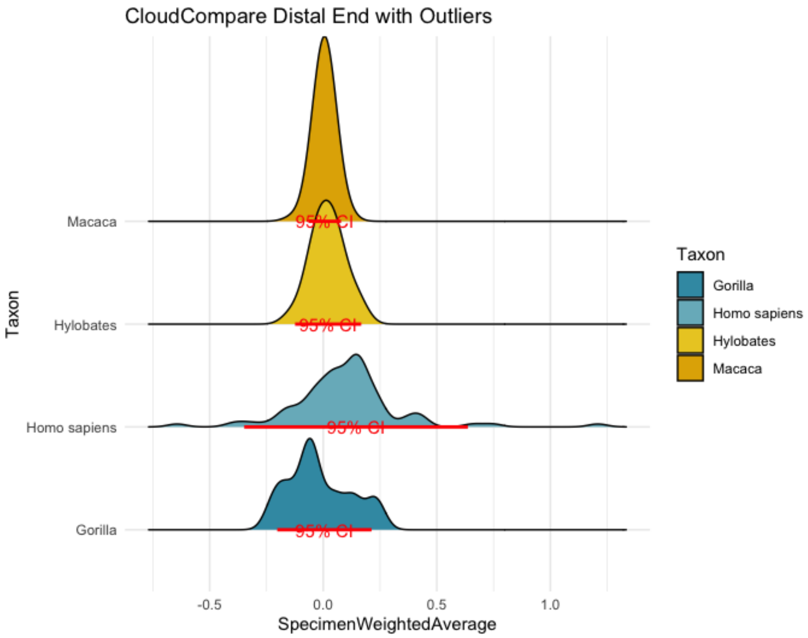

Figure 4.5. Density plot of the weighted asymmetry scores per taxon. 95% confidence intervals are labeled and indicated in red. Negative values indicate left-directional asymmetry, while positive values indicate right-directional asymmetry.

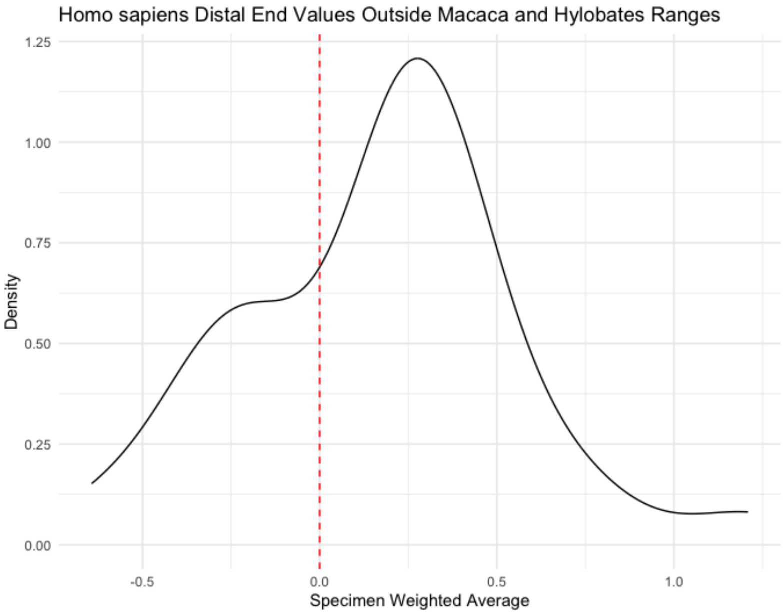

Figure 4.6. Specimen weighted averages for the *Ho. sapiens* specimens that lie outside the range of values for *Macaca* and *Hylobates*. The red line denotes 0. Positive values indicate right-directional asymmetry, while negative values indicate left-directional asymmetry.

The Influence of Shaft Asymmetry on Distal End Asymmetry

A moderate amount (r=0.62) of the asymmetry present in the distal end is correlated with asymmetry from the shaft portion of the bone (Figure 4.7), which supports H_1, which stated that shaft asymmetry would predict a corresponding asymmetry in the distal end of the bone. This result is expected, since opposition of the thumb is a combination of flexion, pronation, and abduction (Komatsu and Lubhan, 2013). Movement during opposition occurs across all three joints of the thumb (Lin et al., 2011), meaning that opposition does not occur without also engaging the metacarpophalangeal joint (as well as the trapeziometacarpal and interphalangeal joints).

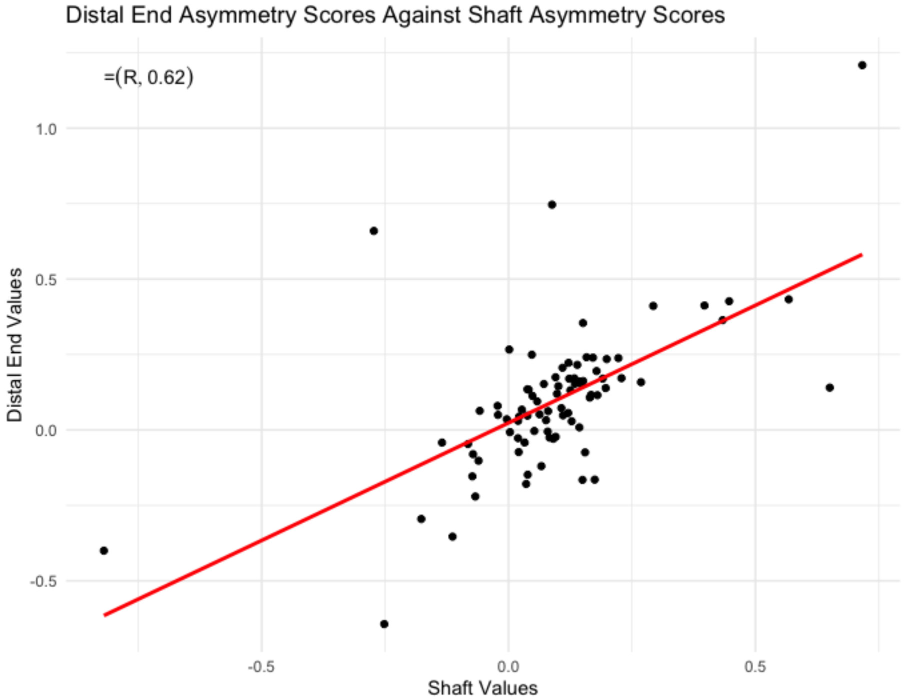

Figure 4.7. Showing linear regression of distal end asymmetry scores against shaft asymmetry scores from humans.

Collateral Ligaments

Nevertheless, the observed asymmetry in the distal end of the bone cannot be solely attributed to the correlation with shaft asymmetry, suggesting there are other factors contributing to the results seen in this study. A portion of the remaining variability in the distal bone segment can likely be attributed to the attachment sites of the radial and ulnar collateral ligaments, which are shown in Figure 4.8. When the thumb is opposed, the three joints of the thumb are highly coordinated in flexion; the average rotation of the trapeziometacarpal joint flexes roughly 50 degrees, while the MCP joint flexes roughly 42 degrees (Li and Tang, 2011), meaning that engaging in opposition will strongly recruit the soft tissue structures that are recruited to stabilize the MCP joint during flexion.

Figure 4.9 visualizes variation between the right and left side for the distal end of the bone in four *Ho. sapiens* specimens. As demonstrated by the heat maps, variation in these individuals appears to be driven largely by the collateral ligament attachment sites. Red regions signify very high values on the right side compared to the left, indicating right-directed asymmetry in those areas. Yellow values denote moderate right-directed asymmetry, while green regions suggest minimal or no variation between the left and right sides.

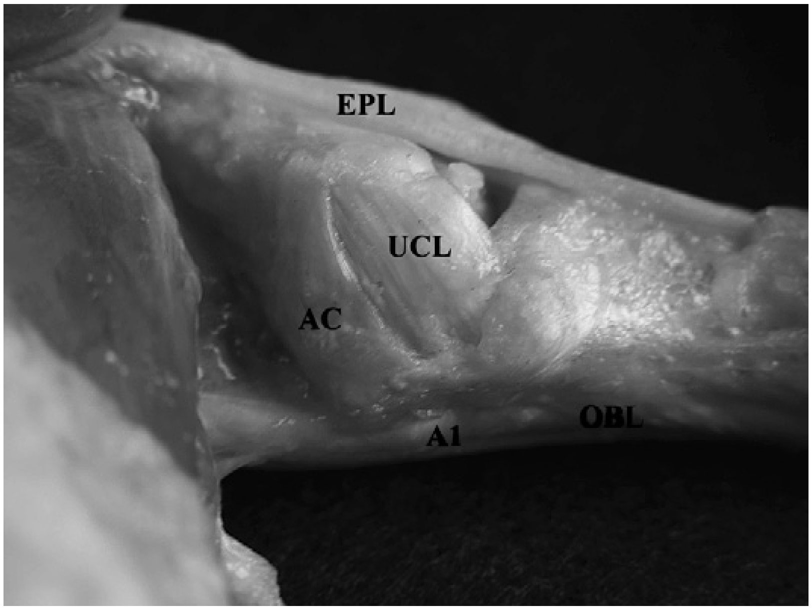

Figure 4.8. The adductor aponeurosis has been removed in this anatomic dissection, revealing the ulnar aspect of the thumb MCP joint. The UCL and the AC originate at the dorsal-ulnar margin of the head of the metacarpal; the UCL inserts into the ulnar base of the proximal phalanx and the AC inserts into the volar plate of the MCP joint. The EPL is dorsal to the MCP joint and the A1 and oblique (OBL) pulleys of the flexor sheath are noted volar to the MCP joint and the proximal phalanx. Figure from Leversedge, 2008.

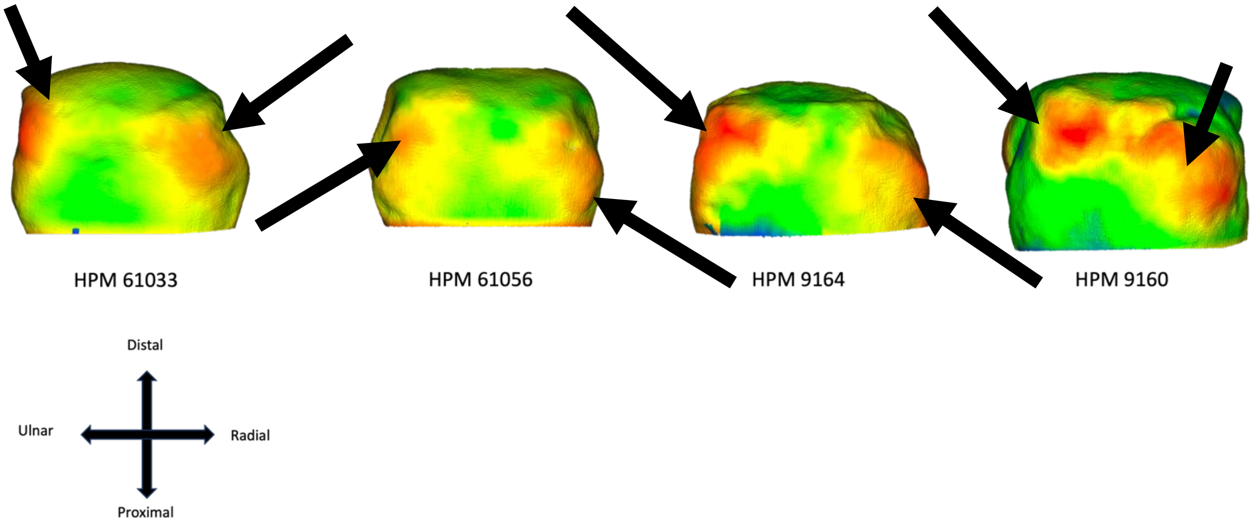

Figure 4.9. *Homo sapiens* distal end examples of asymmetry at the attachment sites for the radial and ulnar collateral ligaments. All metacarpals are shown in dorsal view. Areas of high right-directional asymmetry are indicated by red. Areas of little right-directional variation are

indicated by yellow. Areas of little-to-no variation are indicated by green. Heat maps are based on distances between the right and left, reference side.

Palmar Condyles

It is probable that some amount of variation in the distal segment that cannot be accounted for by either correlation with shaft asymmetry or from variation driven by the collateral ligament insertion sites is attributable to variation on the palmar condyles. Figure 4.10 shows heat maps generated from three modern *Ho. sapiens* specimens that exhibit high levels of right-directional asymmetry at the palmar condyles on either the radial (Figures 4.10A and 4.10B) or ulnar (Figure 4.10C) condyle. The variation seen here is surprising, as no soft tissue structures attach to the palmar condyles that would induce bony remodeling upon recruitment. As such, the factors influencing the observed variation at these structures remain uncertain.

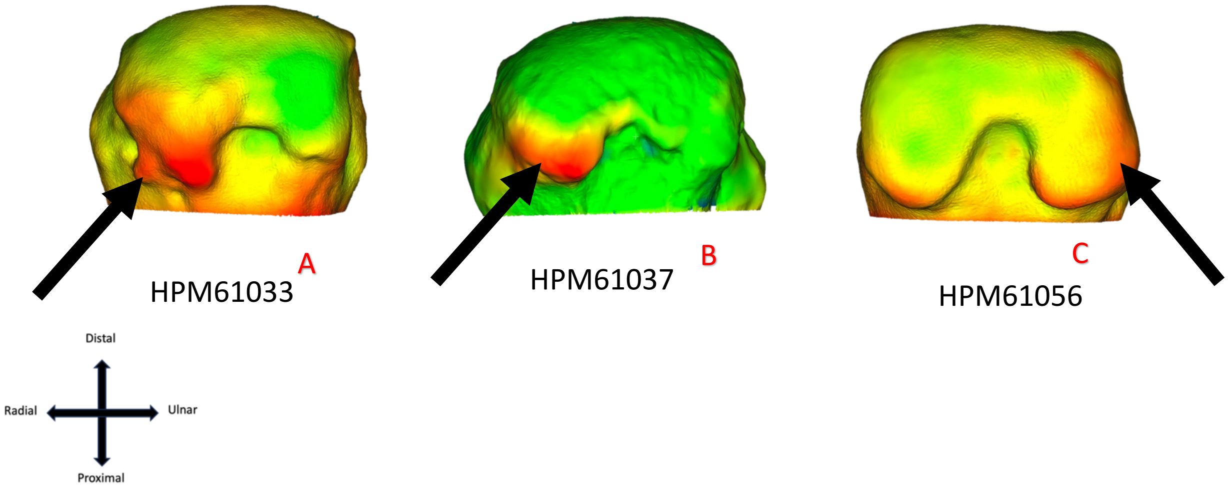

Figure 4.10. Heat maps generated from three *Ho. sapiens* specimens with right-directional asymmetry at the palmar condyles. Areas of high right-directional asymmetry are indicated by red. Areas of little right-directional variation are indicated by yellow. Areas of little-to-no variation are indicated by green. Black arrows indicate areas of high variation on the radial palmar condyle (A and B) and the ulnar palmar condyle (C). Metacarpals are shown in palmar view.

Although there are no soft tissue structures directly attaching to these condyles, the joint capsule and condyles are enveloped by a volar plate composed of thick fibrocartilage that contains the metacarpal sesamoid bones. The volar plate plays a role in stabilizing the joint and preventing hyperextension by working in tandem with the collateral ligaments (Leversedge, 2008). Additionally, there is a tendon for the flexor pollicis longus travels that between the condyles on its path toward the distal pollical phalanx (Bojsen-Moller, 1976).

It is unclear what role the condyles play in flexion at the MCP joint, though is it likely they aid in stabilizing the joint during forceful precision gripping (Galletta et al., 2019). It has been proposed (Bojsen-Moller, 1976; Barmakian, 1992) that the larger radial palmar condyle in humans acts as a "locking mechanism" by fitting into a depression on the proximal phalanx articular surface to prevent radioulnar movement during flexion by providing greater stability when subjected to loading. However, more recent research suggests that joint stability is instead provided more through ligaments rather than by bony reinforcement (Lovejoy et al., 2001; Galletta et al., 2019). Further research into the role these palmar condyles play in MCP joint stability is needed to better understand the results seen here.

DISCUSSION

This chapter investigated asymmetry in the distal end of the first metacarpal in humans and non-human primates due to differential use of the right and left hand because of handedness. It was hypothesized that the asymmetry present in the shaft of modern *Ho. sapiens* would be correlated with asymmetry in the distal end, as both segments of the bone are recruited during flexion and opposition of the thumb (Yoshida et al., 2003). The results reported here supported this hypothesis, as there is a moderate correlation (r=0.62) between the weighted asymmetry scores for the shaft and the distal end of the bone, indicating that shaft asymmetry does predict some of the asymmetry present in the distal end. This is expected, as asymmetry in the shaft is driven by the opponens pollicis muscle insertion site, which reflects muscle recruitment during opposition of the thumb. As opposition is a coordinated action involving all three thumb joints (Lin et al., 2010), engaging the muscle requires flexing the MCP joint. This, in turn, activates the collateral ligaments to stabilize the joint against radioulnar movement (Earp et al., 2019). This corresponding recruitment of the collateral ligaments during forceful precision grips is reflected in the right-directional asymmetry seen at their attachment sites on the dorsoradial and dorsoulnar aspects of the metacarpal head (Figure 4.9).

While it is beyond the scope of this project to further investigate how the recruitment of collateral ligaments during flexion impacts bony remodeling at proximal attachment sites, the findings do suggest that recruitment of these ligaments is reflected in the bony morphology of this area. As mentioned previously, there is very little quantitative work on the MCP joint in primates, and to my knowledge, nothing on the influence of collateral ligament recruitment on bony remodeling at the joint. Future research on the bony morphology of this joint in primates would benefit from considering these soft tissue structures in future analyses.

CHAPTER 5: CONCLUSIONS AND FUTURE DIRECTIONS

CONCLUSION

This study investigated how differential recruitment of the opponens pollicis muscle influenced the bony morphology of the first metacarpal in a sample of modern humans and non-human primates. It was predicted that because humans exhibit species-wide right-hand dominance (Papadatou-Pastou et al., 2020), muscle insertion sites would be larger on right hand bones compared to the left side, while non-human primates that do not exhibit species-wide handedness should not exhibit any significant degree of asymmetry in their manual entheses. In summary, the study revealed right-directional asymmetry in the first metacarpal among humans, contrasting with the absence of a directional bias in non-human primates, supporting the study's predictions. The observed right-directional trend in enthesis development in humans remained consistent across both linear caliper measurements and measurements derived from distance-based heat maps obtained from 3D renderings of the bones. This mutual reinforcement of results across methods underscores the robusticity of the findings. Notably, results were consistent when controlling for sex or body size. Furthermore, the study revealed that right-directional asymmetry in the metacarpal shaft serves as a predictor for a moderate degree of right-directional asymmetry in both the proximal and distal ends of the pollical metacarpal within modern humans.

Additionally, this study predicted that asymmetry in the metacarpal shaft would predict asymmetry in the proximal portion of the bone because of differential hand use within modern humans. The shape of the trapeziometacarpal joint correlates with hand use across primates (Van Leeuwen et al., 2019), and it has been proposed that the mediolaterally expanded tmcj in modern humans is an adaptation to increased loads incurred during recruitment of relatively large thenar muscles during forceful manipulation (Bowland et al., 2021). It was also predicted that most of the variation present in the proximal portion of the bone would be concentrated on the radial aspect of the articular surface, as most of the joint reaction forces incurred during stable grips (high-force, power grips, etc.) are displaced through the radial side of the hand (Stephens et al., 2018). The results supported the hypothesis that shaft asymmetry would predict proximal end asymmetry, as the right-directional asymmetry observed in modern humans showed a moderate correlation with shaft asymmetry. However, contrary to predictions, the most significant variation was not present in the radial aspect of the articular surface but was instead concentrated on the dorsal aspect of the joint surface or spread evenly across the articular facet. Moreover, asymmetry was also detected at the attachment site for the dorsal ligament complex, which works to stabilize the joint during thumb flexion (Ladd et al., 2012). It is beyond the scope of this project to further explore how ligamentous recruitment influences bony morphology, but future research will benefit from further exploring this possible relationship.

Finally, this study predicted that metacarpal shaft asymmetry would predict corresponding asymmetry in the distal end of the bone, as opposition of the thumb, facilitated by the opponens pollicis muscle, also involves metacarpophalangeal joint (MCP) flexion (Li and Tang, 2007). As such, variation between dominant and non-dominant hand use during forceful precision grips were expected to be reflected in the distal thumb joint in humans. Results from this study supported this prediction, as humans demonstrated a moderate correlation between right-directional asymmetry in the shaft and distal end of the first metacarpal. Much of the additional variation present in the distal portion of the bone appears to be driven by recruitment of the collateral ligaments, which originate on the metacarpal head and act to stabilize the MCP joint during flexion (Tang, 2011). Significant variation in the distal end of the bone was also present at the radial and ulnar condyles on the palmar aspect of the metacarpal. It is unclear what (if any) functional significance this variation implies, as the role of the palmar condyles during flexion is still uncertain. It is possible they aid the joint in flexion by working to stabilize the metacarpal head against the proximal phalanx, though this is still debated (Barmakian, 1992; Galletta et al., 2019).

Inferring Muscle Use from Bony Morphology is Problematic

Nevertheless, caution is needed when interpreting lifetime activity patterns based on enthesis morphology, as the bias demonstrated here may not consistently indicate hand preference during manipulative activities. Despite this study establishing that enthesis morphology can predict handedness, it also indicated that being right-handed does not necessarily correlate with the presence of a well-developed, asymmetrical opponens pollicis enthesis. In other words, being right- (or left) handed does not on its own indicate that the dominant hand will have asymmetrically larger entheses, and that frequent muscle recruitment alone is not sufficient to induce asymmetrical enthesis development. The results of this study suggest the existence of a threshold for enthesis development, which most individuals do not exceed through frequent muscle recruitment achieved through daily activities alone.

However, even when accounting for the complexities inherent in inferring muscle use from bony morphology, the results of this study support the hypothesis that intensity is more crucial for enthesis development than frequency, as frequent recruitment of the opponens pollicis for various key grips does not appear to produce asymmetrical development for most individuals based on the findings of this study. The results instead imply that the frequency of muscle recruitment might not sufficiently strain the bone to induce noticeable remodeling. This is unsurprising, as the larger loads have been shown to disproportionately remodeling process, regardless of the frequency of smaller loads (Jurmain, 1999). This likewise supports the hypothesis that there is a threshold for enthesis development that most individuals do not exceed through their daily activities. This is in line with previous findings from Silman and Hochberg (1993:446, quoted in Jurmain, 1999), who noted that, "repetitions of habitual daily activities…" are unlikely to stimulate osteogenic changes.

AREAS FOR FUTURE RESEARCH

Like any research project, this study has limitations in its scope and findings. One significant constraint stems from the lack of demographic information for the modern humans. There is no information about the occupations for the two populations of modern humans used in this study, which restricts the interpretations that can be drawn from the results. Future studies should strive to incorporate samples with more demographic information, including known occupation and lifetime activity patterns. Previous research (Karakostis et al., 2017) on enthesis morphology within modern humans with known occupations found correlations between manual enthesis morphology and lifetime occupations, and it is likely that any future studies incorporating the methods developed here would support those findings and add to this growing body of knowledge.

This study also made assumptions about the distribution of left/right handedness among the modern human sample and relied on distribution rates reported in the literature to establish a baseline for right/left handedness expectations (Papadatou-Pastou et al., 2020). However, it is unknown whether the individuals in this study accurately reflected these reported values. Additionally, as mentioned in an earlier chapter, the traditional binary classification of left/right handedness may oversimplify true variation in hand use patterns among primates, particularly in modern humans. Future research should strive to include subjects with known hand preferences to address this issue but would also benefit from adopting a more nuanced perspective on hand use within primates.

Additionally, despite an extensive literature on this topic concerning *Ho. sapiens*, the utility of muscle insertion sites for reconstructing activity patterns in modern humans is still debated. This issue is even more pronounced in non-human primates, where research on the subject is very limited. While this study contributed to the growing body of knowledge, future research exploring muscle insertion site use in non-human primates would provide valuable insights for understanding their applicability in studies regarding both *Ho. sapiens* and non-human primates. The limited information about primate muscles outside of humans and great apes also constrains the study's scope and interpretations drawn. For instance, it has been reported that the opponens pollicis might not consistently insert on the radial aspect of the first metacarpal in *Hylobates*, although the sample size for this observation was small (Van Leeuwen et al., 2022). Addressing this gap requires further research on the topic to better understand the complexities of primate muscle variability.

BROADER IMPACTS

This project contributes significantly to the existing literature and highlights the possibly for multiple areas of future research focus regarding primate muscle recruitment, use, and variability. Most significantly, it adds to the understanding of how muscle recruitment influences bony morphology, which remains contested despite decades of research into the topic. This study provides important insight into the issue by demonstrating that there is a threshold required for enthesis development to reflect repetitive muscle recruitment, and that most individuals do not exceed this threshold. Importantly, a major hurdle in studying how enthesis size relates to muscle recruitment has been the inability to accurately quantify enthesis size, particularly outside of modern humans. This study addressed this gap by developing a new method to quantify enthesis size across taxa, offering a methodology to study the utility of using enthesis size to reconstruct activity in primates outside of humans and great apes.

This study also holds significant implications for medical research regarding thumb joint anatomy. The trapeziometacarpal joint (TMCJ) is particularly relevant given its increased susceptibility to arthritis in later life, especially among older women (Lin et al., 2013). Within modern humans, the joint is vulnerable to subluxation because of its saddle-shape and relative lack of soft tissue elements holding it in place (Ladd et al., 2012). A better understanding of the dorsal ligament complex's involvement in joint opposition and flexion can facilitate enhanced treatment plans for TMCJ pathologies or injuries.

Likewise, the metacarpophalangeal (MCP) joint is highly prone to collateral ligament tears, which often lead to avulsion fractures in the proximal phalanx (Tang, 2011). This study accentuates the need to better understand the bony anatomy of the joint by highlighting the central role of the collateral ligaments during thumb flexion. It also underscores the significance of palmar condyles during flexion at the MCP joint, though the exact function the condyles serve during joint flexion remains unclear (Galletta et al., 2019). A more thorough understanding of the structural role of the palmar condyles during thumb flexion can enable medical professionals to better devise comprehensive treatment plans geared towards addressing and preventing future injuries. Lastly, the MCP joint is a largely overlooked subject within anthropology, where the predominant focus tends to be solely on the TMCJ. This study contributes significantly by highlighting the MCP joint's role in flexion across primates while highlighting areas for future research.

FINAL THOUGHTS

The findings within this study collectively suggest that thumb opposition, which incorporates multiple joints across the thumb, induces bony change at multiple areas along the metacarpal. Thumb opposition includes abduction at the trapeziometacarpal joint and flexion and rotation at both the trapeziometacarpal and metacarpophalangeal joints, and the opponens pollicis acts as either a primary or secondary muscle in each of these actions (Cooney et al., 1984). For instance, consider the full range of motion during key grips that involving opposition of the of the thumb (i.e., the three-jaw chuck [Marzke, 1997]). The thumb is first radially abducted at the proximal trapeziometacarpal joint before flexing across all three joints to ultimately oppose the thumb against the other digits. The opponens pollicis is a primary muscle in thumb radial abduction, possibly explaining the signal in both the shaft and proximal portions of the bone. In addition, the opponens pollicis is a secondary thumb muscle in flexion-extension of the MCP joint and acts in concert with the collateral ligaments (Cooney et al., 1985). This would explain both the correlation between the shaft asymmetry and the ends of the bone and also why the amount of asymmetry in each portion of the bone is relatively unchanged across the metacarpal.

The results of this study suggest a similar right-directional trend could be expected in the first digit phalanges, though previous research into the relationship between manual phalangeal morphology and soft tissue anatomy failed to find evidence of a correlation between bony morphology and soft tissue properties. Marzke et al. (2007) looked at the correlation between the length of the lateral fossae on the palmar diaphysis of the middle manual phalanx from the third and fifth digit and the size of the flexor digitorum superficialis tendons that insert into the fossae. They failed to find evidence of a correlation between tendon length or cross-sectional area and fossae length. Furthermore, they reported that the tendons did not insert exclusively into the fossae or occupy the full fossae and cautioned against inferring soft tissue anatomy based on bony morphology.

REFERENCES CITED

Almecija, S., Smaers, J. B., & Jungers, W. L. 2015. The evolution of human and ape hand proportions. Nature comm. 6, 1-11.

Angel, J. L. (1966). Early skeletons from Tranquillity, California. Smithsonian, 2.

Bardo, A., Cornette, R., Borel, A., & Pouydebat, E. 2017. Manual function and performance in humans, gorillas, and orangutans during the same tool use task. Am J Phys Anthropol. 164, 821-836.

Bardo, A., Pouydebat, E., & Meunier, H. 2015. Do bimanual coordination, tool use, and body posture contribute equally to hand preferences in bonobos? J Hum Evol. 82, 159-169.

Bardo, A., Vigouroux, L., Kivell, T. L., & Pouydebat, E. 2018. The impact of hand proportions on tool grip abilities in humans, great apes and fossil hominins: A biomechanical analysis using musculoskeletal simulation. J Hum Evol. 125, 106-121.

Bargallo, A., Mosquera, M., & Lozano, S. 2017. In pursuit of our ancestors' hand laterality. J Hum Evol. 111, 18-32.

Barmakian, J. T. 1992. Anatomy of the joints of the thumb. Hand Clin. 8, 683-691.

Becker, S. K. 2020. Osteoarthritis, entheses, and long bone cross-sectional geometry in the Andes: Usage, history, and future directions. Int J Paleopathol. 29, 45-53.

Benjamin, M., Kumai, T., Milz, S., Boszczyk, B., Boszczyk, A. A., & Ralphs, J. 2002. The skeletal attachment of tendons,-tendon “entheses”. Comp Biochem Phys A.133, 931-945.

Benjamin, M., & Ralphs, J. 1998. Fibrocartilage in tendons and ligaments-an adaptation to compressive load. J Anat. 193, 481-494.

Benjamin, M., Toumi, H., Ralphs, J., Bydder, G., Best, T., & Milz, S. 2006. Where tendons and ligaments meet bone: attachment sites (‘entheses’) in relation to exercise and/or mechanical load. J Anat. 208, 471-490.

Bertram, J. E., & Swartz, S. M. 1991. The ‘law of bone transformation’: a case of crying Wolff? Biol Rev. 66, 245-273.

Bettinger, P. C., Linscheid, R. L., Berger, R. A., Cooney III, W. P., & An, K.-N. 1999. An anatomic study of the stabilizing ligaments of the trapezium and trapeziometacarpal joint. J Hand Surg. 24, 786-798.

Bojsen-Moller, F. 1976. Osteoligamentous guidance of the movements of the human thumb. J Anat. 147, 71-79.

Bowland, L. A., Tocheri, M. W., & Orr, C. M. 2019. Measuring entheseal morphology of the opponens pollicis muscle in digital and physical specimens of Homo sapiens.

Bowland, L. A., Scott, J. E., Kivell, T. L., Patel, B. A., Tocheri, M. W., & Orr, C. M. 2021. Homo naledi pollical metacarpal shaft morphology is distinctive and intermediate between that of australopiths and other members of the genus Homo. J Hum Evol. 103048.

Bucchi, A., Luengo, J., Del Bove, A., & Lorenzo, C. 2020. Insertion sites in manual proximal phalanges of African apes and modern humans. Am J Phys Anthropol, 173, 556-567.

Bucchi, A., Luengo, J., Fuentes, R., Arellano-Villalon, M., & Lorenzo, C. 2020. Recommendations for Improving Photo Quality in Close Range Photogrammetry, Exemplified in Hand Bones of Chimpanzees and Gorillas. Int J Morphol. 38.

Byrne, R. W., & Byrne, J. M. 1991. Hand preferences in the skilled gathering tasks of mountain gorillas (Gorilla g. berengei). Cortex. 27, 521-546.

Byrne, R., & Byrne, J. 2001a. Estimating the complexity of animal behaviour: how mountain gorillas eat thistles. Behaviour. 138, 525-557.

Byrne, R. W., Corp, N., & Byrne, J. M. 2001b. Manual dexterity in the gorilla: bimanual and digit role differentiation in a natural task. Animal Cognition, 4, 347-361.

Cardoso, F. A., & Henderson, C. Y. 2010. Enthesopathy formation in the humerus: Data from known age-at-death and known occupation skeletal collections. Am J Phys Anthropol. 141, 550-560.

Carter, D. R. 1984. Mechanical loading histories and cortical bone remodeling. Calcified Tissue Int. 36, S19-S24.

Cashmore, L. 2009. Can hominin ‘handedness’ be accurately assessed? Ann Hum Biol. 36, 624-641.

Cashmore, L., Uomini, N., & Chapelain, A. 2008. The evolution of handedness in humans and great apes: a review and current issues. J Anthropol Sci. 86, 7-35.

Cashmore, L., & Zakrzewski, S. R. 2013. Assessment of musculoskeletal stress marker development in the hand. Int J Osteoarchaeol. 23, 334-347.

Chapelain, A., Laurence, A., Vimond, M., Maille, A., Meunier, H., Fagard, J., . . . Blois-Heulin, C. 2012. Hand preference and its flexibility according to the position of the object: A study in cercopithecines examining spontaneous behaviour and an experimental task (the Bishop QHP task). Anim Cogn. 15, 937-953.

Cooney, W. P., Linscheid, R. L., & An, K.-N. 1984. Opposition of the thumb: an anatomic and biomechanical study of tendon transfers. J Hand Surg. 9, 777-786.

Cooney III, W. P., An, K.-N., Daube, J. R., & Askew, L. J. 1985. Electromyographic analysis of the thumb: a study of isometric forces in pinch and grasp. J Hand Surg. 10, 202-210.

Cowgill, L. 2018. Juvenile body mass estimation: A methodological evaluation. J Hum Evol. 115, 78-84.

Currey, J. D. 2006. Bones: structure and mechanics. Princeton University Press.

D'Agostino, P., Dourthe, B., Kerkhof, F., Stockmans, F., & Vereecke, E. E. 2017. In vivo kinematics of the thumb during flexion and adduction motion: evidence for a screw-home mechanism. J Orthop Res. 35, 1556-1564.

Davis, C. B., Shuler, K., Danforth, M. E., & Herndon, K. 2013. Patterns of interobserver error in the scoring of entheseal changes. Int J Osteoarchaeol. 23, 147-151.

Diogo, R., Richmond, B. G., & Wood, B. 2012. Evolution and homologies of primate and modern human hand and forearm muscles, with notes on thumb movements and tool use. J Hum Evol. 63, 64-78.

Diogo, R., & Wood, B. A. 2012. Comparative anatomy and phylogeny of primate muscles and human evolution. CRC press.

Doran, D., & MacNeilage, A. 1998. Variation in behavior of gorilla subspecies: what's diet got to do with it? Evol Anthropol. 6, 120-131.

Doran, D. M., & MacNeilage, A. 1998. Gorilla ecology and behavior. Evol Anthropol. 6, 120-131.

Drapeau, M. S. 2008. Enthesis bilateral asymmetry in humans and African apes. Homo. 59, 93-109.

Dunmore, C. J., Bardo, A., Skinner, M. M., & Kivell, T. L. 2020. Trabecular variation in the first metacarpal and manipulation in hominids. Am J Phys Anthropol. 171, 219-241.

Dutour, O. 1986. Enthesopathies (lesions of muscular insertions) as indicators of the activities of Neolithic Saharan populations. Am J Phys Anthropol. 71, 221-224.

Earp, B., Cefalu, C., & Blazar, P. 2019. Thumb metacarpophalangeal joint arthritis. J Am Acad Orthop Surg. 27, e1029-e1039.

Edmunds, J. O. 2011. Current concepts of the anatomy of the thumb trapeziometacarpal joint. J Hand Surg. 36, 170-182.

Elder, A. A. 2009. Hylobatid diets revisited: the importance of body mass, fruit availability, and interspecific competition. The gibbons: New perspectives on small ape socioecology and population biology, 133-159.

Eliot, D. J., & Jungers, W. L. 2000. Fifth metatarsal morphology does not predict presence or absence of fibularis tertius muscle in hominids. J Hum Evol. 38, 333-342.

Fagot, J., Drea, C. M., & Wallen, K. 1991. Asymmetrical hand use in rhesus monkeys (Macaca mulatta) in tactually and visually regulated tasks. J Comp Psychol. 105, 260.

Fagot, J., & Vauclair, J. 1988. Handedness and bimanual coordination in the lowland gorilla. Brain Behav Evol. 32, 89-95.

Fagot, J., & Vauclair, J. 1991. Manual laterality in nonhuman primates: a distinction between handedness and manual specialization. Psychol Bull. 109, 76.

Fischer, R. B., Meunier, G. F., & White, P. J. 1982. Evidence of laterality in the lowland gorilla. Percept Motor Skill. 54, 1093-1094.

Fitch, W. T., & Braccini, S. N. 2013. Primate laterality and the biology and evolution of human handedness: a review and synthesis. Ann NY Acad Sci. 1288, 70-85.

Florencio-Silva, R., Sasso, G. R. d. S., Sasso-Cerri, E., Simoes, M. J., & Cerri, P. S. 2015. Biology of bone tissue: structure, function, and factors that influence bone cells. BioMed Res Int.

Foster, A., Buckley, H., & Tayles, N. 2014. Using enthesis robusticity to infer activity in the past: a review. J Archaeol Method TH. 21, 511-533.

Frost, H. M. 1987. Bone “mass” and the “mechanostat”: a proposal. Anat Rec, 219, 1-9.

Galletta, L., Stephens, N. B., Bardo, A., Kivell, T. L., & Marchi, D. 2019. Three-dimensional geometric morphometric analysis of the first metacarpal distal articular surface in humans, great apes and fossil hominins. J Hum Evol. 132, 119-136.

Gao, J., Messner, K., Ralphs, J., & Benjamin, M. 1996. An immunohistochemical study of enthesis development in the medial collateral ligament of the rat knee joint. Anat Embryol. 194, 399-406.

Godde, K., & Taylor, R. W. 2011. Musculoskeletal stress marker (MSM) differences in the modern American upper limb and pectoral girdle in relation to activity level and body mass index (BMI). Forensic Sci Int. 210, 237-242.

Gumert, M. D., Kluck, M., & Malaivijitnond, S. 2009. The physical characteristics and usage patterns of stone axe and pounding hammers used by long-tailed macaques in the Andaman Sea region of Thailand. Am J Primatol. 71, 594-608.

Hadjidakis, D. J., & Androulakis, I. I. 2006. Bone remodeling. Ann NY Acad Sci. 1092, 385-396.

Hamrick, M. W. 1996. Articular size and curvature as determinants of carpal joint mobility and stability in strepsirhine primates. Journal of Morphology, 230(2), 113-127.

Hamrick, M. W., Churchill, S. E., Schmitt, D., & Hylander, W. L. 1998. EMG of the human flexor pollicis longus muscle: implications for the evolution of hominid tool use. J Hum Evol. 34, 123-136.

Hawkey, D. E. 1998. Disability, compassion and the skeletal record: using musculoskeletal stress markers (MSM) to construct an osteobiography from early New Mexico. Int J Osteoarchaeol. 8, 326-340.

Hawkey, D. E., & Merbs, C. F. 1995. Activity-induced musculoskeletal stress markers (MSM) and subsistence strategy changes among ancient Hudson Bay Eskimos. Int J Osteoarchaeol. 5, 324-338.

Heestand, J. E. 1987. Behavioral lateralization in four species of apes. Ph.D. Dissertation. University of Washington.

Helmkamp, R. C., & Falk, D. 1990. Age-and sex-associated variations in the directional asymmetry of rhesus macaque forelimb bones. Am J Phys Anthropol. 83, 211-218.

Henderson, C. Y., Mariotti, V., Pany-Kucera, D., Villotte, S., & Wilczak, C. 2013. Recording specific entheseal changes of fibrocartilaginous entheses: initial tests using the Coimbra method. Int J Osteoarchaeol. 23, 152-162.

Hopkins, W. D., Phillips, K. A., Bania, A., Calcutt, S. E., Gardner, M., Russell, J., . . . Schapiro, S. J. 2011. Hand preferences for coordinated bimanual actions in 777 great apes: implications for the evolution of handedness in hominins. J Hum Evol. 60, 605-611.

Hopkins, W. D., Stoinski, T. S., Lukas, K. E., Ross, S. R., & Wesley, M. J. 2003. Comparative assessment of handedness for a coordinated bimanual task in chimpanzees (Pan troglodytes), gorillas (Gorilla gorilla) and orangutans (Pongo pygmaeus). J Comp Psychol. 117, 302.

Imaeda, T., An, K.-N., & Cooney III, W. P. 1992. Functional anatomy and biomechanics of the thumb. Hand Clin. 8, 9-15.

Jurmain, R. 1999. Stories from the skeleton: behavioral reconstruction in human osteology. Gordon and Breach, Amsterdam.

Karakostis, F. A., & Lorenzo, C. 2016. Morphometric patterns among the 3D surface areas of human hand entheses. Am J Phys Anthropol. 160, 694-707.

Karakostis, F. A., Hotz, G., Scherf, H., Wahl, J., & Harvati, K. 2017. Occupational manual activity is reflected on the patterns among hand entheses. Am J of Phys Anthropol. 164, 30-40.

Karakostis, F. A., Jeffery, N., & Harvati, K. 2019. Experimental proof that multivariate patterns among muscle attachments (entheses) can reflect repetitive muscle use. Sci Rep, 9, 1-9.

Kawanishi, Y., Oka, K., Tanaka, H., Okada, K., Sugamoto, K., & Murase, T. 2018. In vivo 3-dimensional kinematics of thumb carpometacarpal joint during thumb opposition. J Hand Surg. 182-187.

Kennedy, K. A. 1998. Markers of occupational stress: conspectus and prognosis of research. Int J Osteoarchaeol. 8, 305-310.

Key, A., Merritt, S. R., & Kivell, T. L. 2018. Hand grip diversity and frequency during the use of Lower Palaeolithic stone-cutting tools. J Hum Evol. 125, 137-158.

Kivell, T. L., Baraki, N., Lockwood, V., Williams-Hatala, E. M., & Wood, B. A. 2022. Form, function and evolution of the human hand. Am J of Biol Anthropol. 181, 6-57.

Knigge, R. P., Tocheri, M. W., Orr, C. M., & Mcnulty, K. P. 2015. Three-dimensional geometric morphometric analysis of talar morphology in extant gorilla taxa from highland and lowland habitats. Anat Rec. 298, 277-290.

Komatsu, I., & Lubahn, J. D. 2018. Anatomy and biomechanics of the thumb carpometacarpal joint. Op Tech Orthop. 28, 1-5.

Ladd, A. L., Lee, J., & Hagert, E. 2012. Macroscopic and microscopic analysis of the thumb carpometacarpal ligaments: a cadaveric study of ligament anatomy and histology. J Bone Joint Surg. 94, 1468.

Lanyon, L. E., Goodship, A. E., Pye, C. J., & MacFie, J. H. 1982. Mechanically adaptive bone remodelling. J Biomech. 15, 141-154.

Lazenby, R., Angus, S., Cooper, D., Hallgrimson, B. 2008. A three-dimensional microcomputed tomographic study of site-specific variation in trabecular microarchitecture in the human second metacarpal. J Anat. 213, 698-705.

Lemelin, P., & Diogo, R. 2016. Anatomy, function, and evolution of the primate hand musculature. In: Kivell T., Lemelin, P., Richmond, B., Schmitt, D. (Eds)., The Evolution of the Primate Hand: Anatomical, Developmental, Functional, and Paleontological Evidence. Springer, pp.155-193.

Leversedge, F. J. 2008. Anatomy and pathomechanics of the thumb. Hand Clin. 24, 219-229.

Lewis, O. J. 1977. Functional morphology of the evolving hand and foot. Clarendon Press. Oxford.

Li, Z.-M., & Tang, J. 2007. Coordination of thumb joints during opposition. J Biomech. 40, 502-510.

Lieverse, A. R., Bazaliiskii, V. I., Goriunova, O. I., & Weber, A. W. 2009. Upper limb musculoskeletal stress markers among middle Holocene foragers of Siberia's Cis-Baikal region. Am J Phys Anthropol. 138, 458-472.

Lin, H.-T., Kuo, L.-C., Liu, H.-Y., Wu, W.-L., & Su, F.-C. 2011. The three-dimensional analysis of three thumb joints coordination in activities of daily living. Clin Biomech. 26, 371-376.

Lorenz, R. 1974. On the thumb of the Hylobatidae. Gibbon and siamang, 3, 157-175.

Lovejoy, C. O., Heiple, K. G., & Meindl, R. S. 2001. Palaeoanthropology: Did our ancestors knuckle-walk? Nature. 410, 325-327.

Lozano, M., Estalrrich, A., Bondioli, L., Fiore, I., Bermudez de Castro, J. M., Arsuaga, J. L., . … Frayer, D. W. 2017. Right-handed fossil humans. Evol Anthropol. 26, 313-324.

MacNeilage, P. F., Studdert-Kennedy, M. G., & Lindblom, B. 1987. Primate handedness reconsidered. Behav Brain Sci. 10, 247-263.

Maier, M. A., & Hepp-Reymond, M.-C. 1995. EMG activation patterns during force production in precision grip: I. Contribution of 15 finger muscles to isometric force. Exp Brain Res. 103, 108-122.

Maki, J., & Trinkaus, E. 2011. Opponens pollicis mechanical effectiveness in Neandertals and early modern humans. PaleoAnthropology. 2011, 62-71.

Marchi, D., Proctor, D. J., Huston, E., Nicholas, C. L., & Fischer, F. 2017. Morphological correlates of the first metacarpal proximal articular surface with manipulative capabilities in apes, humans and South African early hominins. Comptes Rendus Palevol. 16, 645-654.

Mariotti, V., Facchini, F., & Belcastro, M. G. 2007. The study of entheses: proposal of a standardised scoring method for twenty-three entheses of the postcranial skeleton. Collegium Antropolo. 31, 291-313.

Marzke, M., Wullstein, K., & Viegas, S. 1992. Evolution of the power (“squeeze”) grip and its morphological correlates in hominids. Am J Phys Anthropol. 89, 283-298.

Marzke, M. W. 1997. Precision grips, hand morphology, and tools. Am J Phys Anthropol. 102, 91-110.

Marzke, M. W., Marzke, R., Linscheid, R., Smutz, P., Steinberg, B., Reece, S., & An, K. 1999. Chimpanzee thumb muscle cross sections, moment arms and potential torques, and comparisons with humans. Am J Phys Anthropol.110, 163-178.

Marzke, M. W., Shrewsbury, M. M., & Horner, K. E. 2007. Middle phalanx skeletal morphology in the hand: can it predict flexor tendon size and attachments? Am J Phys Anthropol. 134, 141-151.

Marzke, M. W., Tocheri, M. W., Steinberg, B., Femiani, J., Reece, S., Linscheid, R., . . . Marzke, R. 2010. Comparative 3D quantitative analyses of trapeziometacarpal joint surface curvatures among living catarrhines and fossil hominins. Am J Phys Anthropol. 141, 38-51.

Marzke, M. W. 2013. Tool making, hand morphology and fossil hominins. Philos T R S B. 368, 20120414.

Matarazzo, S. 2013. Manual pressure distribution patterns of knuckle-walking apes. Am J Phys Anthropol, 152, 44-50.

Mays, S. 2002. Asymmetry in metacarpal cortical bone in a collection of British post-mediaeval human skeletons. J Archaeol Sci. 435-441.

McGrew, W. C., & Marchant, L. F. 1997. On the other hand: current issues in and meta-analysis of the behavioral laterality of hand function in nonhuman primates. Am J Phys Anthropol. 104, 201-232.

Meunier, H., & Vauclair, J. 2007. Hand preferences on unimanual and bimanual tasks in white-faced capuchins (Cebus capucinus). Am J Primatol. 69, 1064-1069.

Microsoft Corporation. 2023. Microsoft Excel.

Milella, M. 2014. The influence of life history and sexual dimorphism on entheseal changes in modern humans and African great apes. Plos One, 9, e107963.

Milella, M., Giovanna Belcastro, M., Zollikofer, C. P., & Mariotti, V. 2012. The effect of age, sex, and physical activity on entheseal morphology in a contemporary Italian skeletal collection. Am J Phys Anthropol. 148, 379-388.

Momose, T., Nakatsuchi, Y., & Saitoh, S. 1999. Contact area of the trapeziometacarpal joint. J Hand Surg. 24, 491-495.

Morino, L. 2011. Left-hand preference for a complex manual task in a population of wild siamangs (Symphalangus syndactylus). Int J Primatol. 32, 793-800.

Morino, L., Uchikoshi, M., Bercovitch, F., Hopkins, W. D., & Matsuzawa, T. 2017. Tube task hand preference in captive hylobatids. Primates. 58, 403-412.

Munson Chapman, N. E. 1997. Evidence for Spanish influence on activity induced musculoskeletal stress markers at Pecos Pueblo. Int J Osteoarchaeol. 7, 497-506.

Napier, J. 1962. The evolution of the hand. Sci Am. 207, 56-65.

Napier, J. R. 1956. The prehensile movements of the human hand. J Bone Joint Surg. 38, 902-913.

Napier, J. R. 1960. Studies of the hands of living primates. P Zool Soc. 134, 647-657.

Neufuss, J. 2017. Hand use and posture during manipulative behaviours and arboreal locomotion in African apes. Ph.D. Dissertation. University of Kent.

Neufuss, J., Robbins, M. M., Baeumer, J., Humle, T., & Kivell, T. L. 2019. Manual skills for food processing by mountain gorillas (Gorilla beringei beringei) in Bwindi Impenetrable National Park, Uganda. Biol J Linn Soc. 127, 543-562.

Niewoehner, W. A. 2000. The functional anatomy of late Pleistocene and recent human carpometacarpal and metacarpophalangeal articulations. Ph.D. Dissertation. The University of New Mexico.

Niinimaki, S. 2012. The relationship between musculoskeletal stress markers and biomechanical properties of the humeral diaphysis. Am J Phys Anthropol. 147, 618-628.

Nolte, M., & Wilczak, C. 2013. Three-dimensional surface area of the distal biceps enthesis, relationship to body size, sex, age and secular changes in a 20th century American sample. Int J Osteoarchaeol., 23, 163-174.

Papadatou-Pastou, M., Ntolka, E., Schmitz, J., Martin, M., Munafo, M. R., Ocklenburg, S., & Paracchini, S. 2020. Human handedness: A meta-analysis. Psychol Bull. 146, 481.

Papademetriou, E., Sheu, C.-F., & Michel, G. F. 2005. A meta-analysis of primate hand preferences, particularly for reaching. J Com Psychol. 119, 33.

Parnell, R. J. 2001. Hand preference for food processing in wild western lowland gorillas (Gorilla gorilla gorilla). J Com Psychol. 115, 365.

Patel, B. A. 2010. Functional morphology of cercopithecoid primate metacarpals. J Hum Evol. 58, 320-337.

Patel, B. A., Orr, C. M., & Jashashvili, T. 2020. Strength properties of extant hominoid hallucal and pollical metapodials. J Hum Evol. 143, 102774.

Prime, J. M. 2014. The ape ecological niche: posture and hand use in gibbons and macaques and the influence of manual skill on cognitive development in apes and humans. Ph.D. Dissertation. Southern Illinois University at Carbondale.

Prime, J. M., & Ford, S. M. 2016. Hand manipulation skills in hylobatids. In: Reichard, U., Hirai, H., Barelli, C. (Eds.) Evolution of gibbons and siamang. pp. 269-289. Springer.

Rawlins, R. 1993. Locomotive and manipulative use of the hand in the Cayo Santiago macaques (Macaca mulatta). In: Preuschoft, H., and Chivers, D. (Eds.). Hands of primates, pp. 21-30.

Regaiolli, B., Spiezio, C., & Vallortigara, G. 2016. Manual lateralization in macaques: handedness, target laterality and task complexity. Laterality. 21, 100-117.

Robb, E. 1998. The interpretation of skeletal muscle sites: a statistical approach. Int J Osteoarch. 8: 363-377.

Rolian, C., Lieberman, D. E., & Zermeno, J. P. 2011. Hand biomechanics during simulated stone tool use. J Hum Evol. 61, 26-41.

Roy, T. A., Ruff, C. B., & Plato, C. C. 1994. Hand dominance and bilateral asymmetry in the structure of the second metacarpal. Am J Phys Anthropol. 94, 203-211.

Rstudio. 2020. Rstudio: Integrated development for R. Rstudio. PBC, Boston, MA.

Ruff, C., Holt, B., & Trinkaus, E. 2006. Who's afraid of the big bad Wolff?:"Wolff's law" and bone functional adaptation. Am J Phys Anthropol. 129, 484-498.

Ruff, C. B., & Jones, H. H. 1981. Bilateral asymmetry in cortical bone of the humerus and tibia-sex and age factors. Hum Biol. 69-86.

Santana-Cabrera, J., Velasco-Vazquez, J., & Rodriguez-Rodriguez, A. 2015. Entheseal changes and sexual division of labor in a North-African population: The case of the pre-Hispanic period of the Gran Canaria Island (11th-15th c. CE). Homo. 66, 118-138.

Sarringhaus, L., Stock, J., Marchant, L., & McGrew, W. 2005. Bilateral asymmetry in the limb bones of the chimpanzee (Pan troglodytes). Am J Phys Anthropol. 128, 840-845.

Schlecht, S. H. 2012. Understanding Entheses: Bridging the Gap Between Clinical and Anthropological Perspectives. Anat Rec. 295, 1239-1251.

Schmitt, V., Melchisedech, S., Hammerschmidt, K., & Fischer, J. 2008. Hand preferences in Barbary macaques (Macaca sylvanus). Laterality. 13, 143-157.

Schrader, S. 2019. Bioarchaeological approaches to activity reconstruction. In: Martin, D. (Ed.). Activity, Diet and Social Practice: Addressing Everyday Life in Human Skeletal Remains. pp. 55-126.

Shafer, D. D. 1987. Patterns of hand preference among captive gorillas. Ph.D. Dissertation. San Francisco State University.

Shaw, H., & Benjamin, M. 2007. Structure-function relationships of entheses in relation to mechanical load and exercise. Scand J Med Sci Spor. 17, 303-315.

Silman, A. J., & Hochberg, M. C. 1993. Epidemiology of the rheumatic diseases. Oxford University Press.

Sims, N. A., & Gooi, J. H. 2008. Bone remodeling: Multiple cellular interactions required for coupling of bone formation and resorption. Semin Cell Dev Biol. 19, 444-451.

Stafford, D. K., Milliken, G. W., & Ward, J. P. 1990. Lateral bias in feeding and brachiation in Hylobates. Primates. 31, 407-414.

Steen, S. L., & Lane, R. W. 1998. Evaluation of habitual activities among two Alaskan Eskimo populations based on musculoskeletal stress markers. Int J Osteoarchaeol. 8, 341-353.

Stephens, N. B., Kivell, T. L., Gross, T., Pahr, D. H., Lazenby, R. A., Hublin, J. J., . . . Skinner, M. M. 2016. Trabecular architecture in the thumb of Pan and Homo: implications for investigating hand use, loading, and hand preference in the fossil record. Am J Phys Anthropol. 161, 603-619.

Stephens, N. B., Kivell, T. L., Pahr, D. H., Hublin, J.-J., & Skinner, M. M. 2018. Trabecular bone patterning across the human hand. J Hum Evol. 123, 1-23.

Susman, R. L. 1998. Hand function and tool behavior in early hominids. J Hum Evol. 35, 23-46.

Tang, P. 2011. Collateral ligament injuries of the thumb metacarpophalangeal joint. J Am Acad Orthop Surg. 19, 287-296.

Thompson, N. E. 2020. The biomechanics of knuckle-walking: 3-D kinematics of the chimpanzee and macaque wrist, hand and fingers. J Exp Biol. 223, jeb224360.

Tiesler, V., Chi-Keb, J. R., & Ortega Munoz, A. 2020. Crossing the threshold of modern life: Comparing disease patterns between two documented urban cemetery series from the City of Merida, Yucatan, Mexico. In: Azcorra, H. and Dickinson, F. (Eds.). Culture, environment and health in the Yucatan peninsula: A human ecology perspective. pp. 243-256. Springer International Publishing.

Tocheri, M. W., Marzke, M., Liu, D., Bae, M., Jones, G., Williams, R., & Razdan, A. 2003. Functional capabilities of modern and fossil hominid hands: Three-dimensional analysis of trapezia. Am J Phys Anthropol. 122, 101-112.

Tocheri, M. W., Razdan, A., Williams, R., & Marzke, M. 2005. A 3D quantitative comparison of trapezium and trapezoid relative articular and nonarticular surface areas in modern humans and great apes. J Hum Evol. 49, 570-586.

Tocheri, M. W., Orr, C. M., Jacofsky, M. C., & Marzke, M. W. 2008. The evolutionary history of the hominin hand since the last common ancestor of Pan and Homo. J Anat. 212, 544-562.

Tuttle, R. 1972. Functional and evolutionary biology of hylobatid hands and feet. Gibbon and siamang, 136-206.

Tuttle, R. H. 1969. Quantitative and functional studies on the hands of the Anthropoidea. I. The Hominoidea. J Morphol. 128(3), 309-363.

Uomini, N. T. 2009. The prehistory of handedness: archaeological data and comparative ethology. J Hum Evol. 57, 411-419.

Van Horn, R. N. 1972. Structural Adaptations to Climbing in the Gibbon Hand 1. Am Anthropol. 74, 326-334.

Van Leeuwen, T., Vanneste, M., D'Agostino, P., & Vereecke, E. E. 2022. Trapeziometacarpal joint mobility in gibbons (fam. Hylobatidae) and rhesus macaques (Macaca mulatta). Am J Biol Anthropol. 177, 708-718.

Van Leeuwen, T., Vanneste, M., Kerkhof, F., Stevens, J., & Vereecke, E. 2019. Relating trapeziometacarpal joint morphology to functional capabilities in the primate thumb. J Morphol.

Vanhoof, M. J., van Leeuwen, T., & Vereecke, E. E. 2020. The forearm and hand musculature of semi-terrestrial rhesus macaques (Macaca mulatta) and arboreal gibbons (Fam. Hylobatidae). Part I. Description and comparison of the muscle configuration. J Anat. 237, 774-790.

Villotte, S., Castex, D., Couallier, V., Dutour, O., Knusel, C. J., & Henry-Gambier, D. 2010. Enthesopathies as occupational stress markers: evidence from the upper limb. Am J Phys Anthropol. 142, 224-234.

Volpato, V., Macchiarelli, R., Guatelli-Steinberg, D., Fiore, I., Bondioli, L., & Frayer, D. W. 2012. Hand to mouth in a Neandertal: right-handedness in Regourdou 1. Plos One.

Wallace, I. J., Winchester, J. M., Su, A., Boyer, D. M., & Konow, N. 2017. Physical activity alters limb bone structure but not entheseal morphology. J Hum Evol. 107, 14-18.

Warren, J. M. 1980. Handedness and laterality in humans and other animals. Phys Psychol. 8, 351-359.

Watanabe, K., & Kawai, M. 1993. Lateralized hand use in the precultural behavior of the Koshima monkeys (Macaca fuscata). In Ward, J. and Hopkins, D. (Eds.). Primate laterality: Current behavioral evidence of primate asymmetries. pp. 183-192. Springer.

Weiss, E. 2007. Muscle markers revisited: activity pattern reconstruction with controls in a central California Amerind population. Am J Phys Anthropol. 3, 931-940.

Weiss, E. 2014. Bipedalism and musculoskeletal stress markers: variation and what it reveals about adaptation, environmental stress, and reconstructing activity patterns. In: Carlson, K., and Marchi, D. (Eds.) Reconstructing mobility: Environmental, behavioral, and morphological determinants. pp. 31-47. Springer.

Weiss, E. 2015a. Examining activity patterns and biological confounding factors: differences between fibrocartilaginous and fibrous musculoskeletal stress markers. Int J Osteoarchaeol. 25, 281-288.

Weiss, E. 2015b. The surface of bones: methods of recording entheseal changes. Surf Topog Metrol Prop. 3, 034003.

Westergaard, G., Lussier, I., & Higley, J. 2001. Between-species variation in the development of hand preference among macaques. Neuropsychologia, 39, 1373-1378.

Westergaard, G. C., Kuhn, H. E., & Suomi, S. J. 1998. Bipedal posture and hand preference in humans and other primates. J Comp Psychol. 112, 55.

Wilczak, C. A. 1998. Consideration of sexual dimorphism, age, and asymmetry in quantitative measurements of muscle insertion sites. Int J Osteoarchaeol. 8, 311-325.

Williams-Hatala, E., Hatala, K., Hiles, S., & Rabey, K. 2016. Morphology of muscle attachment sites in the modern human hand does not reflect muscle architecture. Sci Rep. 6, 1-8.

Yoshida, R., House, H. O., Patterson, R. M., Shah, M. A., & Viegas, S. F. 2003. Motion and morphology of the thumb metacarpophalangeal joint. J Hand Surg. 28, 753-757.

Zeininger, A., Richmond, B. G., & Hartman, G. 2011. Metacarpal head biomechanics: a comparative backscattered electron image analysis of trabecular bone mineral density in Pan troglodytes, Pongo pygmaeus, and Homo sapiens. J Hum Evol. 60, 703-710.

Zumwalt, A. 2006. The effect of endurance exercise on the morphology of muscle attachment sites. J Exp Biol. 209, 444-454.