Childhood Growth: Comparing Long Bone Cortical Thickness and Length in Four Hunter Gatherer Societies

by

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Abstract

This study investigates childhood skeletal growth patterns in four hunter-gatherer groups: Late Stone Age (LSA), Sadlermuit (SAD), Indian Knoll (IK), and Point Hope (PH), by analyzing the cortical thickness and diaphyseal length of the femur and humerus. These measurements provide insights into adaptation to environmental stressors during early-life growth. The research examines how cortical thickness and diaphyseal length vary across these groups, the environmental and dietary factors influencing these variations, and how these growth patterns compare to modern trajectories from the Maresh dataset. Statistical analyses identified significant differences in humeral and femoral measurements. Contrary to expectations, IK exhibited the greatest cortical thickness in both the humerus and femur, suggesting that factors beyond mechanical loading, such as diet and ecological conditions, influenced skeletal growth. This study contributes to understanding how past populations adapted to their environments and provides new insights into childhood skeletal development.

Keywords: Childhood growth, skeletal development, cortical thickness, diaphyseal length, humerus, femur, hunter-gatherers, paleoanthropology, statistical analysis.

Contents

Introduction

The study of skeletal growth patterns provides valuable insights into how past populations adapted to their environments. Childhood growth, in particular, reflects the interplay of biological, nutritional, and cultural factors that shape skeletal development from infancy through adolescence. Despite advances in bioarchaeology, comparative analyses of childhood skeletal growth across diverse hunter-gatherer populations remain underexplored.

This research examines cortical thickness and diaphyseal length in children (ages 0–12) from four archaeological hunter-gatherer groups (N=178): Late Stone Age (LSA) (N=17), Sadlermuit (SAD) (N=31), Indian Knoll (IK) (N=71), and Point Hope (PH) (N=51). These measurements serve as indicators of early life growth trajectories and adaptation to environmental stressors. A comparison with a recent sample of children from industrial USA, the Maresh dataset, offers insight into the ways in which lifestyle, climate, and diet shaped growth patterns in prehistoric populations. (Maresh, 1943, 1955, 1970).

Understanding external influences on skeletal growth is critical for interpreting human adaptation (Welsh & Brickley, 2024). This research aims to provide a comparative perspective on childhood skeletal development in prehistoric populations and examine how environmental and cultural influences shaped early-life growth. This will be addressed through the following questions:

(1) How does cortical thickness and diaphyseal length vary among the SAD, PH, IK, and LSA groups?

(2) What environmental and dietary stressors may contribute to these variations?

(3) How do these growth patterns compare with modern growth trajectories from the Maresh dataset?

(4) Do the observed differences align with our expectations based on previous knowledge of the groups?

The study does not examine adult skeletal remains or attempt to determine genetic influences on growth variation. While genetic factors undoubtedly play a role in skeletal development, the primary focus is on how external factors—such as climate, diet, and habitual activity—shape bone morphology. Additionally, this study does not reconstruct individual life histories but rather analyzes population-level trends to assess general patterns of growth and adaptation.

Background

Bone Growth

Prior to skeletal maturation, longitudinal bone growth takes place at the cartilage found at both the proximal and distal ends of the bone (Kember, 1972). This region, known as the growth plate, is where chondrocytes follow a tightly regulated sequence of proliferation, hypertrophy, and eventual ossification into bone tissue. The rate at which this elongation occurs is largely influenced by how many cells undergo hypertrophy and how much they expand in volume (Lampl & Schoen, 2017).

Long bone growth is tightly regulated by the timing of chondrocyte differentiation at the growth plate, which is influenced by morphogens—signaling molecules that guide structural development through spatial and temporal concentration gradients (Lampl &

Schoen, 2017; Tabata & Takei, 2004). One key morphogen in this process is Indian hedgehog (Ihh), a protein secreted by pre-hypertrophic chondrocytes. Ihh plays a central role in regulating the progression of chondrocytes by stimulating the perichondrium to produce parathyroid-related protein (PTHrP), which then delays the transition of pre-hypertrophic cells into hypertrophic chondrocytes (Lee et al., 1996; Kronenberg, 2006; Lanske et al., 1996; Vortkamp et al., 1996, as cited in Lampl & Schoen, 2017)). Additionally, Ihh promotes the proliferation of less mature chondrocytes, thereby sustaining a reservoir of growth-competent cells and modulating growth timing (St-Jacques et al., 1999; Mak et al., 2008, as cited in Lampl & Schoen, 2017). The eventual decline in PTHrP, either directly or via reduced Ihh signaling, permits hypertrophy and contributes to the pace of bone elongation (Karaplis et al., 1994; Wilsman et al., 1996). This regulatory mechanism operates within the extracellular matrix of the growth plate, which must remain pliable to accommodate chondrocyte expansion (Behonick & Werb, 2003).

The microenvironments within each zone of the growth plate—resting, proliferative, and hypertrophic—also play a central role (Lampl & Schoen, 2017). Chondrocytes in each zone express specific matrix proteins that support their stage of development, with a gradual shift in extracellular matrix composition from type II and IX collagen and aggrecan in earlier stages to type X collagen in the hypertrophic zone (Alini et al., 1992; Mwale et al., 2002, as cited in Lampl & Schoen, 2017). Enzymes such as matrix metalloproteinases (e.g., MMP-13) degrade components like type II collagen, facilitating hypertrophic swelling and preparing the matrix for vascular invasion and ossification (Breur et al., 1992; Ortega et al., 2004).

In contrast, appositional growth occurs at the surface of the bone diaphysis (Kurki, 2022). Osteoblasts in the periosteum deposit new layers of compact bone along the external surface, while osteoclasts in the endosteum resorb bone from the inner surface surrounding the medullary cavity (Boskey & Coleman, 2010). This process contributes to the positioning and thickness of cortical bone. Appositional growth continues after maturation, reflecting activity and bone loading throughout life (Kurki, 2022).

These processes are sensitive to environmental signals, external factors like climate, habitual activity, and nutrition can significantly affect bone growth patterns. This is directly relevant to my study, which explores variation in diaphyseal length and cortical development in subadult long bones across hunter-gatherer populations living in different environmental contexts.

Bone Variation

Theoretical frameworks in bioarchaeology and growth studies emphasize that skeletal morphology is not merely a reflection of genetic potential, but a dynamic outcome of environmental, behavioral, and nutritional influences, particularly during childhood. Bone is a plastic tissue that responds to both acute and chronic stressors, and its development offers a critical window into past lived experiences. Metrics such as cortical thickness and diaphyseal length are key indicators of biomechanical loading, nutritional sufficiency, and overall health during growth.

Environmental conditions, including climate, resource availability, and ecological stability, significantly influence skeletal development. Colder climates have been found to cause body variations among similar species. Bergmann’s rule states that animals have larger body size in colder climates (Salewski & Watt, 2017). Allen’s rule states that animals have shorter appendages (tails, ears, and limbs) in colder climates. (Allen, 1907) Both of these rules reflect adaptations that allow for greater retention of body heat.

Additionally, populations exposed to harsh or unstable environments often experience higher physiological stress, leading to disruptions in growth. Welsh and Brickley (2024) demonstrated that early femoral growth disruptions in children from medieval Toulouse were linked to maternal malnutrition, especially in the 1–3.99 age range. Their findings highlight the sensitivity of young children to environmental and nutritional stress, reinforcing the importance of early-life conditions in shaping skeletal outcomes. In contrast, Dhavale et al. (2017) found no evidence of growth disruption during the agricultural transition in Southeast Asia, suggesting that some populations display resilience to dietary shifts highlighting the need for context-specific interpretations of growth data.

Physical activity, particularly habitual biomechanical loading, is another factor influencing bone geometry. Biomechanical theory posits that mechanical stress stimulates modeling and remodeling, especially during development. Cowgill et al. (2023) emphasized the role of activity in shaping long bone geometry, noting that cortical thickness is a reliable indicator of both physical activity and nutritional status. For example, variations in subsistence patterns—such as the intensive upper-body activity associated with watercraft use or the high mobility required in terrestrial foraging—are expected to leave discernible signatures in long bone morphology. Kurki et al. (2022) further supports this by illustrating how appositional growth adapts to ecological demands, reinforcing the idea that bone responds not only to physiological stress but also to mechanical strain imposed by daily activities.

Nutrition plays a parallel and often intersecting role. Growth studies, including Lampl (2021), have underscored how modern environmental and dietary conditions affect skeletal development, offering insight into long-term patterns of plasticity and adaptation. Nutritional adequacy, especially protein and micronutrient intake, supports robust bone growth, while deficiencies can manifest as thinner cortical thicknesses and shorter diaphyses. This is particularly relevant when comparing prehistoric groups to modern populations. Spake and Cardoso’s (2020) refinement of the Maresh dataset, along with Ruff’s (2022) longitudinal analyses, provides a more precise and dynamic baseline for understanding deviations from expected growth patterns, thereby strengthening comparisons between ancient and modern skeletal growth trajectories.

Finally, social and cultural stressors also influence growth. Gooderham et al. (2019) linked growth disruptions in medieval Portuguese children to sociopolitical instability and resource scarcity, paralleling the effects seen in environmentally stressed populations. Ruff’s (2022) work on modern social determinants, including healthcare and resource access, similarly shows how contemporary inequality affects growth. These studies broaden the theoretical landscape by positioning skeletal growth as an outcome of both ecological and sociocultural pressures.

Together, these studies inform the comparative and cross-temporal approach of the present research. By analyzing four hunter-gatherer populations alongside modern Maresh data, this study builds on established models of plasticity and developmental stress to explore how environment, activity, and diet shaped childhood growth. The integration of cortical thickness and diaphyseal length as key variables allows for a nuanced interpretation of bone variation as both a biological and cultural product—one that reflects the adaptive strategies and stress experiences of diverse human populations across time.

Groups

Understanding the biological and cultural contexts of each hunter-gatherer group is essential for interpreting variation in long bone cortical thickness and diaphyseal length. This section outlines the key characteristics of the four archaeological populations included in this study, Sadlermuit (SAD), Indian Knoll (IK), Point Hope (PH), and Late Stone Age (LSA), as well as the modern Maresh dataset, which serves as a comparative framework for assessing growth trajectories. See Figure 1 for a map of the geographic locations of these four hunter-gatherer groups.

Figure 1: World map showing the four hunter-gatherer population: LSA (blue star), IK (red circle), SAD (purple triangle), and PH (green diamond) (MacKinnon, 2023).

Later Stone Age

The LSA group spans the longest time period of all populations included in this study, with individuals dated between approximately 9,000 and 220 years before present (Humphreys, 1970; Kurki, 2005; Pfeiffer & Harrington, 2011; Pfeiffer & Sealy, 2006; Sealy & Pfeiffer, 2000; Sealy, 2006, as cited in MacKinnon, 2023). The individuals were recovered from approximately 40 archaeological sites distributed across ecologically diverse regions of South Africa, including forest, fynbos, savanna, and karoo biomes (MacKinnon, 2023). For this study a subset of 17 individuals aged between approximately 2.5 and 11.5 years was utilized.

LSA populations are understood to have been highly mobile terrestrial foragers, with skeletal evidence indicating elevated levels of habitual mobility (Cameron, 2017). There is also evidence to suggest that LSA children began walking at an early age (Harrington, 2010). Subsistence practices were primarily focused on land-based foraging and hunting, although coastal populations made extensive use of marine resources (Sealy et al., 1992; Stock & Pfeiffer, 2001, as cited in MacKinnon, 2023).

LSA individuals were characteristically small-bodied. However, this reduced stature is interpreted as a selected trait rather than a consequence of environmental stress or malnutrition (Deacon & Deacon, 1999; Schuster et al., 2010; Pfeiffer & Sealy, 2006). Growth trajectories in LSA children do not exhibit evidence of stunted or catch-up growth; instead, growth appears to end earlier than in contemporary populations (Pfeiffer & Harrington, 2010; Pfeiffer & Harrington, 2011). The consistency of small body size across millennia suggests long-term selection, potentially shaped by efficiency in hunting or reproductive preferences (Lee, 1984; Pfeiffer, 2012).

Additionally, LSA experienced low levels of stress comparatively. Infectious disease was low, and the most common skeletal stress markers observed (degenerative joint changes and trauma) are commonly caused by sustained physical activity (Gibbon & Davies, 2020; Pfeiffer, 2007; Pfeiffer, 2016, as cited in MacKinnon, 2023).

Sadlermuit

The SAD group inhabited the Southampton, Walrus, and Coats Islands in Hudson Bay, Nunavut (Ryan & Young, 2013). They occupied the region for approximately 500 years, with the earliest radiocarbon date being 977 years before present (±54 years)

(Coltrain, et al., 2004; Merbs, 1983). The primary archaeological site for this sample is Tunermiut, located on Southampton Island (Merbs, 2019). For the purposes of this study, a subset of 31 individuals aged 0–12 years was analyzed. The youngest individual in this subset was estimated to be approximately 0.125 years (1.5 months) old, and the oldest around 11.5 years old.

Due to their Arctic location, SAD was a highly isolated group with minimal outsider contact (MacKinnon, 2023). Their diet primarily consisted of high-trophic-level marine animals such as walrus, seal, and seabirds (Boas, 1888; Coltrain et al., 2004; Coltrain, 2009, as cited in MacKinnon, 2023). The SAD population relied heavily on marine resources and made extensive use of watercrafts. However, during the summer months, they also hunted caribou and harvested salmon to supplement their diet (Coltrain, 2009). Whale hunting was a culturally important activity beyond subsistence, with whale bones being used in the construction of houses (Comer, 1910).

SAD individuals are noted for having robust upper bodies, a trait consistent with habitual activities such as kayaking, sled driving, and hide processing (Mathiassen, 1927; Merbs, 1983). Previous studies have found evidence of child engagement in these activities (Boas 1907, as cited in MacKinnon, 2023). Additionally, the SAD population experienced considerable stress, both environmentally and physiologically. Between 1902 and 1903, the remaining population, approximately 60 individuals, succumbed to diseases introduced by European whalers (Mathiassen, 1927; Ryan & Young, 2013, as cited in MacKinnon, 2023).

Indian Knoll

Indian Knoll is a large shell midden site located along the Green River in Kentucky, USA (Herrmann & Konigsberg, 2002; Winters, 1974, as cited in MacKinnon, 2023). The surrounding area was fertile and heavily forested, providing a rich environment for foraging and hunting (Snow, 1948). Radiocarbon dates derived from both midden debris and human remains place the site between approximately 6415 and 4134 years before present (Herrmann & Konigsberg, 2002; Winters, 1974, as cited in MacKinnon, 2023). Human skeletal remains were recovered during two major excavations: 298 burials were excavated in 1915 (Moore, 1916), and an additional 880 burials in 1939 (Webb, 1946). For this study subset of 71 individuals aged 0 to 12 years was selected for this study, with the youngest being an infant and the oldest estimated to at 12 years old.

IK foragers primarily relied on a terrestrial subsistence strategy, with a diet that included freshwater mussels, deer, plants, and nuts (MacKinnon, 2023). This subsistence pattern suggests a high degree of terrestrial mobility, as resources would have been seasonally and spatially dispersed. This interpretation is further supported by previous research that identified skeletal features associated with elevated levels of physical activity indicating habitual movement across the landscape (Snow, 1948; Cowgill, 2008). Additionally, remnants of atlatls were found amongst the burial contents, including in child burials (Webb, 1946). This suggests that atlatl use was not only widespread but also began at early ages, likely as part of skill development and participation in communal activities. This interpretation is further supported by evidence of humeral asymmetry in the population, which is consistent with the habitual, one-sided use of throwing tools and the physical demands associated with their regular use over time (Cowgill, 2008).

Point Hope

The PH group inhabited Point Hope, the northwestern edge of Alaska (Holliday & Hilton, 2010). Excavations conducted between 1939 and 1941 recovered approximately 500 skeletal remains (Rainey, 1947; Larsen & Rainey, 1948). For the purposes of this study, a subset of 51 individuals aged 0–12 years was analyzed. The youngest individual in the subset was an infant, while the oldest was estimated to be 12 years old

PH is unique as it can be divided into two distinct cultural periods: Ipiutak and Tigara (Larsen & Rainey, 1948). The Ipiutak period (1600-1100 years before present) heavily relied on caribou hunting and terrestrial resources while the Tigara period (800-300 years before present) relied on marine resources and the hunting of whales, walruses, and seals (Hilton et al., 2014). However, both of these periods are reflective of cold environment adaptations, including shorter limbs and wide bi-iliac breadths. Additionally, individuals from the Ipiutak and Tigara periods exhibit different skeletal stress markers, reflecting variation in lived experience and subsistence strategies (MacKinnon, 2023). The Ipiutak period shows higher rates of chronic stress indicators, such as infection and degenerative joint disease, while the Tigara period is marked by increased evidence of acute stress, including linear enamel hypoplasia and trauma (Dabbs, 2011). These disparities are likely tied to the differing subsistence practices of each cultural period. The Ipiutak’ s terrestrial, caribou-focused hunting strategy required greater mobility, which may explain the elevated rates of degenerative joint disease and could have increased exposure to infectious agents through broader regional interaction. In contrast, the Tigara period's reliance on whale hunting, a highly dangerous activity, may account for the greater prevalence of trauma-related skeletal evidence

Maresh Data

To provide a modern comparison for growth, we utilized health data from the Denver Longitudinal Study. This study, conducted from 1927-1967, periodically measured various aspects of bone growth from infancy to 18 years of age (Himes, 2006; McCammon, 1970, as cited in Ruff, 2022). The participants in the Denver study were primarily from the Denver area and were predominantly from Northwestern European ancestry (Ruff, 2022). Furthermore, these individuals came from middle to upper-middle-class families, ensuring that their basic needs, including access to food and healthcare, were met (McCammon, 1970, as cited in Ruff, 2022). Given these factors, the Denver sample serves as a reasonable representation of a modern, healthy population when compared to international growth standards (Schillaciet al., 2012).

For the purposes of this study, we used the same modern subset employed by Gooderham et al. (2019), which includes previously unpublished data on cortical bone provided by Dr. Christopher Ruff. Consistent with Gooderham et al. (2019), this study focuses solely on measurements from the Denver study that were taken at 12 years of age or younger.

Methodology

Data Collection

This study investigates patterns of long bone growth in past populations by analyzing two key skeletal metrics: cortical thickness and diaphyseal length of the humerus and femur. These measurements were drawn from previously published osteological research involving subadult remains from four hunter-gatherer populations: Indian Knoll, the Late Stone Age (LSA) group, the Sadlermuit, and Point Hope. These groups were chosen for their differing ecological, nutritional, and activity contexts, allowing for comparative insights into the environmental and cultural influences on bone development. Accurate sex estimations cannot be made for juvenile archaeological remains, therefore the combined-sex values from the Maresh dataset we used for comparisons.

Cortical thickness refers to the width of the dense outer layer of the bone (the cortical layer) and serves as an indicator of mechanical loading, physical activity, and overall bone robustness. In this study, cortical thickness was measured using radiographs and was taken at the midshaft of each bone. Diaphyseal length reflects the longitudinal growth of the bone and is commonly used as a proxy for overall growth and development. To control for developmental stage, only bones that lacked epiphyseal fusion were included in diaphyseal length analyses, ensuring that the comparisons were limited to individuals who were still actively growing. These measurements serve as indicators of early life growth trajectories and adaptation to environmental stressors. Comparing these populations with modern Maresh data will provide insights into how lifestyle, climate, and diet influenced growth patterns in prehistoric societies (Maresh, 1943, 1955, 1970).

Data Preparation

To ensure valid comparisons across populations that may have differed in age at death and growth rate, raw cortical thickness and diaphyseal length values were standardized into Z-scores. This was done using modern growth standards from the Maresh dataset, which provides baseline expectations for long bone growth in contemporary, presumably well-nourished children. This standardization approach helps account for age-related variation and facilitates the detection of deviations from expected growth trajectories. A similar method was employed by Gooderham et al. (2019), providing a precedent for this comparative framework. Once converted, the data were organized into four main variables:

- Humerus cortical thickness
- Femur cortical thickness
- Humerus diaphyseal length
- Femur diaphyseal length

These were treated as independent variables and analyzed separately to detect differences in growth and bone development patterns across the four populations. All data processing and statistical analysis was conducted using R (R Core Team, 2025) and RStudio (Rstudio Team, 2022)

Statistical Design

To enable meaningful comparisons of skeletal growth across the four hunter-gatherer populations this study employed the modern Maresh dataset as a standard reference for age-specific growth expectations. Measurements of cortical thickness and diaphyseal length were converted into Z-scores using Maresh's published age-specific means and standard deviations. These Z-scores quantify each individual's deviation from expected modern growth patterns at a given age.

Prior to conducting comparative analyses, all statistical assumptions were evaluated to determine the appropriate test for each variable. Because many parametric tests assume both normal distribution and homogeneity of variance, each variable was first tested for these conditions.

Normality was assessed using the Shapiro-Wilk test, applied to each variable within each population. This test is well suited for small sample sizes and evaluates whether the distribution of values significantly deviates from a normal distribution. If any one of the four populations showed non-normality for a given variable, the variable was treated as non-normally distributed overall.

For variables meeting the normality assumption across all groups, Levene's test was then used to assess homogeneity of variance. Variables that passed both assumptions were analyzed using parametric methods. In contrast, variables failing either assumption were analyzed using non-parametric methods.

Parametric analyses (i.e., one-way ANOVA followed by Tukey's Honest Significant Difference [HSD] test) were applied only to variables that showed normal distributions in all groups and homogeneity of variance. Non-parametric analyses (i.e., Kruskal-Wallis test followed by Dunn's test with Bonferroni correction) were used for variables where at least one group showed non-normality or unequal variances.

Humerus cortical thickness met both the normality and homogeneity of variance assumptions and was analyzed using ANOVA with Tukey HSD for post hoc comparisons. All other variables (**f**emur cortical thickness, femur length, and humerus length) deviated from normality in at least one group and were therefore analyzed using Kruskal-Wallis tests. Where overall group differences were significant, Dunn's test with Bonferroni correction was used to identify specific pairwise differences.

This analytical framework ensured that each variable was assessed using the most statistically appropriate method given its distributional properties, while minimizing Type I error in post hoc comparisons.

Maresh Comparison

The purpose of using the Maresh dataset was not to compare archaeological individuals directly to modern populations, but to provide an age-adjusted framework that allows for standardized comparisons within and among the four hunter gatherer groups. By controlling for age-related variation in bone development, this approach isolates population-level differences in growth and allows for meaningful evaluation of environmental, dietary, and biomechanical influences on skeletal development.

Because accurate sex estimation was not possible for juvenile archaeological remains, combined-sex values from the Maresh dataset were used in all transformations. This ensured that all individuals were evaluated against the same standardized growth trajectory.

Expectations

Based on existing knowledge of the four groups and the well-documented influence of environment, diet, and activity on bone growth, expectations about how these groups would compare were established prior to statistical analysis.

Indian Knoll

For the IK population it was expected that individuals would exhibit long diaphyseal lengths and increased cortical thickness. These expectations are primarily based on the temperate environment and the comparatively lower levels of stress experienced by this group. The IK population is anticipated to display the longest limb lengths in the study, not only because of the reduced stress compared to other groups but also because the other warm-climate population (LSA) is known for its small body size (Deacon & Deacon, 1999; Schuster et al., 2010).

For cortical thickness, both the femur and humerus were expected to exhibit relative robustness compared to other populations. The femur, in particular, was anticipated to show increased cortical thickness, likely due to the group's high levels of mobility and reliance on terrestrial resources (Snow, 1948; Cowgill, 2008). Such increased mobility would contribute to greater biomechanical loading, resulting in more robust bone structure. The expectation for humeral cortical thickness is more nuanced. IK is known to use atlatls (Webb, 1946), an upper-body intensive activity that typically promotes greater cortical thickness in the humerus. However, because atlatls are used unilaterally, this results in asymmetrical loading, which may lead to variations in cortical thickness between sides of the body. As this study does not prioritize one side over the other, any asymmetry could moderate the observed humeral cortical thickness in the overall sample.

Sadlermuit

For the SAD population it was expected that individuals would exhibit shorter diaphyseal lengths, increased humeral cortical thickness, and reduced femoral cortical thickness in comparison to other groups. As an Arctic population, SAD is expected to demonstrate cold-weather adaptations, one of which is shorter limb lengths. Additionally, SAD individuals were subject to higher levels of stress (MacKinnon, 2023), which also contribute to shorter limb development. Consequently, SAD is anticipated to display the shortest limb lengths of all the groups included in the study.

The expectation for greater humeral cortical thickness is based on previous knowledge that this population engaged in upper-body intensive activities, such as spear hunting and kayaking (Mathiassen, 1927; Merbs, 1983). Both activities place significant mechanical demands on the upper body and are expected to result in increased cortical thickness in the humerus. In contrast, femoral cortical thickness is predicted to be lower. This is primarily due to their relatively limited lower-body mobility. Although watercraft usage would have required substantial upper-body effort, it is unlikely that the legs were subjected to similar loading. Extended periods spent using watercrafts would result in the lower limb being less frequently loaded, leading to a less robust femur.

Point Hope

Expectations for the PH group include shorter limb lengths, lower femoral cortical thickness, and moderate humeral cortical thickness. As an Arctic population, PH is expected to exhibit cold weather adaptations, including shorter diaphyseal lengths. The group's history of stress further supports the expectation of shorter limb lengths.

The cortical thickness expectations for PH are more complex, given that the sample reflects two distinct cultural periods, each with different subsistence strategies (Larsen & Rainey, 1948). Both periods involved upper-body intensive activities such as whale and deer hunting, which are expected to lead to greater humeral cortical thickness. Although both of these activities load the upper body the difference in activity may results in a moderate result comparatively.

Additionally, the PH sample is expected to exhibit relatively thin femoral cortical thickness compared to the other groups. This expectation stems from the cultural and subsistence differences between the two periods represented in the sample. Individuals from the earlier Ipiutak period were more terrestrially focused and likely exhibited higher mobility, whereas those from the later Tigara period relied more heavily on marine resources and demonstrated reduced mobility (Hilton et al., 2014). The pooling of individuals from these distinct cultural contexts may moderate the overall femoral cortical thickness observed in the PH group. As a result, while femoral cortical thickness in PH is anticipated to be relatively low, it is not expected to be the lowest among the comparative populations.

Later Stone Age

Expectations for the LSA group include moderate diaphyseal length, lower humeral cortical thickness, and greater femoral cortical thickness. The temperate environment and consistent access to resources associated with LSA populations support the assumption of relatively longer diaphyseal lengths. Furthermore, the absence of stunted or catch-up growth aligns with expectations of more continuous growth trajectories (Pfeiffer & Harrington, 2010; Pfeiffer & Harrington, 2011). However, LSA individuals are also characterized by a small-bodied morphology, which may reflect long-term physical adaptation rather than nutritional or environmental stress (Deacon & Deacon, 1999; Schuster et al., 2010; Pfeiffer & Sealy, 2006). This presents an interesting point of comparison with groups that exhibit higher physiological stress but lack comparable adaptations in body size. As such, expectations for LSA diaphyseal length are nuanced: while their limb lengths may be shorter than those of the IK group, they are likely to be similar to or longer than those observed in the Arctic populations (SAD and PH).

In terms of cortical thickness, LSA individuals are expected to display greater femoral cortical thickness due to the high levels of mobility associated with the group. The presence of LSA individuals at a large number of sites further indicates their considerable mobility (MacKinnon, 2023). In contrast, LSA individuals are expected to have smaller humeral cortical thickness than the Arctic populations, such as PH and SAD, due to the lower emphasis on upper-body intensive activities.

Results

This study compared cortical thickness and diaphyseal length in the femur and humerus across four hunter-gatherer populations: Indian Knoll (IK), Point Hope (PH), Sadlermuit (SAD), and the Later Stone Age (LSA) group. All measurements were standardized using modern Maresh growth data to produce Z-scores, allowing for age-adjusted comparisons.

To provide an overview of relative growth, Table 1 presents the mean Z-scores for each group across the four skeletal variables. Indian Knoll consistently exhibited the highest values, suggesting relatively robust growth. In contrast, Sadlermuit showed the lowest mean Z-scores across all variables, consistent with stunted growth. Point Hope and LSA samples demonstrated intermediate patterns, with LSA displaying notably low cortical values despite warmer environmental conditions.

Table 1: Mean Z-scores and standard deviations for femur and humerus length and cortical thickness by Population. All values are standardized using the modern Maresh growth dataset. Sample sizes reflect the total number of individuals available for each group.

Population	**Sample size**	**Femur Length Z (± SD)**	**Humerus Length Z (± SD)**	**Femur CT Z (± SD)**	**Humerus CT Z (± SD)**
Indian Knoll (IK)	71	-1.29 ± 2.41	-0.23 ± 2.03	-0.81 ± 1.87	-0.24 ± 1.57

Late Stone Age (LSA)	17	-2.39 ± 1.50	-2.61 ± 2.82	-3.29 ± 1.56	-3.09 ± 2.19
Point Hope (PH)	51	-2.39 ± 2.43	-0.87 ± 2.38	-1.61 ± 2.18	-1.62 ± 1.61
Sadlermuit (SAD)	31	-3.79 ± 3.68	-3.08 ± 2.63	-2.19 ± 1.79	-3.16 ± 1.42

These trends are visually represented in the scatterplots for each variable (Figures 2-5).

A Kruskal-Wallis test indicated significant differences in femoral length Z-scores among the groups. Dunn’s post-hoc tests revealed that Indian Knoll femora were significantly longer than those of both Point Hope and Sadlermuit (see table 2). Point Hope femur diaphyseal length was also significantly longer than those of Sadlermuit (see table 1). No significant differences were found between LSA and any other group.

Table 2: Dunn's multiple comparisons test for femur length

Comparison	**Z-Statistic**	**p-value**	**Adjusted p-value**	**Significance**
IK - LSA	1.34	0.55	0.55	Not Significant
IK - PH	2.75	0.02	0.02	Significant
LSA - PH	0.37	1.00	1.00	Not Significant

IK - SAD	5.18	0.00	6.72e-07	Significant
LSA - SAD	2.22	0.08	0.08	Not Significant
PH - SAD	2.64	0.03	0.03	Significant

See Figure 2 for scatterplot of femur length Z-scores.

Kruskal-Wallis testing indicated significant differences among the groups in humeral diaphyseal length. Post-hoc tests revealed that IK individuals had significantly longer humerus diaphyseal length than both SAD and LSA (see Table 3). Point Hope individuals also had significantly longer humerus diaphyseal length than SAD.

Table 3: Key Comparisons for Humerus Length (Dunn's Test)

Comparison	**Z-Statistic**	**p-value**	**Adjusted p-value**	**Significance**
IK - LSA	3.19	0.01	0.01	Significant
IK - PH	1.63	0.31	0.32	Not Significant
LSA - PH	-1.85	0.20	0.30	Not Significant
IK - SAD	5.93	0.00	9.22e-09	Significant
LSA - SAD	1.07	0.86	0.856	Not Significant
PH - SAD	3.73	0.001	5.78e-04	Significant

See Figure 3 for scatterplot of humerus length Z-scores.

A one-way ANOVA revealed significant differences in humerus cortical thickness among the groups. Tukey HSD post-hoc comparisons showed that Indian Knoll had significantly larger humerus cortical thickness than all other groups (see Table 4). Additionally, Point Hope had significantly higher humerus cortical thickness than LSA and SAD.

Table 4: Post-Hoc Tukey HSD Results for Humerus Cortical Thickness

Comparison	**Mean Difference**	**95% Confidence Interval**	**p-value**	**Significant/Not Significant**
LSA vs. IK	-2.85	(-4.08, -1.62)	0.0000001	Significant
PH vs. IK	-1.39	(-2.27, -0.50)	0.0004	Significant
SAD vs. IK	-2.92	(-3.83, -2.02)	0.000	Significant
PH vs. LSA	1.46	(0.12, 2.80)	0.026	Significant
SAD vs. PH	-1.54	(-2.59, -0.49)	0.001	Significant
SAD vs. LSA	-0.07	(-1.42, 1.28)	0.999	Not Significant

See Figure 4 for scatterplot of humerus cortical thickness Z-scores.

A Kruskal-Wallis test revealed significant differences in femoral cortical thickness among the groups. Dunn’s test showed that IK had a significantly greater femur cortical thickness than all other groups, and LSA also had significantly greater femur cortical thickness than PH. No significant differences were observed between SAD and the other groups (see Table 5).

Table 5: Post-Hoc Dunn's Test Results for Femur Cortical Thickness

Comparison	**Z Statistic**	**p-value**	**Adjusted p-value**	**Significance**
IK vs. LSA	4.29	0.00	5.24e-05	Significant
IK vs. PH	2.74	0.02	0.02	Significant
LSA vs. PH	-2.48	0.04	0.04	Significant
IK vs. SAD	3.31	0.00	2.80e-03	Significant
LSA vs. SAD	-1.69	0.27	0.27	Not Significant
PH vs. SAD	0.90	0.27	1.00	Not Significant

See Figure 5 for scatterplot of femur cortical thickness Z-scores.

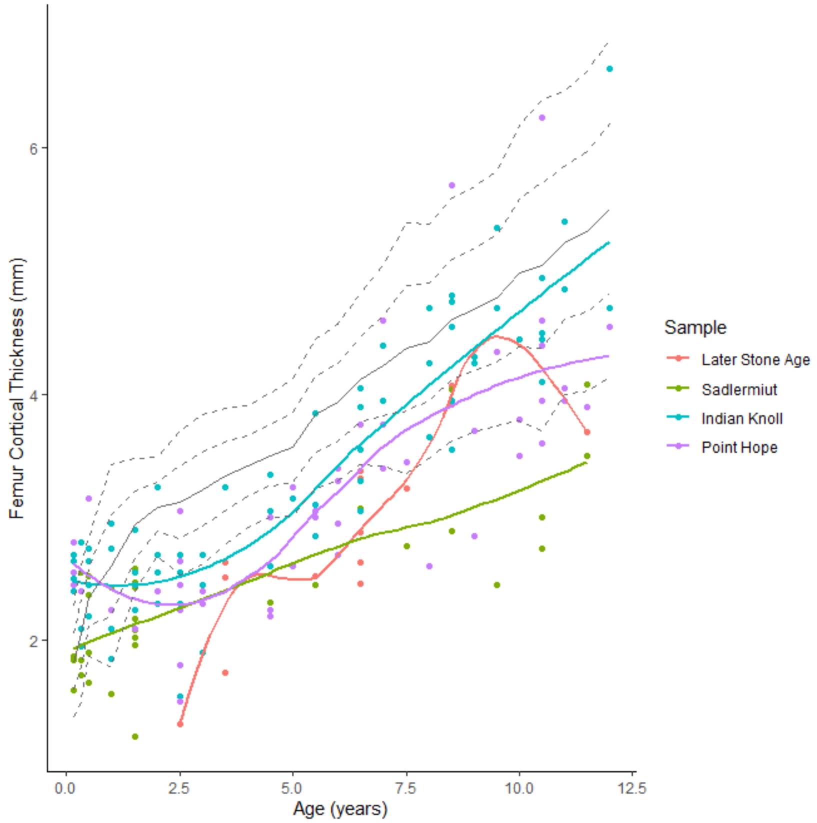

Figure 2: Scatterplot of femur cortical thickness against age for SAD, LSA, PH, and IK, compared with the Denver Growth Study. The solid grey line represents the mean of the Maresh data, and the dotted grey lines represent ± 1 and 2 standard deviations.

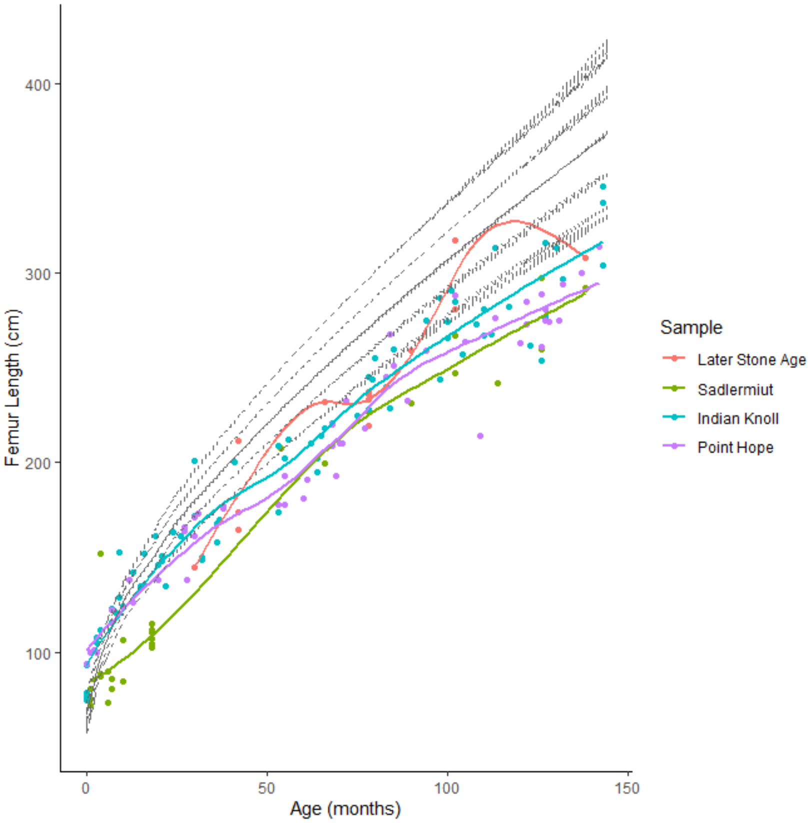

Figure 3: Scatterplot of femur diaphyseal length against age for SAD, LSA, PH, and IK, compared with the Denver. The solid grey line represents the mean of the Maresh data, and the dotted grey lines represent ± 1 and 2 standard deviations.

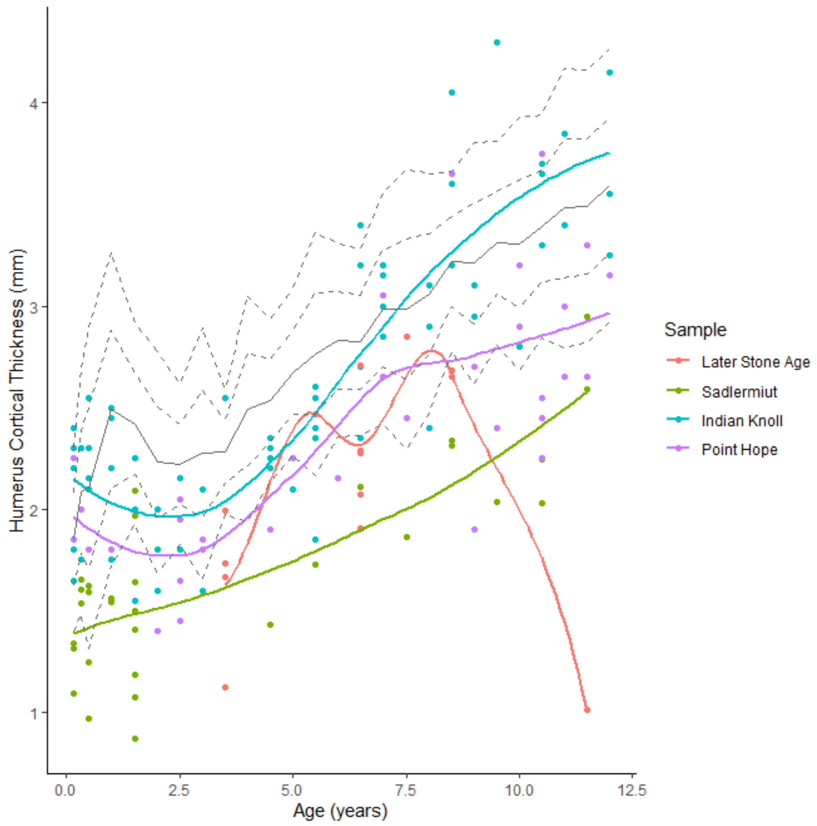

Figure 4: Scatterplot of humerus cortical thickness against age for SAD, LSA, PH, and IK, compared with the Denver Growth Study. The solid grey line represents the mean of the Maresh data, and the dotted grey lines represent ± 1 and 2 standard deviations.

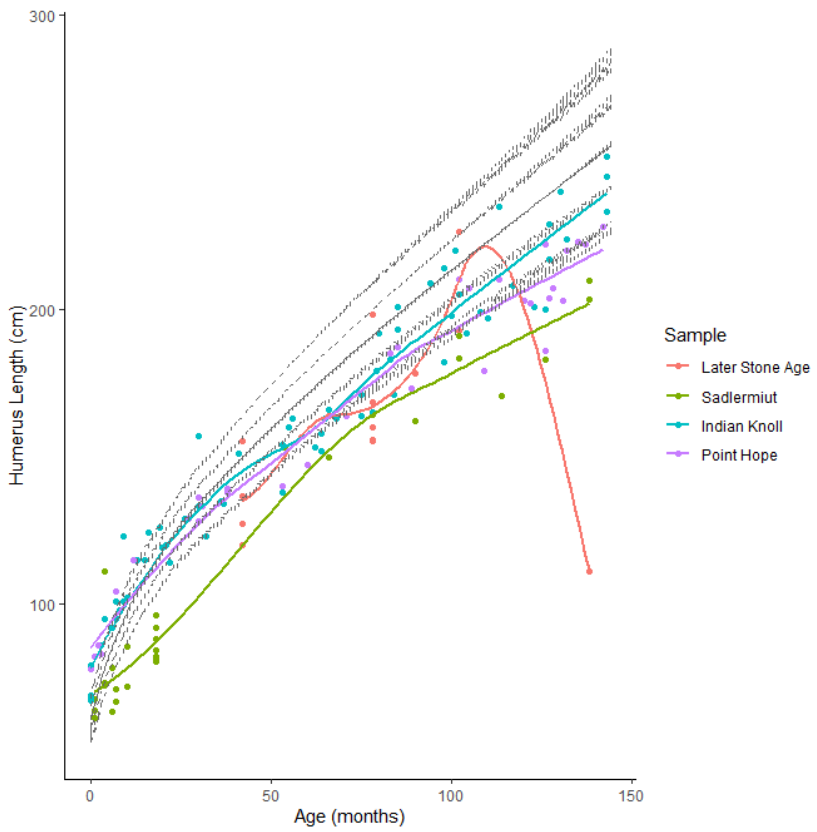

Figure 5: Scatterplot of humerus diaphyseal length against age for SAD, LSA, PH, and IK, compared with the Denver Growth Study. The solid grey line represents the mean of the Maresh data, and the dotted grey lines represent ± 1 and 2 standard deviations.

Discussion

Statistical analysis revealed significant differences in both cortical thickness and diaphyseal length. These differences can be attributed to a combination of environmental, dietary, and activity-based factors that shaped bone growth. The results of this analysis are framed within broader theoretical discussions about the relationship between human skeletal morphology and ecological pressures, as well as insights into the adaptive responses of populations to varying stressors.

Overall, the results largely conform to expectations based on subsistence strategies, environmental conditions, and levels of physical stress. The IK group demonstrated the greatest femoral cortical thickness, which is consistent with their active foraging lifestyle and reliance on terrestrial mobility. IK also exhibited the longest femur and humerus diaphyseal lengths. This aligns with expectations given their favorable environment, access to resources, and relatively low levels of physiological stress compared to Arctic groups.

The SAD group, by contrast, showed the shortest diaphyseal lengths for both the femur and humerus, which is consistent with predictions based on their exposure to chronic disease and environmental challenges. SAD also displayed relatively low femoral cortical thickness, which is in line with their heavy reliance on upper-body intensive activities like paddling and marine subsistence. The LSA group exhibited reduced humeral cortical thickness, which aligns with expectations based on their smaller body size and reduced upper-body biomechanical loading.

Both the PH and SAD groups had lower femoral cortical thickness than the IK group, which was expected due to IK's greater terrestrial mobility. Additionally, PH showed greater femoral cortical thickness than SAD, which supports the hypothesis that combining individuals from two cultural periods within the PH sample would yield a more moderate result. These findings emphasize the strong relationship between mobility, subsistence strategies, and bone robusticity across these diverse hunter-gatherer populations.

Unexpected findings

One of the unexpected findings was the relatively thin humerus cortical thickness observed in the PH sample. This result is surprising given that both periods represented in the PH group engaged in hunting strategies that were upper body intensive, particularly whale and deer hunting (MacKinnon, 2023). However, this discrepancy may be explained by the nature of these hunting activities. Whale and deer hunting were group-based activities, where physical exertion was likely distributed across the group, reducing the biomechanical stress placed on any single individual (Ryan & Young, 2013). Additionally, the cumulative environmental and social stressors faced by PH individuals could have contributed to the observed reduction in humeral cortical thickness (MacKinnon, 2023).

Additionally, the IK group exhibited the greatest humerus cortical thickness. This was unexpected given the presence of humeral asymmetry. It was anticipated that the observed asymmetry would result in a more moderate cortical thickness due to the potential for uneven biomechanical loading (Cowgill, 2008). However, as previously discussed, this study did not specifically account for this asymmetry. The IK group also experienced less environmental and physiological stress compared to the Arctic populations (SAD and PH) (MacKinnon, 2023). The relatively lower stress levels in IK individuals may have mitigated the humeral asymmetry, leading to the observed greater cortical thickness. This hypothesis would benefit from further investigation in future research to better understand the potential interactions between asymmetry and stress in shaping bone morphology.

Furthermore, Point Hope PH exhibited a significant difference in humeral diaphyseal length compared to the SAD group. This was unexpected given that both populations inhabited Arctic environments and employed similar subsistence strategies, particularly marine resource exploitation (Ryan & Young, 2013). This discrepancy may be explained by the varying degrees of stress experienced by each group. SAD was heavily impacted by disease, likely causing a profound effect on growth and skeletal development (Ryan & Young, 2013). PH experienced different types of stress depending on the cultural period. For the PH group, disease stress was only highly prevalent during one of the cultural periods (Ipiutak) (Dabbs, 2011). Variation in trauma and disease exposure between these periods could have resulted in different stress impacts on the population, leading to a more moderate statistical result when the group as a whole is considered. A more detailed comparison between SAD and each of the PH cultural periods, considering temporal differences in disease exposure and trauma, might offer deeper insights into how these stressors affected skeletal growth and contributed to the significant difference observed between the two groups. This approach could highlight the complex relationship between environmental and socio-cultural factors in shaping skeletal morphology across Arctic populations.

Another unexpected finding is that the LSA group had the smallest femur cortical thickness. This was unexpected because of the resources abundance and high terrestrial mobility associated with LSA, both of which are typically linked to increased biomechanical loading and more robust bone development (MacKinnon, 2023). One potential explanation for this finding is the estimated time period for this group. The LSA group spanned the largest time period, and due to this, it is possible that the group was less mobile during certain periods than previously thought. Moreover, in this study, only 17 individuals from the LSA group were analyzed, thus providing a narrow representation of a group that spanned thousands of years.

Broader Implications

This study contributes to bioarchaeological debates on childhood health, growth, and adaptation. By analyzing long bone metrics across different ecological settings, it enhances our understanding of how environmental stressors impact skeletal development. Furthermore, comparing prehistoric growth trajectories with modern Maresh data provides insight into long-term changes in human development. Ultimately, this research informs broader discussions on human plasticity and resilience in response to environmental challenges.

Future research should continue exploring comparative frameworks that link past and present populations to better understand the long-term impacts of environment, lifestyle, and stress on human growth. Expanding cross-population comparisons sheds light on how modern health challenges align with or diverge from historical patterns. These comparisons can help identify which skeletal responses are consistent across time and which are shaped by specific cultural or ecological conditions. Such insights have the potential to inform our understanding of contemporary childhood growth and health disparities, particularly in relation to physical activity, nutrition, and chronic stress. By situating modern populations within a broader evolutionary and biocultural context, bioarchaeological studies like this one contribute valuable perspectives to current debates on health equity and human adaptability.

Limitations

Several limitations in this study may have influenced the interpretation of the results. First, humeral asymmetry was not accounted for in the IK group, which could affect cortical thickness measurements. This omission may have impacted the accuracy of comparisons within and across groups.

Second, the PH sample pooled individuals from two distinct cultural periods, potentially masking intra-group variation. This could explain the more moderate statistical outcomes for this group, as differing behaviors and environmental exposures across periods may have influenced growth patterns in opposing ways.

The LSA group presented two related limitations. The sample size was small (n=17), limiting the generalizability and statistical power of the findings. Additionally, the LSA group spans a long time period, which likely introduced behavioral and ecological variability not captured in a single expectation model. This temporal breadth complicates the interpretation of results, particularly when comparing the group to others with narrower timeframes.

Furthermore, while this study emphasized subsistence strategies and ecological context as primary influences on bone growth, the resolution of specific environmental and cultural variables was limited by the available data. Factors such as seasonal variation in resource availability, the intensity and type of physical activity, and intra-group differences in mobility or diet were not analyzed in fine detail. Additionally, it is important to recognize that skeletal growth and morphology are also shaped by genetic influences, which were beyond the scope of this study. Rather than isolating individual causal factors, this research aimed to develop a broader understanding of how lived experiences may have shaped growth patterns within each population. Future studies that incorporate more nuanced environmental reconstructions, cultural practices, and genetic data could further clarify the complex interactions influencing long bone development, particularly in childhood.

Lastly, it is important to recognize the Osteological Paradox (Wood et al., 1992). The individuals included in this study were all children who died, meaning they may not represent those in the population of the same age who survived and thrived. Something had to occur, whether disease, trauma, or another stressor, that led to their early death. As a result, these remains may reflect the most vulnerable members of their communities rather than typical growth trajectories. Cause of death was not a considered factor in this study as it is unknown, which limits the ability to distinguish between growth disruptions related to broader population trends versus those related to individual health crises.

Conclusion

This study explored the cortical thickness and diaphyseal length of long bones in children from four distinct hunter-gatherer populations—IK, SAD, PH, and LSA—to understand the complex interplay between environmental, nutritional, and cultural factors in shaping skeletal development (MacKinnon, 2023). By comparing these populations to modern Maresh data (Maresh, 1970), this research has shed light on how diverse ecological settings and subsistence strategies influence human bone morphology, particularly during childhood.

The findings highlight significant differences in skeletal traits across populations, with groups from temperate environments (IK) showing more robust long bones (Cowgill, 2008), and those from Arctic regions (SAD and PH) exhibiting adaptations suited to colder climates and physically demanding lifestyles (Ryan & Young, 2013). This variation suggests that environmental stressors, including temperature, mobility, and resource availability, are key drivers of skeletal growth and development. Additionally, cultural factors, particularly subsistence strategies like hunting and watercraft use, have played an essential role in shaping the biomechanics of these populations (Webb, 1946; Dabbs, 2011).

Furthermore, the study emphasizes the role of stress in skeletal development. Populations exposed to higher levels of stress demonstrate thinner cortical thickness and shorter diaphyseal lengths in the humerus and femur (Dabbs, 2011). This supports the hypothesis that bone growth is a highly adaptive process influenced by both internal and external factors. In contrast, groups with more stable environments and abundant resources exhibited more robust bone development, reflecting reduced physiological stress and increased mobility (MacKinnon, 2023).

The data presented in this thesis underscores the importance of early environmental and cultural experiences in influencing growth patterns, which can provide insight into modern health outcomes. This highlights the lasting impact that early life conditions can have on skeletal and overall health (Pfeiffer & Sealy, 2006).

Ultimately, this study contributes to our understanding of human adaptation. Through examining how past populations adapted to their specific environments and subsistence strategies, we gain valuable insights into the ongoing relationship between culture, biology, and the environment. These findings have broader implications for understanding the evolutionary processes that shaped human skeletal morphology and for applying these insights to modern anthropological and bioarchaeological studies. Future research in this area could expand to include genetic analyses to explore the molecular basis of these skeletal adaptations (Cowgill, 2008). By integrating both biological and cultural perspectives, this research allows for a more nuanced understanding of the complexities of human adaptation and development across time.

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