More Stages for Better Ages: An Investigation into the Applicability of a Seven-Stage Epiphyseal Scoring System in Age Estimation Methods

by

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Abstract

The process of long bone development - epiphyseal maturation - is a canalized process that progresses through distinct maturational stages at relatively consistent ages across juveniles. Because of this consistency, epiphyseal maturation is a common proxy for chronological age in age estimation methods. Ages at which epiphyses are expected to appear, undergo fusion to the diaphysis (active fusion), and completely fuse to the diaphysis, are well-established. However, age reference standards for these maturational stages can be broad, particularly for active fusion; this is largely because epiphyseal fusion studies commonly combine individuals at all degrees of active fusion into one 'partial fusion' stage, thereby limiting the precision of age estimates from these reference standards. In an effort to increase age estimation accuracy, this study investigates the applicability of a precise, seven-stage epiphyseal scoring system developed by Dr. Kyra Stull and Dr. Louise Corron. To do so, this study utilizes a known age-at-death sample of American juveniles aged between 5 and 20 years old and raises the following question: How might Stull and Corron's (2022) seven-stage scoring system be used to refine epiphyseal age estimation methods? Quantitative descriptive analysis via relative frequency distribution revealed consistent patterns in how individuals progress through active fusion of the humeral and femoral epiphyses. These patterns indicate that narrower, more precise expected age ranges can potentially be produced for use in age estimation methods based on degree of fusion for slower fusing epiphyses. Results of this study can be used to inform further development of precise age estimation methods for American populations.

Keywords: Age estimation, humerus, femur, American, skeletal growth and development, scoring system, epiphysis, juvenile, epiphyseal fusion, forensic anthropology.

Introduction

Within forensic anthropology, precise, accurate age estimations are a critical component in the process of identifying individuals from skeletal remains (Nawrocki, 2016). Currently, a variety of methodological approaches to age estimation exist, one of which is the assessment of an individual's degree of epiphyseal maturation at the time of death (Langley et al., 2017). Juveniles are known to progress through distinct epiphyseal maturation stages at relatively consistent ages because of the highly regimented nature of the process, thereby allowing it to be used as a proxy for chronological age (total time elapsed since birth) (Scheuer & Black, 2000; Langley et al., 2017).

Currently, ages at which epiphyses are expected to appear, undergo fusion to the diaphysis (active fusion), and completely fuse to the diaphysis, are well-established. However, ages at which individuals reach certain degrees of active fusion remains understudied; this is largely because studies commonly utilize a three-stage scoring system that combines individuals at all degrees of active fusion into one ‘partial fusion’ stage to generate age reference standards (Langley et al., 2017). As a result, age reference standards produced for active fusion are broad, which can limit the precision of age estimates made from them.

In an effort to refine age estimates, this research investigates the applicability of a precise, seven-stage epiphyseal scoring system developed by Dr. Kyra Stull and Dr. Louise Corron (2022) in age estimation methods. To do so, this study utilizes humeral and femoral epiphyseal maturation data from a known age-at-death sample of Americans between 5 and 20 years old and raises the following question:

1) How might Stull and Corron’s (2022) seven-stage scoring system be used to refine epiphyseal age estimation methods?

This research exclusively investigates juveniles and young adults, as epiphyseal maturation is not applicable in estimating the age of individuals that have completely matured. Additionally, this study does not endeavour to produce age reference standards nor determine the statistical strength of Stull and Corron's (2022) scoring system at predicting chronological age; rather, this study serves as a pilot study to explore its potential applicability. Results of this study can be utilized to inform future age estimation methodological advancements, thereby ensuring accurate identification of individuals in forensic contexts.

Background

Biology of Epiphyseal Maturation

During growth and development, long bones do not grow as a single ossified structure. Rather, they are divided into the diaphysis (shaft of the bone) and the epiphyses (ends of the bone). Within utero and throughout childhood, these features develop and grow through endochondral ossification (replacement of cartilage with bone) via primary and secondary ossification centres (Figure 1). Primary ossification centres appear in long bone diaphyses while in utero and begin to ossify the diaphysis; therefore, at the time of birth, diaphyses are partially ossified while the epiphyses remain completely cartilaginous. Then, at different times throughout adolescence, the cartilaginous epiphyses are infiltrated by blood vessels; thus, nutrients and osteogenic (bone forming) cells are able to enter the cartilage and begin ossification of the epiphysis. This infiltration of blood vessels and infusion of osteogenic cells results in the formation of the secondary ossification centre and appearance of the epiphysis (Biga et al., 2025).

Following creation of the secondary ossification centre, the cartilaginous epiphysis will get replaced by bone through endochondral ossification. However, a small plate of cartilage will remain between the epiphysis and diaphysis throughout adolescence. This cartilage is referred to as the growth plate. Within the growth plate, chondrocytes (cartilage cells) progress through four distinct zones, with each zone associated with different cellular activities and processes involved in longitudinal growth (Figure 2). Closest to the epiphysis are the reserve and proliferative zones. In these zones, chondrocytes multiply and form hyaline cartilage. The zones closest to the diaphysis include the hypertrophic and calcification zones; here, chondrocytes mature, die, and calcify before becoming bone as a result of infiltration by diaphyseal blood vessels and osteoblasts. This process of endochondral ossification via the growth plate is what grows long bones in length and occurs after the appearance of the epiphysis and prior to complete fusion with the diaphysis (Biga et al., 2025).

Once chondrocytes stop multiplying and producing cartilage, the growing diaphysis eventually reaches the remaining cartilaginous growth plate and begins to fuse with the epiphysis via endochondral ossification. Ultimately, complete fusion results in the growth plate being completely replaced by bone (Biga et al., 2025). Because bone growth does not happen as a completely synchronous process, the process of fusion happens gradually, meaning certain parts of the epiphysis and diaphysis can possess different levels of fusion simultaneously; this is reflected in the varying degrees of active fusion described in Stull and Corron's (2022) seven-stage scoring system, which will be discussed further in future sections (see *Data Collection)* (Scheuer & Black, 2000).

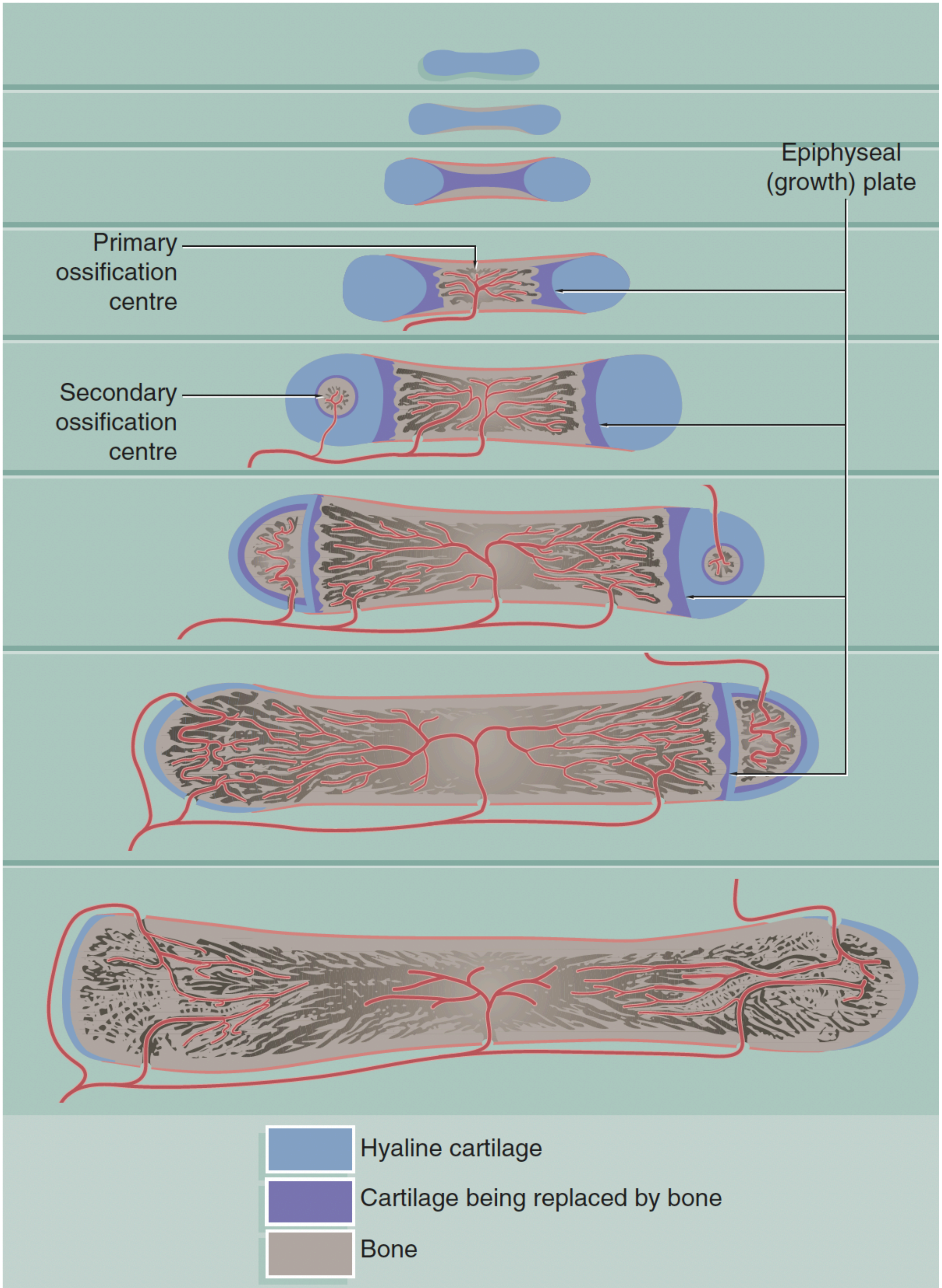

Figure 1. *Process of Endochondral Ossification.* Image from Young et al. (2013).

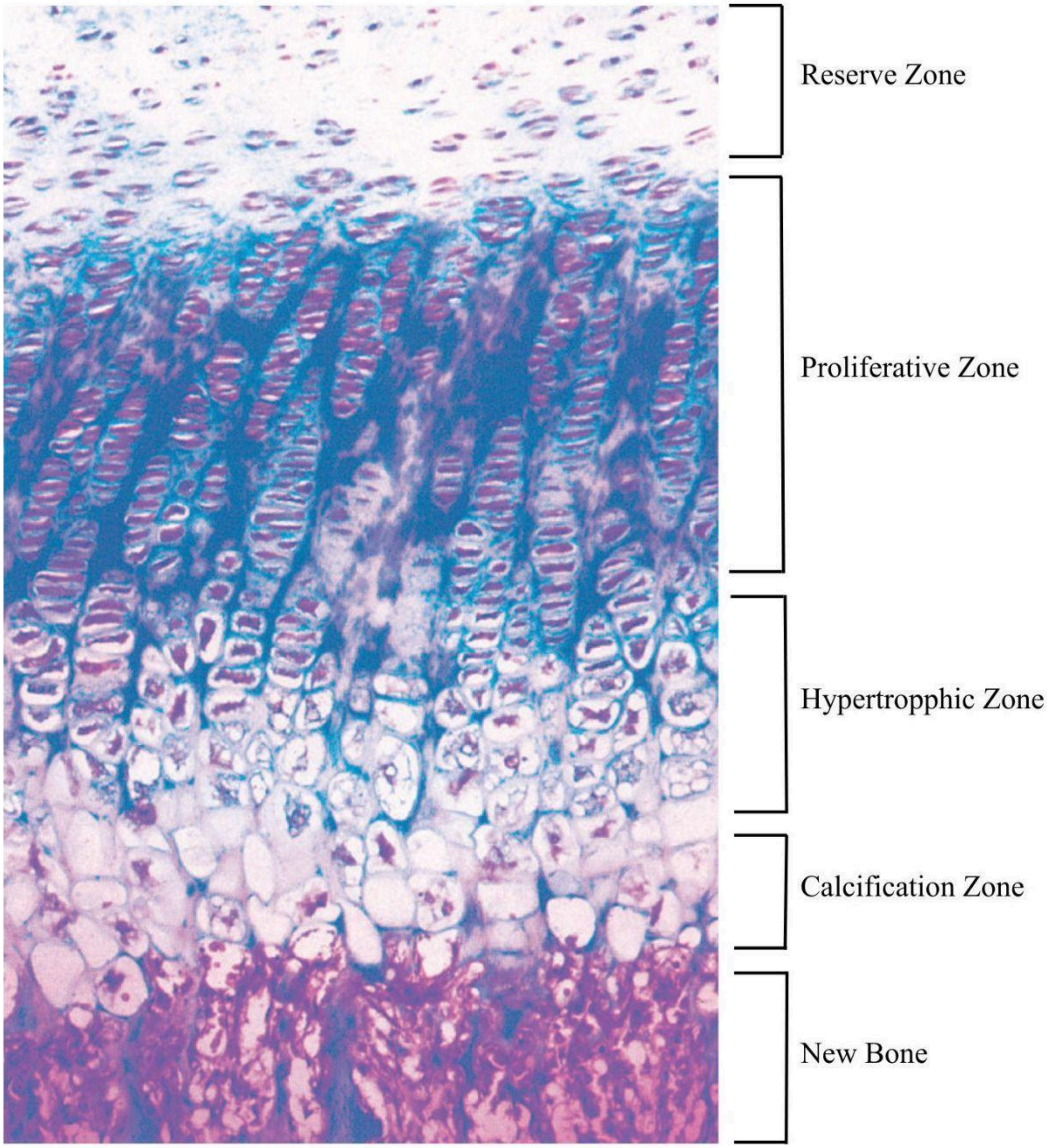

Figure 2. *Epiphyseal Growth Plate Zone.* Image modified from Young et al. (2013).

Long Bone Epiphyseal Age Estimation Methods

Within biological anthropology, developmental theoretical frameworks posit that the aforementioned epiphyseal developmental process is a tightly regulated sequence that goes through distinct maturational stages at relatively consistent chronological ages across subadults. Notably, different skeletal elements progress through epiphyseal maturational stages at different ages. These maturational stages include the following: appearance of the epiphysis/epiphysis is open, active fusion between the epiphysis and diaphysis, and complete fusion between the epiphysis and diaphysis (Scheuer & Black, 2000). Because of this regularity and correlation with chronological age, degree of epiphyseal maturation commonly serves as a proxy for chronological age in skeletal age estimation methods (Langley et al., 2017).

To estimate the age of an unknown individual, forensic anthropologists compare the degree of epiphyseal maturation of an unaged individual to published age reference standards (Passalacqua, 2018). Age reference standards are produced through studies such as those by Johnston (1961), Coqueugniot and Weaver (2007), and Cardoso (2008a, 2008b). These studies work by observing the epiphyses of an array of bones with known ages and scoring them based on their degree of maturation using a scoring system. Scoring systems used in these studies work by dividing the process of epiphyseal maturation into varying degrees, referred to as stages. Across epiphyseal fusion studies, a three-stage system including the stages 'open,' 'active fusion,' and 'completely fused' is most commonly utilized (Langley et al., 2017). However, as previously mentioned, this tripartite system can yield broad age reference standards, particularly for active fusion, at times producing up to eight year age ranges (Coqueugniot & Weaver, 2007). Unlike a three-stage system, which considers all degrees of active fusion as a single stage, the scoring system used in this study, as will be discussed further (see *Data Collection*), divides the process of active fusion into four stages. Therefore, by investigating the applicability of Stull and Corron's (2022) seven-stage system, this study will determine whether intermediate stages of active fusion can potentially serve as reliable indicators of chronological age, in turn, narrowing age range estimates.

While other studies have been done that utilize more precise scoring systems, they often possess severe limitations. For example, a study by McKern and Stewart (1957) employed a five-stage scoring system but only utilized male data from individuals between the ages of 17 and 50 years old. In this case, age and sex representation was extremely limited since it only included ages at which most epiphyseal maturation is expected to have been completed and excluded females, despite the need for sex-specific reference standards due to the well-established phenomenon of females maturing ahead of males (Cunningham, 2019; Scheuer & Black, 2000).

Importance of Precise Age Estimation Methods in Forensic Identification

Chronological age is one of the most defining features of an individual's biological profile; thus, determination of the age of an unknown deceased individual is a crucial step in their forensic identification. Ensuring age estimations are as narrow and precise as possible increases the likelihood of positive identification by eliminating large portions of the population as potential matches (Rogers, 2016).

The importance of this is highlighted by the Royal Canadian Mounted Police National Centre for Missing Persons and Unidentified Remains. As of April 2026, there are 2724 missing individuals in Canada, 384 of which are unidentified remains. Some age estimates provided in the profiles of unidentified remains are staggeringly vague, at times being as broad as 15-70 years old (RCMP, 2026). As a result, the likelihood of accurately identifying these individuals is exceptionally low, unless narrower estimates can be produced.

As the accuracy of age estimations rely largely on the scoring system used to produce age reference standards, continual work is necessary to ensure age estimation scoring systems are as precise and accurate as possible. Therefore, as previously mentioned, this study explores the potential of a seven-stage scoring system at refining epiphyseal age estimation methods (Stull and Corron, 2022).

Materials and Methods

Data Source

All data used in this study were retrieved from the open-access Subadult Virtual Anthropology Database (SVAD). Established in 2022 by Dr. Kyra Stull and Dr. Louise Corron, the SVAD is currently the largest contemporary subadult reference data repository, including both dental and skeletal maturational data. It houses medical images and standardized osteological data collected between 2010 and 2019 from individuals between 0 and 22 years old, from eight countries (Angola, Brazil, Colombia, France, the Netherlands, Taiwan, South Africa, and the United States). All data are cross-sectional and were derived from radiographs (CT scans, Lodox scans, conventional X-ray, and panoramic radiographs) of both living and deceased individuals and were provided by medical examiners offices, hospitals, and dental practices. The type and source of these radiographs vary by country and variable. Skeletal and dental maturational data are provided in the form of the following variables: epiphyseal maturation stage, diaphyseal dimensions, vertebral neural canal measurements, craniometrics, and dental developmental stage. Readily available demographic information is limited to country, age, and sex (Stull & Corron, 2022).

Data Selection

Although the SVAD contains epiphyseal maturation data from eight different countries, certain intricacies in its data collection led to some countries' samples missing substantial data points. Some of these inconsistencies arise from the fact that the collaborating hospitals and dental practices often only provided images of a particular region or element; this is especially pertinent in the Brazilian, Dutch, French, Taiwanese, South African, Colombian and Angolan samples (Stull & Corron, 2022). Therefore, the American sample was selected for this study as it is the country with the most sufficient epiphyseal maturation data (Stull & Corron, 2022).

Within the SVAD, the American sample is unique in its source of data. Data were retrieved from the medical examiner's offices in Baltimore, Maryland and Albuquerque, New Mexico, thus, making it one of two samples within the SVAD that is composed of deceased individuals. Ages represented in the sample range from <1 to 21 years old. All radiographs used in the American sample were full body CT scans, which allowed for data to be collected for nearly all variables of every individual. Scans from the New Mexico population were retrieved from The New Mexico Decedent Image Database, whereas the Maryland medical examiner's office was in direct collaboration with the SVAD (Stull & Corron, 2022).

To create the sample used in this study (n=1,120), individuals between 5 and 20 years old from each sex were selected from the total American SVAD sample and combined into the following eight age categories: 5-6, 7-8, 9-10, 11-12, 13-14, 15-16, 17-18, and 19-20 years of age. This age range (5-20 years) was selected because the epiphyses of interest (Figure 3) do not typically appear until early childhood and usually complete fusion in the late teenage/early adult years (Scheuer and Black, 2000). Ages were combined into two-year ranges to increase the sample size of each age range.

Prior to sample selection, individuals missing data points were removed. Then, to ensure a representative sample, a simple random sample was taken. To do so, a random number generator was used to select ten males and ten females from each age category, for each epiphysis. Thus, the total sample size for each sex was 80 individuals per epiphysis, comprised of 10 individuals per age category. As is common in epiphyseal fusion studies, only left-sided elements were utilized in this research based on the assumption of bilateral symmetry which contends that individuals typically possess equal degrees of epiphyseal maturation in each skeletal element on both the right and left side. Therefore, results from left-sided elements can be treated as reflective of the overall maturation of a given skeletal element (Cardoso, 2008a; Cardoso, 2008b; Scheuer & Black, 2000).

Humeral and femoral epiphyses were selected due to their high preservation rates in forensic contexts. Epiphyses utilized in this study are shown in Figure 3. In a forensic context, skeletal remains are often disposed of outdoors, meaning they are subjected to taphonomic processes. Over time, these processes can lead to bones being degraded, dispersed, buried, etc., which can result in incomplete recovery of skeletal remains (Nawrocki, 2016). However, bioarchaeological studies have demonstrated that certain elements are more likely to be preserved due to their skeletal characteristics. It is suggested that as a baseline, juvenile bones are less likely to preserve due to their higher level of organic material than adult bones (Manifold, 2012; Biehler-Gomez et al., 2025). As for individual elements, long bones, such as the humerus and femur, are among the most likely to preserve due to their higher bone mineral density and increased cortical bone (Biehler-Gomez et al., 2025). Therefore, by utilizing epiphyseal data from bones likely to be recovered in forensic contexts, results of this research are directly relevant to forensic anthropology.

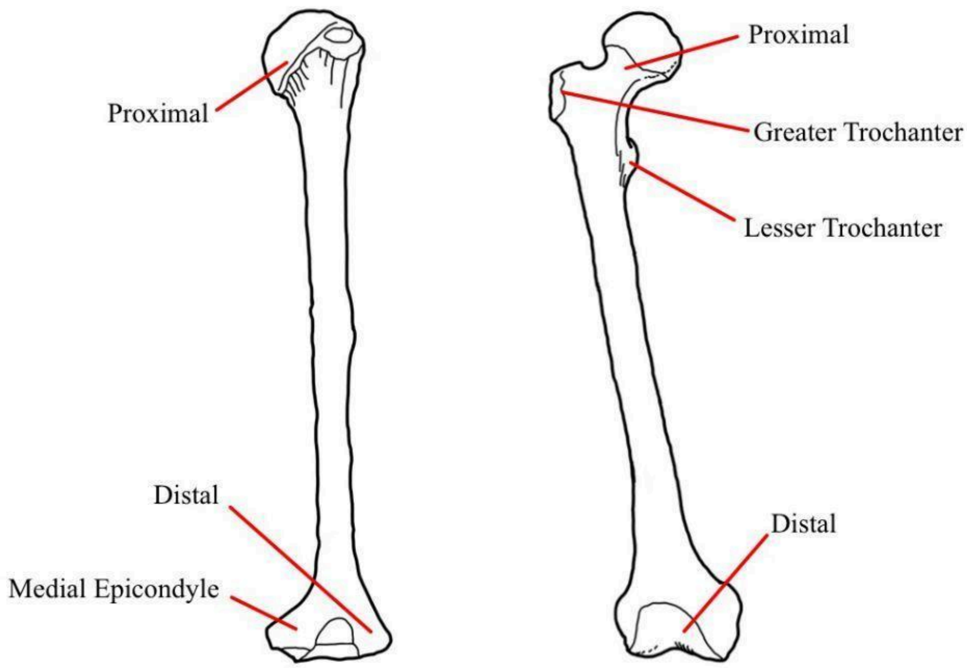

Figure 3. *Humeral and Femoral Epiphyses Utilized in this Study. L*eft) humeral epiphyses; Right) femoral epiphyses.

Data Collection

As mentioned, this research utilizes cross-sectional epiphyseal maturation data for the humeral and femoral epiphyses of American juveniles and young adults. All data used in this study were originally collected by Dr. Kyra Stull and Dr. Louise Corron for inclusion in the SVAD, following ethical approval by the University of Nevada, Reno's Ethical Committee (Stull & Corron, 2022). Data were collected by analyzing individuals' radiographs and applying a standardized seven-stage scoring system to each epiphysis as a way of reflecting its degree of maturation. The seven-stage scoring system used includes the following maturational stages:

0) The epiphysis is absent

1) The epiphysis has appeared but has not begun fusing to the diaphysis

1-2) The epiphysis is 1-25% fused to the diaphysis

2) The epiphysis is 25-50% fused to the diaphysis

2-3) The epiphysis is 50% fused to the diaphysis

3) The epiphysis is greater than 50% fused to the diaphysis

4) The epiphysis is completely fused to the diaphysis

The stage of each epiphysis was determined by analysis of radiodensity between the epiphysis and diaphysis, as this reflects the percentage of the cartilaginous growth plate (radiolucent) that had been replaced with bone (radiodense). Epiphyses classified as absent possessed no radiodense structures in the epiphyseal region, whereas epiphyses classified as fully-fused to the diaphysis possessed homogeneous radiodensity between the epiphysis and diaphysis. Stages of active fusion (1-2, 2, 2-3, 3) were classified based upon varying amounts of radiolucent gaps between the epiphysis and diaphysis (Stull & Corron, 2021). Radiographic examples of each stage are shown in Figure 4.

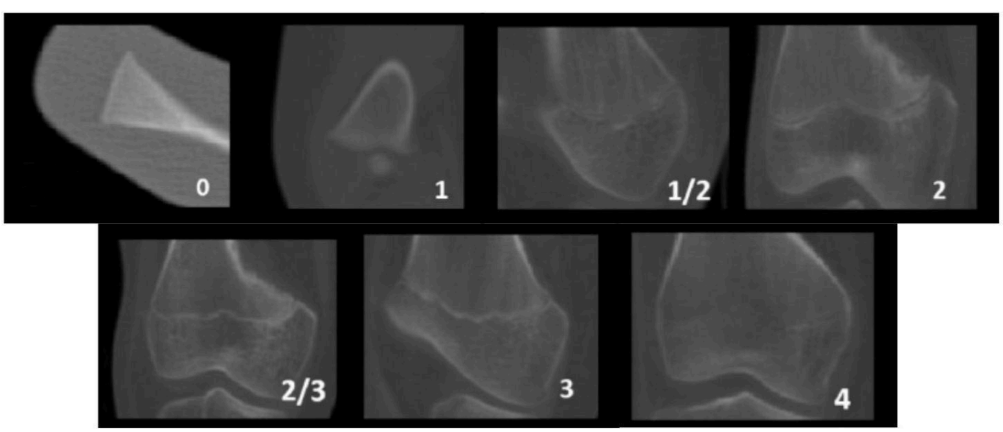

Figure 4. *Radiographic Examples of the Seven Stages created by Stull and Corron (2022).:* Image modified from Stull and Corron (2022). Bone shown in example is a distal femur.

Analytical Approach and Methodology

Due to the aims of this research and its sample constraints, this study opted to utilize a quantitative descriptive analytical approach. This approach is commonly used in quantitative studies to assess patterns and trends within a sample prior to more rigorous statistical testing and has been employed by multiple epiphyseal fusion studies (O'Dwyer & Bernauer, 2014; Cardoso, 2008a; Cardoso, 2008b). An inferential statistical approach is also commonly used to assess the relationship between epiphyseal maturation and chronological age in epiphyseal maturation studies. However, the small sample size for each age category per epiphysis in this research (n=10 per sex) has the potential to skew common statistical tests and lead to unreliable results (Cao et al., 2024). Therefore, a quantitative descriptive analytical approach was deemed most appropriate for the purposes of this research.

Quantitative descriptive analysis was done via an assessment of the relative frequency distribution of Stull and Corron's (2022) seven stages of epiphyseal maturation. To ensure accurate representation of the frequency distribution of each stage, male and female data were analyzed separately due to well-established differences in maturational timelines between sexes (Cunningham, 2019). Similarly, epiphyses were also analyzed independently as different epiphyses are known to develop at different points in childhood (Scheuer & Black, 2000). Raw counts of individuals at each stage of maturation were recorded for each age category and separated by sex and epiphysis (see *Appendix 1*). Total counts for each stage were then converted into relative frequencies for each respective age range and repeated for each sex and epiphysis. To aid in analysis and interpretation, stacked proportion plots faceted by age range were then created in RStudio for each epiphysis and sex (Posit team, 2026). Proportion plots were then visually analyzed. No predetermined criteria were followed to conduct visual analysis, rather, broad patterns were sought in how individuals progressed through epiphyseal maturation, along with age categories at which each of the seven stages were observed at.

Results

Stacked proportion plots created for each sex and epiphysis are shown in Figure 5 and Figure 6. Some deviations from the expected maturational trajectory were apparent in certain epiphyses as some individuals appeared to have regressed in maturation from the prior age category. This is likely the result of the data being cross-sectional rather than longitudinal in nature. In these instances, such individuals were considered outliers and thus excluded from interpretations. Epiphyses in which this phenomenon occurred are the following: female distal humerus, female femoral head, female greater trochanter, female distal femur, male femoral head, and male greater trochanter.

Humeral Epiphyses

Proximal Humerus

In females (Figure 5A), the earliest any active fusion could be identified was ages 9-10, by which point 10% of individuals had begun fusion. By ages 11-12, 50% of individuals had begun fusion, with some individuals scoring as high as stage 2. By ages 13-14, 80% of individuals had entered active fusion, with some individuals already scoring as high as stage 2-3. By ages 15-16, all individuals had entered active fusion and progressed to at least stage 2, while 30% had completed the process fully by this point. By ages 17-18, slower fusers were in the latter stages of fusion, with 30% of individuals being in stages 2-3 and 3, and 70% of individuals having fully completed fusion. By ages 19-20, all individuals still in active fusion (30%) were in stage 3.

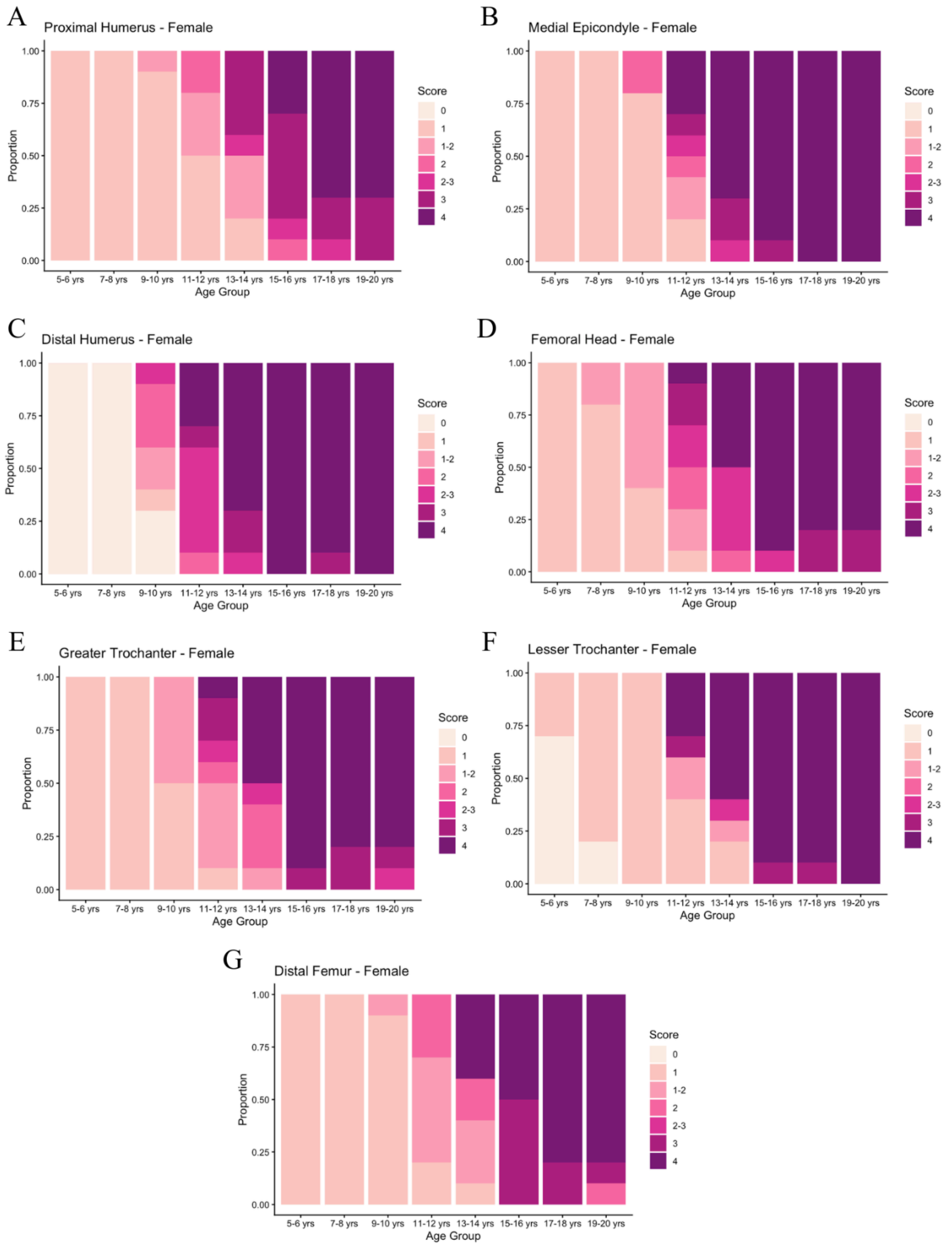

Figure 5. *Female Stacked Proportion Plots for Each Epiphysis.* Each proportion plot includes age category (x-axis) and proportion (y-axis). Stages of epiphyseal maturation are indicated via colour in accordance with the legend on the right of each plot. All age categories include 10 individuals.

In males (Figure 6A), the earliest any active fusion could be identified was 11-12, by which 10% of individuals had begun fusion. By ages 13-14, 50% of individuals had entered active fusion. Within this age range, some individuals scored as high as stage 2-3, indicative of rapid progression through early stages of active fusion, while 50% had not yet begun fusion. By ages 15-16, 90% of individuals had entered active fusion. Most individuals undergoing active fusion in this age range were in stage 2-3; others were in stages 1-2 and 2, and 10% had not yet begun fusion. By ages 17-18, all individuals had begun active fusion and progressed to at least stage 3, while early fusers had completed the process (20%). By ages 19-20, 80% of individuals had completed fusion, with 20% still in stage 3.

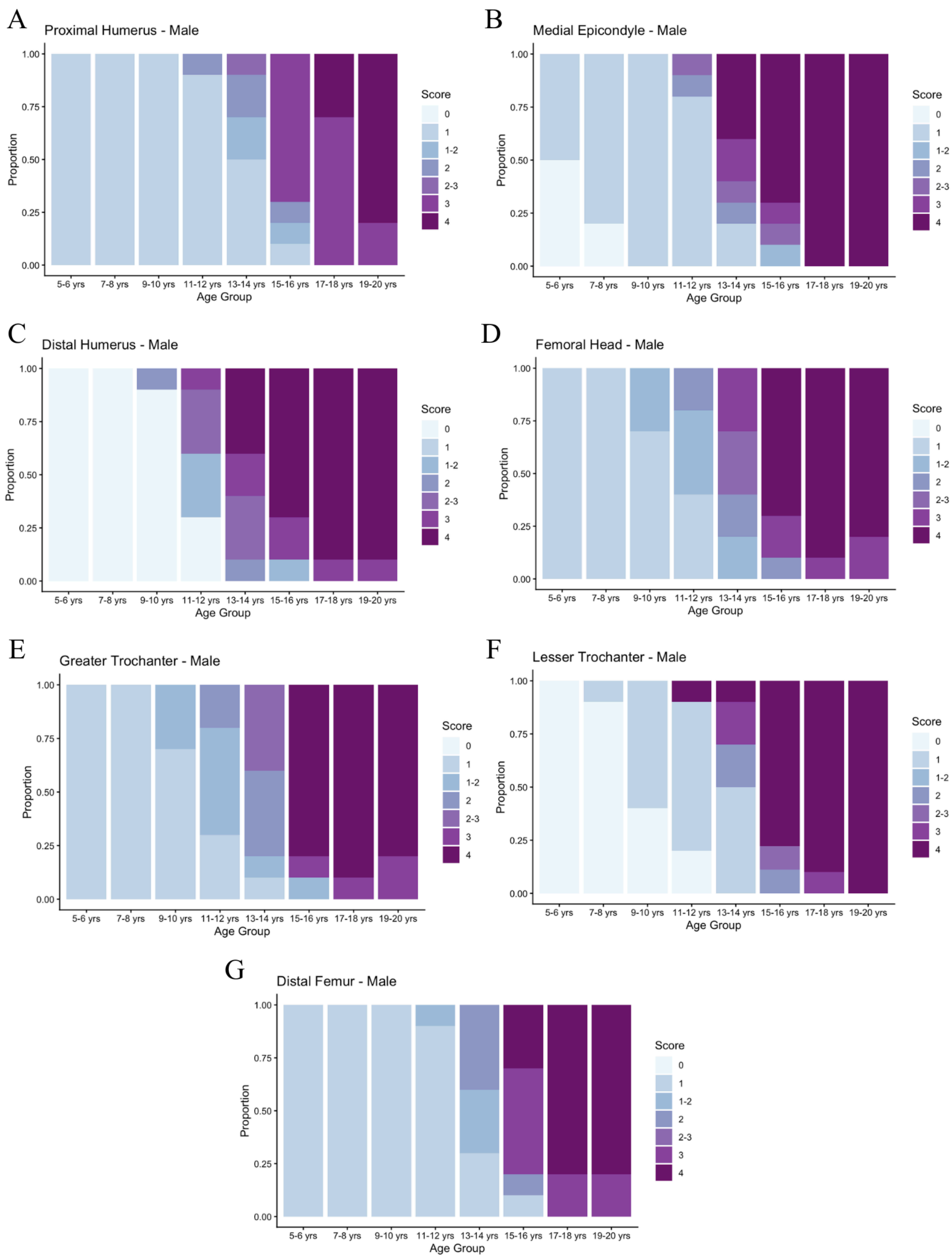

Figure 6. *Male Stacked Proportion Plots for Each Epiphysis.* Each proportion plot includes age category (x-axis) and proportion (y-axis). Stages of epiphyseal maturation are indicated via colour in accordance with the legend on the right of each plot. All age categories include 10 individuals.

Medial Epicondyle

In females (Figure 5B), the earliest any active fusion could be identified was ages 9-10, by which point 20% of individuals had begun fusion. By ages 11-12, 80% of individuals had begun fusion, with some individuals having already completed fusion, indicative of very rapid progression following the onset of fusion. By ages 13-14, slower fusing individuals were in the latter stages of fusion, with 30% of individuals being in stages 2-3 and 3, and 70% of individuals being completely fused. By ages 15-16, 90% of individuals had completed fusion, while 10% remained in stage 3. By ages 17-18, all individuals had completed fusion.

In males (Figure 6B), the earliest any active fusion could be identified was ages 11-12, by which point 20% of individuals had begun fusion and were at stage 1-2 or 2. By ages 13-14, 80% of individuals had begun fusion, with 40% having already completed fusion, once again indicative of very rapid progression following the onset of fusion. By ages 15-16, all individuals had begun fusion and progressed to at least stage 1-2, while 70% of individuals had completed the process. By ages 17-18, all individuals had completed fusion.

Distal Humerus

In females (Figure 5C), the earliest any active fusion could be identified was ages 9-10, by which point 60% of individuals had begun fusion; some individuals scored as high as stage 2-3, while 40% of individuals had yet to begin fusion, indicative of rapid progression once fusion begins. By ages 11-12, all individuals had begun fusion and progressed to at least stage 2, and 15% of individuals had completely fused. By ages 13-14, individuals still undergoing fusion were nearing completion, with 30% of individuals in stage 2-3 and 3, and 70% of individuals having fully completed fusion. By 15+, all individuals were fully fused.

In males (Figure 6C), the earliest any active fusion could be identified was ages 9-10, by which point 10% of individuals had begun fusion. By ages 11-12, 70% of individuals had begun fusion, with some individuals scoring as high as stage 2-3, while 30% of individuals had yet to have the epiphysis appear, indicative of rapid progression once the epiphysis appears and commences union. By ages 13-14, all individuals had begun fusion and progressed to at least stage 2, while 40% of individuals had completed fusion. By 15-16, most individuals still undergoing fusion were nearing completion, with 20% having reached stage 3, and 70% of individuals were fully complete. By 17+, 90% of individuals were completely fused, while 10% were still in stage 3.

Femoral Epiphyses

Femoral Head

In females (Figure 5D), the earliest any active fusion could be identified was ages 7-8, by which point 20% of individuals had begun fusion. By ages 9-10, 60% of individuals had begun fusion, all of which were in stage 1-2. By ages 11-12, 90% of individuals had begun fusion, with 10% having already completed fusion, indicative of a rapid progression through stages following the onset of fusion. By ages 13-14, 50% of individuals had completed fusion, while 50% of individuals were still in active fusion and were in stages 2 and 2-3. By ages 15-16, 90% of individuals were completely fused, while 10% remained in stage 2-3. By 17+ years, the remaining 10% of individuals in active fusion had progressed to stage 3.

In males (Figure 6D), the earliest any active fusion could be identified was ages 9-10, by which point 30% of individuals had begun fusion. By ages 11-12, 60% of individuals had begun fusion, all of which were in stages 1-2 and 2. By 13-14, all individuals had begun fusion and progressed to at least stage 1-2, with some individuals scoring as high as stage 3, indicative of rapid progression. By ages 15-16, most individuals were mid-late fusion, with 30% of individuals in stages 2 and 3, and 70% of individuals fully fused. After reaching 17+, 90% of individuals had completed fusion, while 10% were in stage 3.

Greater Trochanter

In females (Figure 5E), the earliest any active fusion could be identified was ages 9-10, by which point 50% of individuals had begun fusion. By ages 11-12, 90% of individuals had begun fusion, with 10% having already completed fusion, indicative of rapid progression through stages following the onset of fusion. By ages 13-14, all individuals had begun fusion and progressed to at least stage 1-2, with 50% of individuals having already completed fusion. By 15+, 90% of individuals had completed fusion, with 10% still in stage 3.

In males (Figure 6E), the earliest any active fusion could be identified was ages 9-10, by which point 30% of individuals had begun fusion. By ages 11-12, 70% of individuals had begun fusion and were in stages 1-2 and 2. By ages 13-14, 90% of individuals had begun fusion and progressed to at least stage 1-2, with some scoring as high as stage 2-3. By ages 15-16, 80% of individuals had completed fusion, indicating rapid progression through the latter stages of fusion. Those still actively fusing were at stages 1-2 and 3. By 17+ years, 90% of individuals had completed fusion and 10% remained in stage 3.

Lesser Trochanter

In females (Figure 5F), the earliest any active fusion could be identified was ages 11-12, by which point 30% of individuals were in stages 1-2 and 3, and 30% of individuals had already completed fusion, indicative of very rapid progression following the onset of fusion. By ages 13-14, 20% of individuals were in stage 1-2 and 60% of individuals had already completed fusion. By ages 15-16, 90% of individuals had completely fused and 10% were in stage 3. By ages 17-18, 90% of individuals had completely fused and 10% were in stage 3. By 19+, all individuals had completely fused.

In males (Figure 6F), the earliest any active fusion could be identified was ages 13-14, by which point 50% of individuals had begun fusion and progressed to at least stage 2 and 10% of individuals had already completed fusion, indicative of very rapid progression following the onset of fusion. By ages 15-16, 70% of individuals had completed fusion, with those still actively fusing being in stages 2 and 2-3. By ages 17-18, 90% of individuals had completed fusion and slower fusing individuals were nearing completion, with 10% of individuals in stage 3. By 19+, all individuals were completely fused.

Distal Femur

In females (Figure 5G), the earliest any active fusion could be identified was ages 9-10, by which point 10% of individuals had begun fusion. By ages 11-12, 80% of individuals had begun fusion and were in stages 1-2 and 2. By ages 13-14, 60% of individuals were in active fusion stages 1-2 or 2 and 40% of individuals had already completed fusion. By ages 15-16, all individuals had begun union and progressed to at least stage 3, with 50% having completed fusion. By 17+, 80% of individuals had completed fusion, with the remaining 20% in stage 3.

In males (Figure 6G), the earliest any active fusion could be identified was ages 11-12, by which point 10% of individuals had begun fusion. By ages 13-14, 70% of individuals had begun fusion, with some individuals scoring as high as stage 2. By ages 15-16, 60% of individuals were in stages 2 and 3, and 30% had already completed fusion. By 17+, 80% of individuals had completed fusion, with the remaining 20% in stage 3.

Discussion

This study has investigated the process of epiphyseal fusion of the humeral and femoral epiphyses of juvenile and young adult Americans in an effort to assess the applicability of Stull and Corron's (2022) seven-stage scoring system in age estimation methods. Through quantitative descriptive analysis, it was found that the ability of Stull and Corron's (2022) seven-stage scoring system to refine age estimation methods is largely dependent on the rate at which an epiphysis fuses.

Across all epiphyses, with the exception of the greater trochanter and distal humerus, males followed the well-established pattern of progressing through maturation approximately two years behind females (Scheuer & Black, 2000). In the greater trochanter, the age range of active fusion was the same between sexes. In the distal humerus, males typically completed fusion two years after females; however, the age at which the earliest males began fusion aligned with the earliest females. Apart from these instances, females and males showed similar patterns of progression through active fusion across all epiphyses. Therefore, the findings of this study can be applied regardless of sex.

Pace of Active Fusion

By utilizing Stull and Corron's (2022) seven-stage scoring system, the pace at which individuals progressed through active fusion of the humeral and femoral epiphyses was able to be understood on a minute level. Through relative frequency analysis, it was found that the duration of active fusion is highly variable between epiphyses, with some fusing rapidly within 1-3 years, and others more gradually over approximately 4-7 years. However, though pace varied between epiphyses (i.e., inter-epiphyseal variation in pace was high), individuals were found to progress through active fusion at relatively similar rates for each epiphysis following the onset of fusion. Epiphyses found to fuse most rapidly include the medial epicondyle, distal humerus, lesser trochanter, greater trochanter, and femoral head. Epiphyses found to fuse most gradually were the proximal humerus and distal femur.

The findings of this study indicate that the ability of Stull and Corron's (2022) seven-stage scoring system to refine age estimation methods is largely dependent on the rate at which an epiphysis fuses. In rapidly-fusing epiphyses, multiple stages of active fusion were observed to occur within a limited age range. For example, in the medial epicondyle of females (Figure 5B), all stages of active fusion (stages 1-2, 2, 2-3, and 3) were seen in the 11-12 year age category while in the subsequent age category (13-14), active fusion was complete in most individuals. This phenomenon limits the applicability of Stull and Corron's (2022) scoring system in refining age estimates since no stage is more or less likely to dominate a given age range, thus making expected age ranges for each stage of active fusion futile. Furthermore, age ranges produced via the seven-stage scoring system for these epiphyses would show no more refinement than a three-stage system.

In contrast, the seven-stage scoring system does show potential for refining age estimation methods for slow-fusing epiphyses. In slow-fusing epiphyses, particularly the proximal humerus and distal femur, stages of active fusion were shown to persist for longer and displayed less overlap within age ranges. Therefore, each stage could be more definitively associated with a given age range. As a result, narrower expected age ranges could potentially be produced based on the stages of active fusion used in Stull and Corron's (2022) seven-stage scoring system. For example, if estimating the age of a female undergoing active fusion at the proximal humerus, utilizing age ranges produced via a three-stage system (Figure 7) would result in the individual being aged 9-20+ years old. In contrast, if the individual was observed to be, for example, 25% fused, Stull and Corron's (2022) scoring system would indicate the individual is likely 9-14 years old, significantly narrowing the approximate age range. Although a difference of approximately six years may seem negligible, narrowing age estimates can significantly aid in the identification of deceased individuals in forensic contexts by eliminating large portions of the population as potential matches (Rogers, 2016).

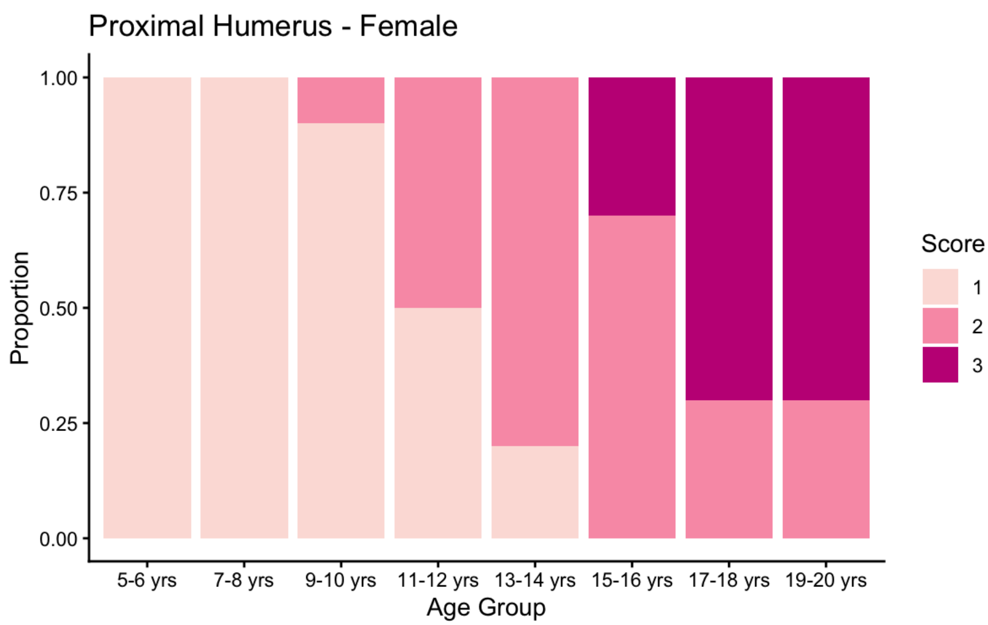

Figure 7. *Proportion Plot for Female Proximal Humerus Using a Three-Stage Scoring System.* Seven-stage epiphyseal data was modified to emulate a three-stage scoring system in order to create the data used in this plot. Age category is on the x-axis and proportion is on the y-axis. Stages of epiphyseal maturation are indicated via colour in accordance with the legend on the right. All age categories include 10 individuals.

Considerations and Future Research

This study has demonstrated the potential application of Stull and Corron's (2022) seven-stage scoring system in epiphyseal age estimation methods. However, additional research is needed to further establish its accuracy and applicability across other skeletal elements, populations, and observational modalities.

As previously mentioned, this study opted for a quantitative descriptive analytical approach rather than an inferential statistical approach, largely because the relatively small sample size would limit the statistical power of common statistical tests. Because of this, the ability of each stage to accurately and reliably predict chronological age was unable to be determined. Therefore, larger sample sizes and inferential statistics (e.g. regression and correlation analyses) should be used in future research to more precisely assess the ability of Stull and Corron's (2022) scoring system to serve as an accurate method in age estimation.

The present study shows promising results for the potential use of this scoring system in contemporary American individuals. However, it should be noted that the results of this study may not apply to other populations. Previous research, such as that done by Schaefer and Black (2005), has found that the pace at which epiphyses fuse can be variable between populations and ancestries. Therefore, although this research has found Stull and Corron's (2022) seven-stage system to be applicable in age estimation methods for slow-fusing epiphyses (i.e., the proximal humerus and distal femur) in American individuals, the extent of its applicability remains unclear given the variability in pace across different populations. As a result, future research should investigate the applicability of Stull and Corron's (2022) scoring system in a more diverse range of populations.

It should also be recognized that age ranges of active fusion observed in this study do not fully align with commonly published age standards. Across all epiphyses, ages at which individuals completed fusion were largely similar to published age standards. However, individuals in this study tended to commence fusion earlier than age reference standards, at times, up to 6 years earlier (Cardoso, 2008a; Cardoso, 2008b; Schaefer et al., 2009). As a result, the total range of active fusion observed in this study is broader than those commonly seen in age reference standards, which may have impacted results. However, this difference in the age ranges of active fusion is likely due to differences in sample size, population, and observational modality (radiography versus dry bone) between this study and previous research, such as the study conducted by Cardoso (2008a, 2008b). This further highlights the need for additional research using this scoring system in other populations to ensure accuracy.

Lastly, it should be noted that this study utilized radiographically derived epiphyseal maturation data to draw its conclusions. While radiography has become commonplace in many forensic anthropology methods and investigations, assessment of epiphyseal maturation via dry bone visual observation remains a common approach in age estimation (Cardoso & Severino, 2010). Although this study has demonstrated the promising potential of Stull and Corron's (2022) seven-stage system in refining epiphyseal age estimation methods, distinguishing between its stages of active fusion requires a precise measure of the total percentage of fusion completed, which may not be discernible on dry bone (Corron et al., 2021; Cardoso & Severino, 2010). Therefore, additional research should be done into the applicability of this scoring system using dry bone specimens.

Conclusion

This study has investigated the potential ability of Stull and Corron's (2022) precise, seven-stage epiphyseal scoring system to refine epiphyseal age estimation methods. To do so, this research utilized humeral and femoral epiphyseal maturation data of American males and females between 5 and 20 years old retrieved from the SVAD. Through relative frequency distribution, the results of this study revealed that Stull and Corron's (2022) seven-stage scoring system does have potential to refine epiphyseal age estimation methods for contemporary American populations.

The findings of this study highlighted a significant difference in the potential applicability of Stull and Corron's (2022) seven-stage scoring system in estimating age from rapidly and slow-fusing epiphyses. In rapidly-fusing epiphyses, including the medial epicondyle, distal humerus, femoral head, lesser trochanter, and greater trochanter, considerable overlap between stages of active fusion was found within limited age ranges. Consequently, Stull and Corron's (2022) seven-stage scoring system would be futile in refining age reference standards for these epiphyses. Alternatively, the proximal humerus and distal femur were found to fuse more gradually in this population. As a result, stages of active fusion were observed to persist for longer and possess less overlap between age categories in which case active fusion stages were able to be more definitively associated with particular age ranges. Thus, for these epiphyses, Stull and Corron's (2022) seven-stage scoring system may produce more refined age reference standards than those generated via a three-stage system for this population.

Future research in this area should further investigate the applicability of Stull and Corron's (2022) seven-stage scoring system across other skeletal elements, populations, and observational modalities. Additionally, the implementation of inferential statistics is needed to better-establish the ability of the stages used in Stull and Corron's (2022) system to accurately predict chronological age. Ultimately, the findings of this study have broader implications in forensic anthropology and age estimation methods. By investigating the applicability of a highly-detailed scoring system, the results of this study can aid in further methodological development of more precise, accurate, and reliable epiphyseal age estimation techniques and scoring systems.

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Appendix 1

Raw Counts of Individuals at Each Stage of Epiphyseal Maturation

Male Sample									Female Sample								
Age	Stage	FH	GT	LT	DF	PH	ME	DH	Age	Stage	FH	GT	LT	DF	PH	ME	DH
5-6 yrs	n	10	10	10	10	10	10	10	5-6 yrs	n	10	10	10	10	10	10	10
	0			10			5	10					7				10
	1	10	10		10	10	5			1	10	10	3	10	10	10	
	1-2									1-2							
	2									2							
	2-3									2-3							
	3									3							
	4									4							
7-8 yrs	n	10	10	10	10	10	10	10	7-8 yrs	n	10	10	10	10	10	10	10
	0			9			2	10		0			2				10
	1	10	10	1	10	10	8			1	8	10	8	10	10	10	
	1-2									1-2	2						
	2									2							
	2-3									2-3							
	3									3							
	4									4							
9-10 yrs	n	10	10	10	10	10	10	10	9-10 yrs	n	10	10	10	10	10	10	10
	0			4				9		0							3
	1	7	7	6	10	10	10			1	4	5	10	9	9	8	1
	1-2	3	3							1-2	6	5		1	1		2
	2							1		2						2	3
	2-3									2-3							1
	3									3							
	4									4							
11-12 yrs	n	10	10	10	10	10	10	10	11-12 yrs	n	10	10	10	10	10	10	10
	0			2				3		0							
	1	4	3	7	9	9	8			1	1	1	4	2	5	2	
	1-2	4	5		1			3		1-2	2	4	2	5	3	2	
	2	2	2			1	1			2	2	1		3	2	1	1
	2-3						1	3		2-3	2	1				1	5
	3							1		3	2	2	1			1	1
	4			1						4	1	1	3			3	3
13-14 yrs	n	10	10	10	10	10	10	10	13-14 yrs	n	10	10	10	10	10	10	10
	0									0							
	1		1	5	3	5	2			1			2	1	2		
	1-2	2	1		3	2				1-2		1	1	3	3		
	2	2	4	2	4	2	1	1		2	1	3		2			
	2-3	3	4			1	1	3		2-3	4	1	1		1	1	1
	3	3		2			2	2		3					4	2	2
	4			1			4	4		4	5	5	6	4		7	7

Male Sample									Female Sample								
Age	Stage	FH	GT	LT	DF	PH	ME	DH	Age	Stage	FH	GT	LT	DF	PH	ME	DH
15-16 yrs	n	10	10	10	10	10	10	10	15-16 yrs	n	10	10	10	10	10	10	10
	0									0	0						
	1				1	1				1							
	1-2		1			1	1	1		1-2							
	2	1		1	1	1				2					1		
	2-3			1			1			2-3	1				1		
	3	2	1		5	7	1	2		3		1	1	5	5	1	
	4	7	8	7	3		7	7		4	9	9	9	5	3	9	10
17-18 yrs	n	10	10	10	10	10	10	10	17-18 yrs	n	10	10	10	10	10	10	10
	0									0							
	1									1							
	1-2									1-2							
	2									2							
	2-3									2-3					1		
	3	1	1	1	2	7		1		3	2	2	1	2	2		1
	4	9	9	9	8	3	10	9		4	8	8	9	8	7	10	9
19-20 yrs	n	10	10	10	10	10	10	10	19-20 yrs	n	10	10	10	10	10	10	10
	0									0							
	1									1							
	1-2									1-2							
	2									2				1			
	2-3									2-3		1					
	3	2	2		2	2		1		3	2	1		1	3		
	4	8	8	10	8	8	10	9		4	8	8	10	8	7	10	10

Note: Abbreviations) FH - Femoral Head; GT - Greater Trochanter; LT - Lesser Trochanter; DF - Distal Femur; PH - Proximal Humerus; ME - Medial Epicondyle; DH - Distal Humerus.