

Exploring Development in Relation to Terrain: 3D Skeletal Analysis of the Femoral Neck-Shaft  
Angle

by

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## Abstract

Bioarchaeologists have expressed interest in the study of past populations and their mobility, with studies focusing on behavioural adaptations and subsistence strategies. While the effect of the topographical terrain on bone expression has been explored briefly, our understanding of it, especially in juvenile specimens, is limited. The object of this essay is to explore the effect of terrain in two archaeological samples, Indian Knoll (Green River, Kentucky) and Later Stone Age South Africans (Cape Fold Mountains, South Africa). These are both considered highly active populations, who inhabited vastly different geographical areas. To study skeletal expression, the femoral neck-shaft angle was chosen for study, due to its importance in clinical literature – cited as being highly developmentally plastic, and bioarchaeologists such as Erik Trinkaus have found changes in its expression that correspond to behavioural patterns. While no effect of terrain was observed in this study, future research with juveniles, the femoral neck-shaft angle, and the 3D method created for this project can benefit bioarchaeology and wider understandings of juvenile skeletal expression and attendant terrain-based effects.

## Keywords

Biomechanics; juveniles; terrain; bony response; plasticity; environment; evolutionary constraint; femoral neck-shaft angle; 3D methods

# 1 INTRODUCTION

For bioarchaeologists, the analysis of skeletal material is the greatest resource for understanding the health, behavior and mobility of past archaic and modern human populations. Such analysis is based in the principles of biomechanics and bony response. Recently, bioarchaeologists have focused on cross-section geometry (CSG) studies of the diaphyseal shafts of long bones for insights into the mobility of past populations (Ruff and Larson 2014, 13), where changes in rigidity and shape are attributed to bony responses to loading. Although studies exploring terrain effect are limited, Ruff's work with North American samples found greater rigidity of the femora of samples from mountainous regions when compared with those from plains regions (Ruff and Larson 2014, 18), a finding corroborated in later studies by Stock and Pfeiffer (2001). These studies suggest that skeletal response can be elicited as an effect of terrain, but these studies are limited to the analysis of adult bone.

In order to study the effect of terrain in developing bone, the femoral neck-shaft angle was selected for analysis in this research project. This feature was selected due to its clinical importance in the hip joint, and the fact that its expression changes over development from a high angle to a low angle (as a result of genetics, loading, muscle activation, and other factors). This feature was also selected because it is thought, in bioarchaeology, to constitute a developmentally plastic feature (Trinkaus 1993), but this assertion solely relies on the work of anatomists, clinical and biomechanical researchers, rather than rigorous bioarchaeological study.

This research project developed a new 3D methodology for measuring the femoral neck-shaft angle (FNSA), in hopes of understanding the terrain effect on skeletal expression in this region of the proximal femur. This project analyzed the femora (n=91) of two archaeological samples inhabiting vastly different geographical terrains but with similar activity levels. The

samples were Indian Knoll, from Green River Kentucky (6415-4143 cal. years B.P.) (Winters 1974, xviii), and the Later Stone Age South Africans, from the Cape Fold Mountains (9120-220 years BP, uncalibrated) (Kurki and Harrington 2017). By analyzing samples with similar activity levels, any effect of terrain could be easily distinguished from an established relative norm.

## **2 THEORETICAL FRAMEWORK**

### **2.1 BIOMECHANICS AND THE HIP JOINT**

Biomechanics is simply “the application of mechanical principles to biological systems” (Ruff 2008, 183). These theoretical underpinnings date back to Aristotle, Hippocrates, and Galileo (Mow and Huiskes 2005). Of particular interest to early anatomists and surgeons were the joints of the human body, as they represented a complex interaction of biological materials, and are sites of common bony fractures. As such, research into methods for fracture fixture expanded, and anatomists and surgeons began to ponder the reasons behind why certain locations in the skeleton are more prone to fracture. Works born out of this movement include those by Wilhelm Roux, Fredrich Pauwels, Hermann von Meyer, Karl Culmann, Julius Wolff, and John C. Koch – all of whom analyzed the microstructure of bone for evidence of mechanical response. The research conducted by Wolff is still prevalent today as the concept of “Wolff’s law” or “the law of bone transformation” (Roesler 1987), which asserts that bone is remodeled throughout life – laid down where it is needed and removed where it is not – although some have called for its renaming (Ruff et al. 2006). Wolff’s understandings of bone remodeling sparked the study and identification of re-aligned trabeculae in the proximal femur: a pivotal development for both anthropology and orthopedics, as it displayed response to differing forces acting upon the hip joint (Meyer 1867). Further study of the hip joint is beneficial to anthropology as an avenue for understanding the evolution of bipedalism, while in orthopedic literature, study can contribute to

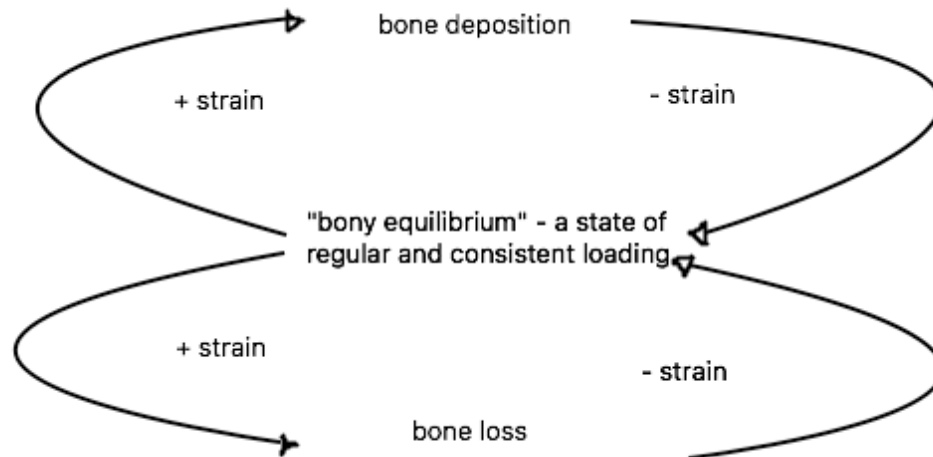
better prediction of fracture and how best to undertake fixation. Orthopedics have also expanded study beyond fracture, into the study of abnormal conditions that inhibit movement at the hip joint. These issues often arise congenitally, or stem from an absence of normal loading conditions. The effects of muscle activation in the hip have also been explored by several researchers (Yadav et al. 2017, Correa et al. 2010), as many muscles in this region play several roles in the lower limb (ex. *Rectus femoris* both flexes at the hip and extends at the knee). A more in-depth review of biological anthropological and orthopedic literature in reference to the FNSA will be provided in Section 2.4.

Biomechanics, as it relates to the hip joint and the skeleton in general, is governed by natural laws defined largely by physics, with models providing the basis for understanding the musculoskeletal system. While these are too complex to review here, the broad mechanical concepts are velocity and acceleration, forces, moments, and Newton's Laws (Mow and Huijskes 2005). When studying bone, these basic concepts still govern, but are applied specifically to the architecture that governs bone growth and response. Bony biomechanical concepts include stiffness and strength, bone density, stress and strain, modeling and remodeling. Especially important to this study is the understanding of bony growth and response during development, and how it differs from adult bony response.

## **2.2 DEVELOPMENTAL GROWTH & BONY RESPONSE**

As established through the foundational works of 18<sup>th</sup>, 19<sup>th</sup> and 20<sup>th</sup> century anatomists and surgeons, bone does indeed respond to the loading environment, and is best conceptualized as a feedback loop (see Figure 1). The feedback loop simply states that changes in the amount of strain experienced by bony tissue will stimulate bone deposition or resorption, leading to changes in structure (Ruff et al. 2006, 485).

Understanding bony response during juvenile development is complicated by changes in architectural and mechanical properties as an individual grows (Mow and Huiskes 2005), and the understanding that “bone responses to mechanical loading appear to be stronger during growth than during adulthood” (Carlson and Marchi 2014, 2).



*Figure 1 The bone remodeling feedback loop, adapted from figure 1 in Ruff et al. 2006*

The above diagram represents basic bone **remodeling**, which is a process that occurs both during and after development, whereas bone **modeling** is the process that governs growth and is present only in juveniles up until epiphyseal fusion (Ruff et al. 2006, 484). Modeling differs from remodeling in that osteoblasts and osteoclasts are present on the inner and outer cortex of bone to “build” it in accordance with the experienced biomechanical environment and genetic programming, whereas bone remodeling is primarily a repair process (Fricke and Schoenau 2007, 3).

Exploring the processes governing osteological modeling and remodeling led to the creation of the mechanostat model in 1960 by Harold M. Frost. Frost asserted that osteocytes, the living cells present in bone tissue, worked like a “thermostat” in which bone mass is monitored

in response to mechanical strain, and once a “minimum effective strain” is reached, the “mechanostat” sends out osteoblasts and osteoclasts to modify bone (Tyrovola and Odont 2015, 2724). From here, the understanding of bony response has extended to include its interaction with muscles, which has been termed the “functional-muscle-bone-unit” (Schoenau 2005, 232), and pivotal work by Matsuoka et al. (2005) has illuminated the fact that both bone and muscle cells are born of the same precursor cells – thus justifying the call for a bone-muscle model of evaluation.

On top of the factors affecting bony response as a result of the “mechanostat” model, the situation is further complicated by the composition of juvenile bone, which is more elastic than adult bone, and responds to mechanical loads slightly differently (Ubelaker and Montaperto 2011, 35). Due to these observed differences between juveniles and adults, research has been taken up in order to further knowledge on skeletal development.

The basic geometric shape a bone takes on through its development is conceptualized as “skeletal patterning” in which final forms are determined via genetic programming, resulting in similar skeletal morphologies within humans and other mammals (Rauch & Schoenau 2001, 310), especially in the functional ends where the experienced mechanical forces are greatest (Currey 1984, 117). When long bones transform from their cartilaginous form through the process of ossification, mineralization encases osteocytes in the bony matrix of lamellar bone, and further growth and development occurs through modeling and remodeling, (Rauch & Schoenau 2001, 311). Since it is generally understood in osteology that bone strength increases with age to create strain-resistant, light-weight bones, the genetic and hormonal basis of this process has been explored (Shoenau et al. 2001, Neu et al. 2001, Schiessl et al. 1998). The role

of estrogen in bone is thought to regulate the processes governing bone deposition and resorption by acting as a moderator in the “mechanostat” equilibrium (Fricke & Schoenau 2007, 3).

While other organs in humans are thought to be governed by cellular and genetic processes, the “mechanostat” concept suggests that these processes are brought about by the bony organ itself in order to adapt itself to mechanical strain (Rauch & Schoenau 2001, 310), while also being privy to developmental environment. From the vast literature that exists to further our understandings of bone both microscopically and macroscopically, it has unequivocally been proven that bone is plastic, although evolutionary constraints such as skeletal patterning restrict the range of phenotypic expression possible.

### **2.3 PLASTICITY AND EVOLUTIONARY CONSTRAINT**

Plasticity in the osteological context is referred to as “the concept that the development of the phenotype of an organism is responsive to variations in the quality and quantity of environmental factors required for life” (Bogin and Varela-Silva 2010, p.1060). Plasticity of bone is seen in bony response, reflecting muscle activations and biomechanical loads and all other non-genetic factors.

The final expression of a phenotype relies not only bone plasticity, but also the interaction of genetics with the developmental environment and the ecological environment. Developmental programming, “the programming of various bodily systems and processes by a stressor of the maternal system during pregnancy or during the neonatal period” (Reynolds et al. 2010, E61), may result in an altered expression of a phenotype as the fetus responds to its environment through maternal cues. The ecological environment (in both its resource availability and geography) also affect the growing skeleton through nutrition and load-bearing.

The degree to which a phenotype can vary is also dependent on the trait being considered and whether or not its evolutionary history restricts its ability to respond to these complex interactions. Evolutionary constraint is simply any factor that inhibits an adaptive response to the experienced environment of an organism. When considering the FNSA, the largest evolutionary constraint is its role in the proper functioning and maintenance of the hip joint, since the hip joint requires direct articulation of the proximal femur with the os coxa. Genetic constraint, where traits are associated and controlled together (Grabowski 2013, 58), likely limits the variation possible in this region. Another evolutionary constraint is the “fundamental form” of long bones, which states that the cartilaginous model of the femur, in terms of its 3D morphology, represents the final form of the ossified bone, regardless of biomechanical demands (Hall 2005, 407). This is not say that the expression of certain features cannot vary, but that the shape of the bone as a whole is pre-set in our evolutionary ancestry.

When studying a skeletal feature in respect to the loading environment, it is useful to consider the other limitations imposed by genetics, developmental and ecological environments, and evolutionary history.

#### **2.4 FEMORAL NECK-SHAFT ANGLE – WHAT IS IT AND HOW HAS IT BEEN PREVIOUSLY STUDIED?**

The interrelationship of the femur and the pelvis, along with our bipedal gait means that the proximal femur, while constrained by genetics, developmental and ecological environments, and evolutionary constraint, is, according to the current literature available, more affected by the “behavioural patterns” associated with load-bearing (Nadell et al. 2016, 411). The effects of load-bearing, as proposed by Trinkaus (1993), Hoaglund & Weng (1980), Clark et al. (1987) and many other biological anthropologists and orthopedic researchers, can be especially viewed from a developmental lens through the study of the FNSA. The FNSA is widely cited and defined by

Braüer (1988) as “the degree of more medial vs. more proximal orientation of the femoral head and neck” (Martin Measurement no. 29). This section is concerned with reviewing the literature on FNSA as it currently stands, and begins with orthopedic study, followed by more relevant research in the realm of bioarchaeology. Early study of the FNSA was done by surgeons, anatomists and clinicians, and bioarchaeological interest was born out of these studies.

#### **2.4.1. Clinical & Orthopedic Literature**

Our primary understanding of the FNSA and its importance in the hip joint comes largely from the research of clinicians. Humphry (1889) was one of the first to confirm the decreasing of the angle from childhood to adulthood, which he attributed to normal weight- and load-bearing activities during development (276). Furthermore, he found that the angle remaining essentially unchanged throughout adulthood (280). Humphry also noted that in cases where normal loading does not occur, a child’s neck-shaft angle is likely to remain high (281). In the clinical literature, the FNSA may also be referred to as the angle of inclination (Moore et al. 2014, 518), the caput-collum-diaphyseal angle (CCD angle) (OrthopaedicsOne... c2012-2015), or the cervico diaphyseal angle (Labronici et al. 2011).

While normal variation exists, the FNSA is generally 150° in infants, decreasing to around 126° in adulthood (OrthopaedicsOne... c2012-2015). When the angle is more than 135°, it is considered clinically to represent the condition of coxa valga, which is often associated with neck anteversion where the neck is oriented more proximally than is normal. Coxa valga is often associated with neuromuscular disorders such as cerebral palsy (Lewis et al. 1964, 6), where the large angle (and often accompanying neck anteversion) lead to an unstable hip joint (Lee et al. 2010, 720) in which spastic hip dislocation is a common symptom (Chang et al. 2015, 3676) that must be treated clinically. Coxa vara refers to a FNSA of less than 120° and can also cause complications in the developing hip joint (Rizk 2017, 365) which, if left unchecked, can lead to

early degeneration of the hip joint due to compressive and shear forces acting upon the femoral neck (Rizk 2017, 366). This condition is surgically corrected either bilaterally or unilaterally, depending on its expression (Rizk 2017, 365). In infants, the measurement of the FNSA may also indicate the presence of developmental dysplasia of the hip (DDH) (Upasani et al. 2012, 173), where treatment becomes complicated if not identified at the birth of a child (OrthoInfo... c1995-2018). The causes of diseases such as cerebral palsy are genetic, but the effects they have on the expression of the FNSA depend on an individual's loading throughout development. Without the careful fixation of these diseases and conditions, children develop gait patterns that expose the joint to loading conditions that may stress the proximal femur, resulting in future deformities and/or fractures (Shefelbine & Carter 2004, 298), while children who are non-ambulatory do not experience normal loading.

The absence of normal load-bearing and its effects on FNSA (and anteversion) have been established by orthopedic researchers (ex. Heimkes et al. 1993), especially in regard to children with cerebral palsy (Shore et al. 2012, 127). Under normal loading conditions, the modelling of the femoral neck is thought to represent an adaptation to bipedalism that allows greater rotation of the hip joint and best resists compressive forces and muscle contractions (Djurić et al. 2012, 743). When children are non-ambulatory, these conditions are not present, and the FNSA remains high, giving credence to the belief that this feature is developmentally plastic (Souza et al. 2015, 75).

The FNSA is also considered relevant in adulthood, as its value can provide insight into individual fracture risk in the femoral neck (Jiang et al. 2015, 1). The adult FNSA reflects developmental loading conditions and may not be well suited if adult mobility is drastically different. Jiang et al. 2015 state that establishing normal adult ranges of FNSAs in populations

may better identify the possibility of hip osteoarthritis, femoroacetabular impingement, and fracture (4).

Understanding of the FNSA and its expression throughout development and its resultant adult form are indispensable to clinical practice. The fact that infants have similar FNSAs at birth suggest a degree of constraint its variation, with a general trend of decrease over development to a population-specific value that reflects normal loading. The genetic diseases and conditions that affect the expression of the FNSA do so through altering gait and muscle activation patterns, or a complete absence of loading. In studying these variations, clinicians are able to diagnose and treat abnormalities in childhood, and predict the risk of future disease and fracture in adults. Bioarchaeological interest in pursuing this feature as an avenue for understanding past population's mobility and habitual activity is based largely out of the clinical study of variation in the FNSA,

#### **2.4.2 Bioarchaeological Study**

While other bioarchaeologists have measured FNSA in population studies, focused interest from bioarchaeology was first seen in 1993 with Erik Trinkaus' study of Neandertals and near-modern early humans. This study aimed to understand the phylogenetic relationship between these groups, both of which lived in the Near East during the turn to the Late Paleolithic (Trinkaus 1993, 393), and how differences in their morphologies might be reflective of behavioural adaptations. Trinkaus states that he has chosen the FNSA to study because "it should primarily reflect variation in activity levels during development" (Trinkaus 1993, 400), citing orthopedic literature to support this statement. His comparison of the samples yielded higher FNSAs in the near-modern early humans, which he attributed to lessened levels of loading activities during development (when compared to a Neandertal sample), where younger children may not have

participated heavily in food-gathering and stays at shelters may have lasted for longer time periods than was common for Neandertal groups. While assigning a degree of individual variation to both samples, Trinkaus concluded that different loading patterns among groups during development are reflected in the adult expression of FNSA.

Other researchers have also utilized FNSA to understand other archaic hominins and the transition to the unique morphology of the modern human proximal femur. Ruff and Higgins (2013) found that both posture and locomotion differences between *Australopithecus* and *Homo* manifest in different FNSA values as well as differences in the distribution of bone in the neck-shaft (517). Weaver (2003) also examined Neandertals and near-modern humans, echoing Trinkaus' 1993 study, but took the perspective of climate adaptation rather than behavioural adaptation. He suggested that differences between the two groups existed because of differences in body breadth attributed to cold- and warm-adapted bodies, but only looked at femoral shape rather than focusing attention on FNSA, calling for future researchers to explore this relationship. In 2017, Child and Cowgill explore the climate-body proportion relationship through the study of several Holocene samples, focusing specifically on the juveniles (3). Their results concluded that FNSA varied greatly with age, but were similar among geographical samples, suggesting stabilizing selection of FNSA throughout development (under normal loading conditions) rather than differences attributed to climate-adapted body breadth. They support behavioural variation, as they noted that the “degree of declination of the NSA is presumably similar among individuals with similar gait patterns” (Child & Cowgill 2017, 12).

Interest in the degree of normal variation of FNSA in different populations has been taken up by both clinical and bioarchaeological researchers. In 1998, Anderson & Trinkaus surveyed historic and prehistoric population samples for sexual, side and behavioural variation. Their analyses did not find significant differences in sexual variation but did find some side asymmetry – although it could not consistently be attributed to one side, with an average of approximately 5° difference between right and left (Anderson & Trinkaus 1998, 283). In terms of subsistence type, they found that “the nonmechanical hunting and gathering peoples have the lowest angles, and the urban samples have the highest ones, with the agricultural groups being more variable and overlapping” (Anderson & Trinkaus 1998, 284). They found no effect of geography, climate or “race” on FNSA expression.

In Gilligan, Chandraphak & Mahakkanukrauh’s 2013 study, an anthropologist and two anatomists explored variation with special interest in the potential effects of climate, clothing, lifestyle, sex, age and side. Although they found some correlation between climate and FNSA, they were modest and reflected general ecogeographic (relating to climatic conditions) body proportion patterns (Gilligan et al. 2013, 140). The decision to analyze clothing and its effect on FNSA was an interesting yet somewhat confusing facet of this study, as it is considered as a cultural buffer against the modest shifts they attributed to climatic conditions. An important finding in this study was the apparently narrowed range of FNSA variation within each lifestyle group (Gilligan et al. 2013, 146) which supports the hypothesis that behavior affects expression. Gilligan, Chandraphak & Mahakkanukrauh, like Anderson & Trinkaus (1998), also found asymmetry in FNSA, although they assert that leg dominance doesn’t seem to be the reason for this occurrence (Gilligan et al. 2013, 147).

It is clear from the above review of literature that a developmental and behavioural focus has dominated most of the literature regarding FNSA (when not directly concerned with fixing abnormal conditions/fractures), and while some have explored climatic relationships, whether or not the navigation of environmental terrain itself has an effect on FNSA has not been researched.

## **2.5 ENVIRONMENTAL TERRAIN AND SKELETAL RESPONSE**

Although no study exists with regards to environmental terrain's effect on the FNSA, bioarchaeologists have explored terrain effect through cross-sectional geometry (CSG) studies, which focus on analyzing the diaphyseal shafts of long bones. The interest in CSG studies has been their ability to shed light on the mobility patterns of past populations by interpreting the shape and robusticity of the femur and tibia (Ruff & Larson 2014, 15). Ruff's work with North American samples during the 1980s and 1990s led him to the conclusion that there was "a marked effect of terrain on relative rigidity of the femur, with femora from mountainous regions exhibiting greater rigidity relative to body size than those from plains or coastal regions" (Ruff & Larson 2014, 18). Bioarchaeologists have also examined terrain effect on the length of lower limb bones, and have noted tibial shortening as a response to navigating mountainous terrain (Higgins & Ruff 2011, 342) (specifically as a Neandertal adaptation).

Other researchers in various fields (kinesiology, biomechanics, engineering) have also explored the ways in which walking on uneven terrain affects biomechanical and energetic outputs. Volushina et al.'s 2013 study found that uneven terrain yielded a higher mechanical output of the hip joint, with greater muscle activation and contraction (3965).

The literature around mobility, as it currently stands in bioarchaeology, tends to focus itself around subsistence (behavioural) patterns and strategies that are often compared to

modern day athletes or ethnographic parallels (ex. Macintosh et al. 2017; Venkataraman et al. 2013). While some recent studies have begun to explore bony response to loading in varying terrains, there is plenty of room for researchers to ask new questions regarding terrain effect, and where in the skeleton its effects might manifest themselves.

### **3 ARCHAEOLOGICAL CONTEXT & BIOARCHAEOLOGY**

#### **3.1 INDIAN KNOLL**

##### **3.1.1 Brief profiles of lifestyles, geography, resources**

The Indian Knoll site (15Oh2) represents one of several middle/late Archaic shell middens of the Green River region, Kentucky. Owing to the fact that most archaeological work was carried out in the first (1916) and second (1937-1941) excavations prior to the advent of radiocarbon dating, the long history of this site was not known until later in the 20<sup>th</sup> century. Original dating of Indian Knoll suggested a time frame of 6415-4143 cal. years B.P. (Winters 1974, xviii), but more recent work has suggested samples cluster most frequently around the range of 5590-4530 cal. years B.P. (Morey et al. 2002, 538). The deposition of the shell midden is currently considered to have occurred between 6500-4500 cal. years B.P. (Morey et al. 2002, 539), thus more dating research could be useful. Morey et al. (2002) posit that the original excavations, and their lack of collecting material helpful to dating, disturbed the original stratigraphy, making later dating complicated.

From the general dates provided above, it is obvious that the area we now identify as Indian Knoll was used for a long period of time, and likely by different groups. Most researchers agree that the sites of the lower Ohio Valley, and specifically the Green River region, represent base-camps (more sedentary), from which middle/late archaic hunter-gatherers would travel seasonally from to exploit the resources of the upperbanks and occupy rockshelters (Jefferies 2008, pg. 214). The river supplied ample marine resources for much of the year, mostly in the

form of mussels. Along with the shell middens, skeletons show tooth-wear consistent with a mussel-rich diet (high grit content), as well as the presence of auditory exostoses on some adult males, which “are commonly caused by brief exposures of the ear to cold water” (Jefferies 2008, 255), suggesting some shallow to mid-depth diving for harvesting. When not exploiting river resources, these small Archaic hunter-gatherer groups took advantage of the oak-hickory forest for nuts and collected seasonally available plants, such as strawberry, blackberry, grape and honey locust, from the surrounding areas (Jefferies 2008, 236). The forest also provided hunting opportunities in the form of small game, with a high presence of deer, as well as rabbits and birds. Such animal populations are evidenced by faunal remains and distinctive ground-stone atlatl weights and hooks (Jefferies 2008, 207), along with many tools and ornaments crafted from bone and antler (Jefferies 2008, 211).

The late Archaic period in the Green River region played host to the shift into modern environmental conditions, where drier conditions were replaced with the appearance of floodplains, backwater swamps, and river shoals (Jefferies 2008, 119), throughout a relatively flat terrain. As these conditions stabilized, the population sizes of groups in this area increased, as more areas became suitable for habitation and resource exploitation.

While we cannot know how many different groups lived at Indian Knoll over time, mating likely occurred with nearby groups, given the presence of permanent structures such as hearths, along with biological distance evidence (Jefferies 2008, 249). In residing in these more permanent settlement areas for at least the summer months of the year, Indian Knoll residents differed slightly from the more mobile predecessors of the region and are considered to be “semi-sedentary” (Cowgill 2010, 17). Interestingly, while Indian Knoll residents were generally similar to other Archaic groups of this time in social organization (egalitarian), burial practices

suggest a slight social division based on status (regardless of age or gender) (Rothschild 1979, 671) and buried dog skeletons suggest a close relationship between these animals and residents (Morey 2006, 162).

### **3.1.1 History of Indian Knoll Archaeology & North American Colonialism**

Despite significant progress in the understanding of the Indian Knoll site over the past 100 years, much could still be learned about the paleo-environment, given that early excavators focused their efforts on the materiality of burials and lithic technology. It is important to understand how the bias of original researchers and their interests determined how excavations would be carried out and interpreted. The original excavation of 1916, conducted by C.B. Moore, was “small scale” in its size and time frame, but quickly captured American interest. A privately wealthy man with an interest in Eastern American artifacts (Schwartz 1967, 22), Moore likely held some problematic views characteristic of early North American archaeology, although scholars seem to agree that his excavation methods were considered quite descriptive for their time (Schwartz 1967, 23). It is worth questioning, however, the rigorousness of his methods given that his team recovered almost 300 burials in a short time span of 20 days (Jefferies 2009, 642). With the Depression era came a federally legislated act of emergency employment (Emergency Relief Appropriation Act, 1935), resulting in a larger labour force than previously available for archaeologists. This allowed the large-scale excavation of Indian Knoll from 1937-1941, conducted by newly appointed Kentucky anthropologists (University of Kentucky) William D. Funkhouser and William S. Webb. The latter would come to be the voice of authority in Kentucky archaeology for the remainder of his life, given that the Indian Knoll excavation recovered an additional 800 burials and thousands of artifacts.

Owing in part to these excavations, the skeletal collection that exists today is one of the largest in North America and has been the subject of many bioarchaeological studies (Jefferies

2008, 45) that make up much of what we know about the health and movements of Archaic Green River peoples.

It is my understanding that no repatriation process has been undertaken for the Indian Knoll collection, given the limitations of NAGPRA and its recognition of only certain indigenous groups, along with the great age of this sample. Despite this, it is important that bioarchaeologists are aware of the circumstances in which skeletal material is obtained, especially given the colonial mindsets that plagued many early North American archaeologists and their understandings of living indigenous populations.

## **3.2 LATER STONE AGE SOUTH AFRICA**

### **3.2.1 Brief profiles of lifestyles, geography, resources**

The context of understanding the archaeology of Later Stone Age South Africans is complicated by the distribution of sites and skeletal material. In the case of this research, skeletal material is drawn from the collections now named Florisbad (specimens NMB), McGregor (specimens MMK), Albany (specimens ALB), and Iziko (specimens SAM & SAM-AP), and within these designations, skeletons come from several sites (example in Stock & Pfeiffer 2004, pg. 1003). As such, our understandings of these people are more landscape-oriented than site-specific. It is generally believed that the switch to drier inland conditions at the dawn of the Holocene bottlenecked populations, pushing smaller groups into the Cape Fold and coastal regions of South Africa, where groups found forest, savannah and fynbos biomes (Stock & Pfeiffer 2004; Deacon 1974). The Cape Fold Mountains, while more difficult to navigate than the flat inner plateaus to the north, maintain a continuous archaeological presence as they provided rockshelters and were in close proximity to resource zones such as the coast and the savannah. In the savannah and fynbos regions, warm conditions allowed for the gathering of coorns, a dietary staple (Deacon 1974, 9), and the opportunity to hunt small game browsers such

as antelope (Deacon & Deacon 1999, 121). The presence of thousands of shell middens along the coast illuminate the importance of these areas for resource collection in winter months, with the collection of mussels, fish and coastal bird species (Deacon & Deacon 1999, 155). The general timeframe given to the range of samples used for this study is 9120-220 years BP, uncalibrated (Kurki and Harrington 2017).

Due to paleoenvironmental conditions, our knowledge of Later Stone Age South Africans prior to 5000 7500 – 4500 years ago is sparse, but by about 5000 years ago, the El Niño factor reached its current condition and the record reappears (Deacon & Deacon 1999, 155).

Movement of the Later Stone Age South Africans during the Holocene is attributed to drought cycles that frequently hit fynbos and savannah regions, decimating resource availability (Deacon 1993, 89). It has been suggested by some researchers, such as Sealy & Pfeiffer (2000) and Stock & Pfeiffer (2004) that Later Stone Age South Africans moving along the southern and western Cape represented two distinct groups, although this is still a topic of debate (Stock & Pfeiffer 2004, 1010).

In general, the Later Stone Age South Africans are considered to be highly mobile terrestrial foragers who exploited coastal areas during times of seasonal availability stress in the fynbos and savannah regions. As a result of this subsistence strategy, groups were small and experienced highly variable terrain as they moved throughout their territories (Jefferies 2009, 654).

### **3.2.2 History of Archaeology in South Africa and Colonialism**

The situation regarding the practice of archaeology in South Africa is complicated by colonial, national, and imperial interests as well as the discovery of hominin ancestors by Raymond Dart in 1924. Prior to the 1960s, the practice of archaeology was largely done on the

part of self-interested individuals with the financial means to carry out excavations. Most of this early interest focused on the numerous stone artifacts that would eventually be designated as “stone age,” but early researchers often applied European terms such as Paleolithic and Neolithic that reflected their belief that early European migration created these objects (Deacon 1990, 41). Due to the amateur nature of these early excavations, grave robbing and the selling of artifacts to European collectors was commonplace (Deacon 1990, 42). Data on the original contexts of famous rockshelters are not well recorded until the 1960s when the professionalization of archaeology in the form of empirical, positivist “New Archaeology” began to spread from North America to the rest of the world. What lacked here was the connection of contemporary Africans with prehistoric findings: the colonial attitude was to view prehistory with grandeur and attribute a degeneration of culture to living groups (Robertshaw 1990, 4). This ideology, combined with the state of apartheid in South Africa, has meant that archaeology has long focused on the stone age and ancestral hominins, drawing on modern ethnographies only to further understand past populations. As such, one should be acquainted with the colonial context of the excavations of Later Stone Age South Africans, and treat interpretations made by early archaeologists with caution and academic inquiry. The situation in South African archaeology is still dominated by white foreigners, but there has been an effort to nationalize archaeology for contemporary Indigenous groups in the area and to proudly exhibit its variety (Deacon 1999, 48).

### **3.3 BIOARCHAEOLOGY & ETHICS**

The question of whether or not it is ethical to study the skeletal material of past people has plagued bioarchaeology and archaeology since its roots. For people all over the world, the significance of skeletal remains and burials vary, but are generally understood as having enormous cultural and social value. In the Western framework, skeletal material is important to

science as it represents an avenue to understanding past people's lifeways, while also lending insight into the evolution of anatomically modern humans. But for many cultures, removing the dead from their place of rest is not only problematic, it is disrespectful to both ancestors and their descendent group. It is important for bioarchaeologists, whenever possible, to work with the consent and participation of descendent groups, and repatriate remains when desired by the community.

Despite these ethical concerns, bioarchaeologists assert the importance of their field as a way of understanding past populations in hopes of extending this knowledge to living people. In many cases, the work of bioarchaeologists have illuminated stories of the past that would have otherwise been erased, such as in the study of African slaves living in New York (Blakey 2010).

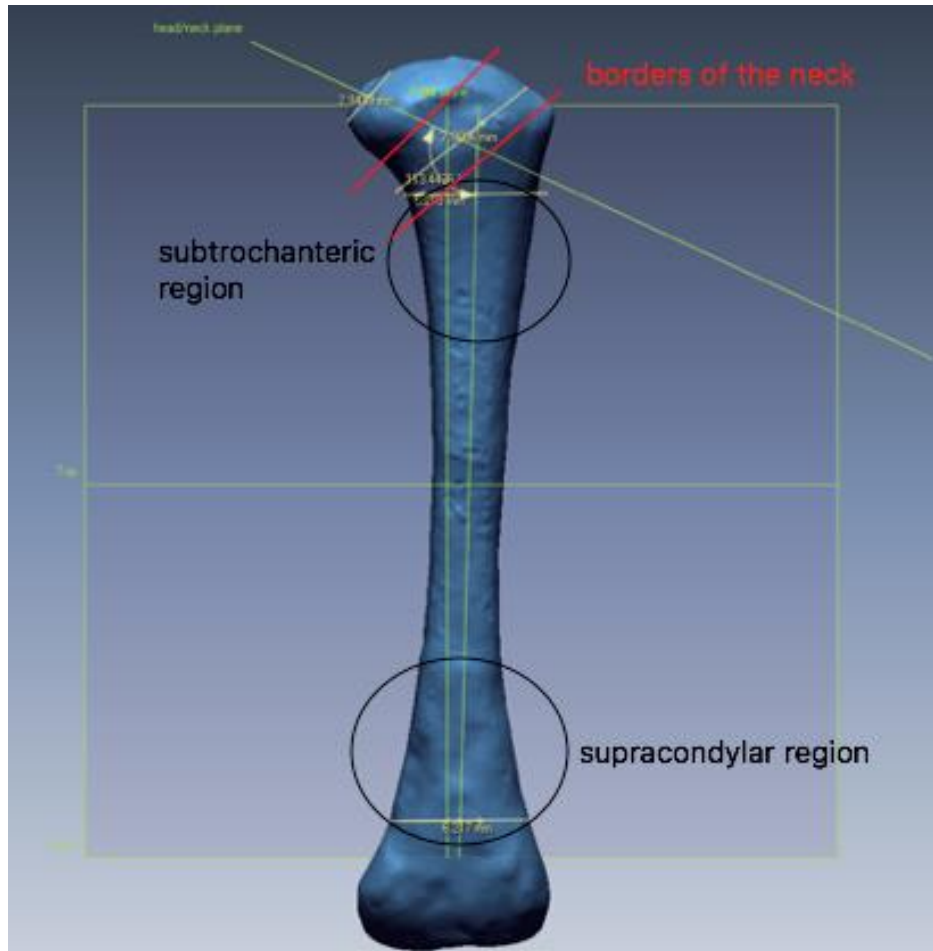
In studying skeletal material, the best practice for bioarchaeologists is to be as informed as possible about the archaeological samples they are working with, and aware of whether or not excavation practices might bias their interpretations. In the case of this study, both the archaeological profiles and the context of archaeology during excavation have been reviewed as a basis for data analysis, and ethical concerns have been addressed through HREB (University of Victoria Human Research Ethics Board) approval.

Also worth noting is the ethical considerations surrounding the manner of data collection through the utilization of 3D models. Ownership of these 3D models belongs to Dr. Helen Kurki as well as the respective institutions that gave access to the skeletal collections, where research is approved by both institutional and descendant groups prior to commencement. These 3D models are not to leave Dr. Kurki's ownership and will be destroyed if so desired by the institutions or descendent groups affiliated with them (personal communication).

## **4 METHODOLOGY**

#### **4.1 DEFINITION OF FEMORAL NECK-SHAFT ANGLE AND ITS MEASUREMENT**

The femoral neck-shaft angle is defined by Braüer (1988) as “the degree of more medial vs. more proximal orientation of the femoral head and neck” (Martin Measurement no. 29) in which measurement is widely varied among researchers, especially in the varied methods of bone study which include radiographs (orthopedic researchers/surgeons), dry bone (e.g., Trinkaus 1993, Trinkaus & Anderson 1998, Child & Cowgill 2017), and more recently, CT scans (e.g., Dimitriou et al. 2016). The main issue with measuring femoral neck-shaft angle comes from the fact that the borders of the neck are not easily defined and vary from individual to individual, as well as compounding factors of anteversion and varying morphology across development in the study of juvenile specimens (Child & Cowgill 2017). In this study, the definition and measurement of FNSA as defined by Trinkaus (1993) as “measured on the anterior surface of the femur; the neck axis is the midline between the proximal and distal borders of the neck, and the diaphyseal axis is defined by the mediolateral diaphyseal midpoints in the subtrochanteric and supracondylar regions” (397) were adapted into the 3D environment of *Geomagic Design X* (see Reference 1 below).



Reference 1 Designation of measurement areas, on an infant femur

## 4.2 WORKING WITH 3D ENVIRONMENT – DEVELOPMENT OF METHOD

While the FNSA has been measured in the 3D environment of biomechanic and orthopedic studies, the method employed here was created by this researcher and is specific to the 3D-modeling software *Geomagic Design X*. Due to the need to develop a method that replicated dry bone measurements upon bone models, the researcher explored, over the course of several weeks, the functionality of the program and its tools. In order to carry out the FNSA measurement, the tools of “radius measurement,” “reference plane” designation, and “angle measurement” were utilized. It is worth noting that the development of this method is restrained

to its use in *Geomagic Design X* (and cannot necessarily be applied in other programs) as well as the researcher's knowledge of the software.

### 4.3 METHOD ISSUES AND CONSTRAINTS

Since the method employed in this research project is brand new, complications did arise that could affect the ability of the FNSA to be obtained correctly. The first issue experienced had to do with developmental stage of the specimens. As exploration of development on the whole was a stated goal of this project, specimens ranged from infant to late adolescent, with varying morphology of the femoral neck and presence and fusion of epiphyseal ends. In terms of

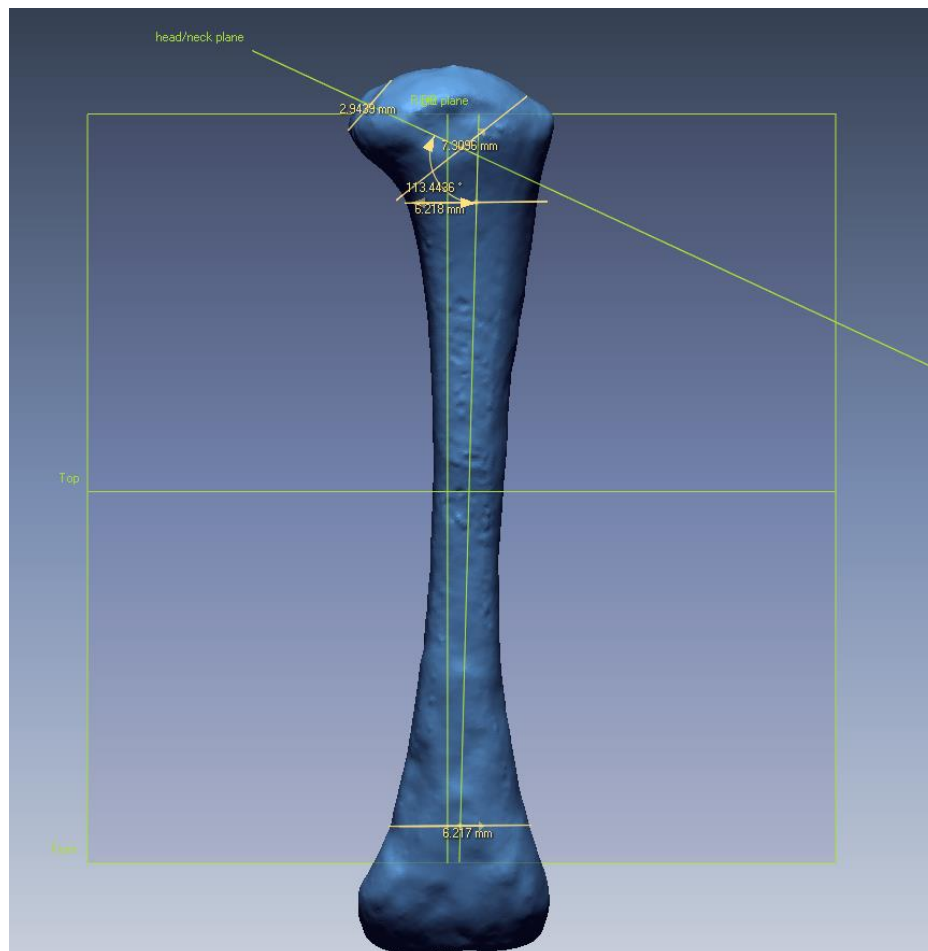


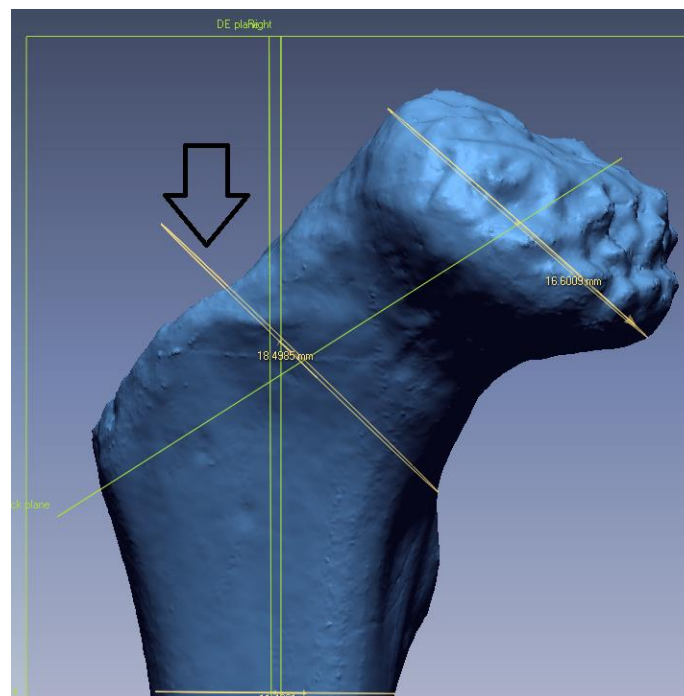
Figure 2 example of an infant femur - note the lack of neck definition

obtaining radii in the neck region, infant specimens were especially difficult to work with due to

a lack of definition (refer to Figure 2). The supracondylar region, where radii were obtained, was difficult to consistently apply to the exact region, even though all measurements were recorded by the same observer (the researcher).

Another issue that occurred in obtaining the FNSA measurement was the restriction of the measurement to the anterior surface. Unlike dry bone that can be placed on a flat surface, 3D models must be manually aligned in reference planes to obtain a position that can be likened to placing the bone on a flat surface. Due to individual alignment process, bones differed very slightly in their reference planes, and thus how the anterior surface was viewed by the program.

The largest issue experienced with this method came in the form the radii measurement function itself. This function was free form, so placing exactly level points for the establishment of the radius sometimes proved difficult. Often after placing the two points, the radius sometimes



*Figure 3 an example of overestimation of the radius function*

overestimated itself (Figure 3), and the midpoint of the radius shifted, making the placement of reference planes more difficult.

Outlined above are some of the complications that occurred with the use of this new method, which arose due to software limitations as well as the varying morphologies of the developing femur that the researcher worked with. Future researchers could refine this method to reduce intra-observer error and refine protocol for measurements in reference to a particular developmental stage.

#### 4.4 DATA COLLECTION

The juvenile femora that were analyzed ranged from infant to late adolescent ages, which were grouped based on the presence of developmental features. 3 groups are used, defined as



Fig 1: Example of age group 1 (specimen 1K91)



Fig 2: Example of age group 2 (specimen SAM4207)



Fig 3: Example of age group 3 (specimen ALB200)

*Figure 4 different developmental stages present in the specimens being studied*

infant (1 - no or very little presence of the femoral neck), child (2 – development of the femoral neck but no epiphyseal fusion) and adolescent (3 – fusion of femoral head or condyles, or both).

Only left femora were analyzed, except in the cases of poor preservation (or complete absence) in which the right was substituted. This was done following normal scientific protocol, along with suggestions that asymmetry in the lower limb is relatively low (Auerbach and Ruff

2005, 213) To obtain the measurement of the femoral neck-shaft angle, radii are recorded in the subtrochanteric region and supracondylar region to determine the diaphyseal plane, then the radii of the greater trochanter region and the epiphyseal plate of the femoral head (or diameter of the head) are measured to determine the head/neck plane. Once these planes are created, the angle between the diaphyseal and head/neck plane can be measured and recorded as the FNSA. This method is adapted from Trinkaus (1993) and Child & Cowgill's (2017) method on dry bone. All measurements were obtained from the anterior surface to negate correction factors (Child & Cowgill 2017). Measurements for each specimen were conducted twice to test the replicability of this newly designed 3D method.

## **5 RESULTS**

### **5.1 STATEMENT OF RESULTS**

All statistical tests were conducted using SPSS. Both archaeological samples were tested for normalcy using Kolmogorov-Smirnov and Shapiro-Wilk – these tests confirmed that the distribution of the curves were normal and that future statistical tests could be carried out. Intra-observer error of FNSA measurements were assessed using a paired T-test, which found a significant difference between the two trials.

		AgeGroup			Cumulative
		Frequency	Percent	Valid Percent	Percent
Valid	Infant	21	23.1	23.1	23.1
	Child	54	59.3	59.3	82.4
	Adolescent	16	17.6	17.6	100.0
	Total	91	100.0	100.0	

		Sample			Cumulative
		Frequency	Percent	Valid Percent	Percent
Valid	Indian Knoll	36	39.6	39.6	39.6
	Later Stone Age	55	60.4	60.4	100.0
	Total	91	100.0	100.0	

Table 1 Descriptive Statistics by Age Group and Sample

Tests of Normality <sup>a</sup>						
	Kolmogorov-Smirnov <sup>b</sup>			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
FNSA2	.145	36	.054	.963	36	.268

a. Sample = Indian Knoll

b. Lilliefors Significance Correction

Table 2 Normalcy test for Indian Knoll

Tests of Normality <sup>a</sup>						
	Kolmogorov-Smirnov <sup>b</sup>			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
FNSA2	.085	55	.200*	.976	55	.350

\*. This is a lower bound of the true significance.

a. Sample = Later Stone Age

b. Lilliefors Significance Correction

□

Table 3 Normalcy test for Later Stone Age South Africans

		Paired Differences				t	df	Sig. (2-tailed)	
		Mean	Std. Deviation	Std. Error	95% Confidence Interval of the Difference				
					Lower				Upper
Pair 1	FNSA1 - FNSA2	2.6186923	6.2880964	.6591716	1.3091329	3.9282518	3.973	90	.000

Table 4 T-test showing significant difference between 2 measurement trials

As such, the second trial of measurements (FNSA2) have been selected for analysis because they represent a more practiced methodological application. Samples were then compared by age group across the two samples using t-tests, with values of 0.946 for infants (age group 1), 0.382 for children (age group 2) and 0.113 for adolescents (age group 3).

Age Group	P-value (t-tests)
Infant (1)	0.946
Child (2)	0.382
Adolescent (3)	0.113

Table 5 T-test values by age group for IK & LSA SA

Then an ANOVA with post-hoc tests Tukey B and Scheffe were conducted on a pooled sample (both IK and LSA SA) to determine whether FNSA varied significantly across the 3 age groups. ANOVA outputted a p-value of 0.541, which was reflected in the Tukey B and Scheffe tests.

## ANOVA

FNSA2

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	61.604	2	30.802	.618	.541
Within Groups	4386.022	88	49.841		
Total	4447.626	90			

Table 6 ANOVA test showing lack of significance among samples

FNSA2			
			Subset for alpha = 0.05
	AgeGroup	N	1
Tukey B <sup>a,b</sup>	Infant	21	125.360348
	Adolescent	16	125.952819
	Child	54	127.247683
Scheffe <sup>a,b</sup>	Infant	21	125.360348
	Adolescent	16	125.952819
	Child	54	127.247683
	Sig.		.661

Means for groups in homogeneous subsets are displayed.

a. Uses Harmonic Mean Sample Size = 23.321.

b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

Table 7 post-hoc tests for ANOVA

## Multiple Comparisons

Dependent Variable: FNSA2

	(I) AgeGroup	(J) AgeGroup	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Scheffe	Infant	Child	-1.8873357	1.8155917	.584	-6.408173	2.633501
		Adolescent	-.5924711	2.3427465	.969	-6.425927	5.240985
	Child	Infant	1.8873357	1.8155917	.584	-2.633501	6.408173
		Adolescent	1.2948646	2.0094917	.813	-3.708785	6.298514
	Adolescent	Infant	.5924711	2.3427465	.969	-5.240985	6.425927
		Child	-1.2948646	2.0094917	.813	-6.298514	3.708785
Games-Howell	Infant	Child	-1.8873357	1.9370981	.598	-6.641435	2.866763
		Adolescent	-.5924711	2.3831200	.967	-6.429016	5.244074
	Child	Infant	1.8873357	1.9370981	.598	-2.866763	6.641435
		Adolescent	1.2948646	1.9176884	.780	-3.480118	6.069847
	Adolescent	Infant	.5924711	2.3831200	.967	-5.244074	6.429016
		Child	-1.2948646	1.9176884	.780	-6.069847	3.480118

Table 8 comparisons among pooled age-groups showing no statistical significance

## 6 DISCUSSION

### 6.1 INTERPRETATION OF RESULTS

As alluded to in the results section, the statistical analyses of this study suggest that neither the samples, nor the age groups differed significantly in FNSA, inferring that the variable of interest to the researcher, terrain, had no visible effect. The t-tests revealed the only significant difference, which was between the measurements recorded for trial 1 (FNSA1) and trial 2 (FNSA2). This difference illuminates the tweaking of the method over time, as the first set of measurements was more exploratory and tried to find the best way to consistently apply the measurement. The 2<sup>nd</sup> trial was carried out as uniformly as possible, and this is likely the reason it differed significantly from the 1<sup>st</sup> trial. A 3<sup>rd</sup> trial was going to be carried out, but the time

frame of this project did not permit this. Future research could involve more trials, observing intra- and inter-observer error.

The statistical analyses of the 2<sup>nd</sup> trial of measurements concluded that no differences exist between the samples or among the pooled-samples age groups. This was a surprising result given the vastly different geographical locations these samples inhabited. A lack of statistical significance between age groups was somewhat expected as the values generally decrease over development but do so gradually - although it is surprising that the values between infants and adolescents were not more marked.

In terms of samples studied, while terrain was drastically different, the behavioural adaptations and subsistence strategies used by these groups may have been similar enough in terms of load-bearing that skeletal expression manifested itself in similar ways. This does not mean that there is no effect of terrain, but suggests that activity levels and their frequencies, rather than types of load, may shape the expression of FNSA, to the point where any terrain effect is masked.

It is also possible, given the functional and geometric constraints of epiphyseal ends (Currey 1984, 117), that the degree to which the FNSA responds to particular forces may be minimized. Similar studies of joints and loading in the ends of bones (Venkataram et al. 2013) also found a lack of effect suggesting the complex interplay of bones, muscles, genetics and phylogeny. A further undertaking of the FNSA and its development must be pursued by bioarchaeologists in order to better understand the processes governing its skeletal expression.

## **6.2 LIMITATIONS & FUTURE DIRECTIONS**

Two limitations of this research project were the samples used and the sample size. As already noted, including more samples with different degrees of activity levels may provide

support for arguments that overall activity levels during development affect FNSA (Trinkaus 1993). While the sample size in total (n=91) is acceptable, the division of sample into archaeological groups (IK & LSA SA) and age groups (infant, child, adolescent) may have contributed to a lack of statistical significance. Future work with larger sample sizes and equal numbers for each sample and age group could allow the identification of statistical significance, or may confirm the lack of terrain effect on FNSA.

Since this study is the first of its kind (i.e. 3D bioarchaeological skeletal analysis of the juvenile FNSA), the lack of statistical significance should not dissuade other researchers from further exploration. Instead, this study should serve as a starting point from which larger, more expansive study takes its cue. First, the understanding of juvenile skeletal development must progress, and the utilization of archaeological samples is necessary in order to understand the variation present in past populations across the globe. Second, while the FNSA has been expansively studied by clinical researchers, the call for bioarchaeological understanding has been left relatively untouched. If bioarchaeologists hope to further knowledge of bone modeling and remodeling processes and the factors that affect them, it is necessary for the FNSA to be studied more frequently through the use of archaeological specimens. Third, the use of 3D skeletal analysis by bioarchaeologists is increasing, and the method outlined here provides an avenue for the future study of the FNSA and could be adapted to suit the needs of the individual research project.

## **7 CONCLUSION**

Bioarchaeology and its engagement with the mobility of past populations is a source of rich information, but it is limited by its focus on CSG studies and the analysis of adult bones. Assertions from anatomists, clinicians, and bioarchaeologists alike have highlighted the

importance of the end of long bones and their role in joint mechanics, but our field of understanding remains limited. The femoral neck-shaft angle and its developmental plasticity were selected for analysis in this honours thesis. The effect of terrain was of particular interest, and a 3D measurement method was developed on the part of the research in order to carry out statistical tests.

Although this research project did not find any terrain effect, it highlights the need for future researchers to explore juvenile specimens, the FNSA, and 3D skeletal methods in order to move the discipline of bioarchaeology forward, and to understand to a greater degree the development of bone and bony response to the topographical environment.

## **8 ACKNOWLEDGEMENTS**

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