AGE ESTIMATION USING EPIPHYSEAL CLOSURE AT THE WRIST JOINT: AN INVESTIGATION OF INDIVIDUALS OF AFRICAN ORIGIN, AGE 14 TO 22 years

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DECLARATION

I Kundisai Adelaide Dembetembe, hereby declare that the work on which this dissertation is based is my original work. Where the works of others have been used, they have been acknowledged using the Council of Biological Editors referencing style. Neither the whole work nor any part of it has been, is being, or is to be submitted for any other degree in this or any other university.

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ABSTRACT OF DISSERTATION

Age estimation using epiphyseal closure at the wrist joint: an investigation of individuals of African origin, age 14 to 22

By

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June 2010

Age estimation techniques allow the researcher to compare chronological age, calculated from the individual's date of birth, to the level of functional and skeletal development known as biological age. This is useful in forensic cases where the age of an individual whether living or post mortem is often unknown.

Current age estimation using bone development in the hand and wrist is based on the standards developed by Greulich and Pyle in 1959. These skeletal age estimation standards are based on a study of wrist radiographs of Euro-American children. Comparative studies on various populations including those of African biological descent have shown that these standards tend to under- or over- estimate biological age in these populations.

Because of these varied results, this project aimed to determine the timing of skeletal maturation characterised by complete epiphyseal closure at the wrist joint and to determine the cause of any differences observed. To date there are no data available that detail the age at which African children reach adult age in terms of skeletal development. The targeted age range is between 13 years and 21 years which is the duration of puberty including the extremes of early and late maturing individuals.

Pre-existing radiographs from the Martin Singer Hand Clinic were used. The results of the radiographic analyses obtained using the Greulich and Pyle standards were compared to the chronological ages of the subjects calculated using the date of birth and date of radiograph. The results of this study have shown that the Greulich and Pyle standards are not directly applicable to South African children of African biological descent. Specifically from ages 16.5 years in males and 15.5 years in females the Greulich and Pyle standards under estimate skeletal age for this sample by an average of 1 year. The

possible reason for this result could be the difference in biological origin of the Greulich and Pyle reference population and that of the current population. In addition socio-economic status as an environmental factor affecting skeletal development cannot be ruled out as the overwhelming majority of the sample was classified as state-sponsored patients and a small percentage of the sample were private patients. The distinction being that ‘state’ patients paid the minimum consultation fees based on income or lack thereof and ‘private’ patients paid much higher medical aid rates.

The consistency of the delay in skeletal maturation of the current sample compared to the Greulich and Pyle standards make it necessary for future studies to formulate standards with the appropriate correction factor or new population specific skeletal age estimation standards.

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Acknowledgements

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I dedicate this dissertation to my nephew, Bhekinkosi Nathanial Moyo. That you may follow your heart and one day also graduate from the University of Cape Town like Mama Kundi and Sekuru Pembe.

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CHAPTER 1: INTRODUCTION

Skeletal growth is a feature of development of an individual and is a reflection of the physiological processes which result in the attainment of the mature adult body form (Tanner, 1978; Harrison *et al.*, 1988; Wheeler, 1991). Wheeler (1991) postulated that the "degree of skeletal development is a reflection of the degree of physiologic maturation". It follows then, that age estimation is the ability to determine the age of an individual by means of measuring and observing skeletal features. Various techniques are available, which are based on the understanding of the patterns of skeletal development. When these techniques of estimating age by examining the skeleton are applied in a legal setting, then the process is referred to as Forensic Age Estimation (Krogman and Işcan, 1986).

The current project was undertaken as a result of the recognition for the need of an appropriate skeletal age estimation standard for all modern South African population groups. Previous research on the growth and development patterns of South African population groups used height-weight tables. Few had used skeletal age as a measure of growth and development and one study in particular by Phillips and Thompson (2000) further supported the need for population specific standards to be developed. The Phillips and Thompson (2000) study found that the current skeletal age estimation standards, the Greulich and Pyle Skeletal Age Estimation Standards (GP), were too inaccurate for South African population groups and if used, would fail to positively identify unknown individuals based on age.

This dissertation will review some of the results from previous research done using the GP Standards on various populations. Comparisons will be made between those results and the results of the current study. The implications of these results will also be explored and contextualise the benefits of performing such a study in the South African research arena. The current study is the first of its kind as skeletal growth data of people of African biological descent, the black people of South Africa, is virtually non-existent.

For this reason, some data on skeletal anomalies and injuries in this sample are presented in the *Appendix E* and *Appendix F*.

1.1 Importance of Skeletal Age Estimation

Forensic age estimation has been in use since the early 20th century (Pryor, 1928; Paterson, 1929; Flecker, 1932). Skeletal age estimation has a number of important applications. It can, for example, assist in determining the identity of an unknown individual (Krogman and Işcan 1986; Schmeling *et al.*, 2007), in the sorting of commingled remains (Schaefer and Black, 2007), for reconstructing the disease patterns, stature and demography of past populations (Cardoso, 2008a; Abrahamyan *et al.*, 2008) and it allows for the application of the law which is age-appropriate. This is especially relevant in countries which experience a high influx of foreign nationals or refugees who may not have documentation stating their identity and date of birth, or where special laws are applied to minors who commit crimes (Garamendi *et al.*, 2005; Shulz *et al.*, 2008; Büken *et al.*, 2007; Schmidt *et al.*, 2008a). Thus age estimation techniques allow the researcher not only to determine chronological age but also to determine the level of functional development or biological age (Mellits *et al.*, 1971). By comparing the measured age against an established standard, the researcher is able to establish if the individual being examined is developing normally with respect to their population of origin (Mellits *et al.*, 1971).

1.1.1 The Use of Skeletal Age Estimation

Forensic odontologists examine panoramic radiographs of a maxilla and mandible of an unidentified individual, while a forensic anthropologist will examine teeth, cranial and post-cranial bones in order to determine an individual's age. In clinical orthodontics, the assessment of skeletal maturity is of great importance as it may determine whether there is a need for surgical correction in estimating facial growth potential (Broadbent and Golden, 1971). Other users of skeletal age estimation include endocrinologists, paediatricians and orthopaedic surgeons and paediatric radiologists (M. Anderson, 1971) who all require an estimate of age relative to a standard in order to determine if an individual is developing normally compared to individuals of the same age and sex. The clinician focuses on a number of maturity indicators including primary and secondary sexual characteristics, height and weight measures, and appearance of ossification centres in the hand and wrist or complete epiphyseal fusion of the long bones of the skeleton. This is done in order to make a decision on the type and intensity of corrective treatment to be taken when an individual is found to have a developmental abnormality.

Current age estimation using the bones of the hand and wrist is based on a set of standard radiographs, which were published by W. W. Greulich and S. I. Pyle in 1959. Since their publication, these standards have been applied in numerous studies. The results of some of the studies conducting by the following authors Malina (1971); M. Anderson (1971); Lee (1971); Mellits *et al.* (1971); Garn *et al.* (1972); Singer and Kimura (1981); Banerjee and Agarwal (1998); Phillips and Thompson (2000); van Rijn *et al.* (2001); Schaefer and Black (2005); Schmidt *et al.* (2007); O'Connor *et al.* (2008); Zhang *et a.* (2009) are discussed later in terms of how they relate to the results of the present study. The current project tests the applicability of the GP skeletal age estimation standards on a modern South African population.

When using established standards to measure or quantify human growth and development it is wise to use the most recent standards. This has been a criticism of the GP standards as they were formulated in the 1940s. Some authors observed and documented an increase in the maximum heights and weights of various populations over a number of decades (Meadows and Jantz, 1995; Kim *et al.,* 2008). Where the researchers noted an increase in long bone lengths, in height and in weight from the period 1965 to 2005 (Kim *et al.,* 2008) and also when comparing the long bone lengths of a sample taken in the 18th century with those taken in the 20th century (Meadows and Jantz, 1995). Due to the relationship between maximum limb height and rate of skeletal development (Tanner *et al.* 1975) it follows that termination of growth in the hand and wrist would also differ over a number of decades. Thus Greulich and Pyle Standards having been formulated in the 1940s may not reflect skeletal growth accurately in modern populations.

The increased use of skeletal maturity as a means of estimating age stemmed from the need to establish growth-rate parameters within which a large proportion of the population developed (Greulich and Pyle, 1959). These parameters were then termed “standards” and often represented what the researchers referred to as the “normal development”, “normal” meaning that the majority of the sample population expressed these parameters termed ‘maturity indicators’ (Greulich and Pyle, 1959).

GP defined ‘maturity indicators’ as the features which can be used as indicators of advancement toward maturity. These features were used because they “tend to occur regularly and in a definite and irreversible order” (Greulich and Pyle, 1950 as cited in Cameron, 1984). These features are visible using radiography techniques.

1.2 The Rationale behind the Technique

The discovery of radiographs and their application in biological imaging meant that human growth and development could be monitored throughout an individual’s life time hence the application in age estimation. Pryor (1928) used radiography to determining the ossification of the bones of the hand and wrist in a sample of males and females. A number of conclusions were made from this study (Pryor, 1928) which are still valid to date: (i) females develop sooner than males with appearance of ossification centres being earlier in females than males; (ii) the termination of skeletal growth as characterised by epiphyseal fusion differs chronologically between the sexes; (iii) the variation in the age at which ossification of the hand and wrist bones occurs is a heritable trait. It follows that the age of termination of growth is genetically determined.

Not long after Pryor’s (1928) results were published Dunham *et al.* (1939) added supporting evidence of the sex and ancestry differences in skeletal development of infants with ‘negro’ infants being in advance of ‘white’ infants. Because of this information Greulich and Pyle (1959) created sex specific standards. They also acknowledged that genetics could affect development by controlling the sequence of development (Greulich and Pyle, 1959). Even though Stevenson (1924) had observed that the sequence of ossification followed a definite pattern, Greulich and Pyle (1959) accepted other research that showed that there was variation in the specific sequence of fusion of the epiphyses in the hand and wrist (Beresowski and Lundie, 1952)

Greulich and Pyle (1959) noted that females who experienced menarche sooner than their peers also underwent epiphyseal fusion in the hand and wrist sooner. Other studies by Wingerd *et al.* (1974) and Zhang *et al.* (2009) have reported noteworthy differences between the skeletal development of populations of different races. However there has been some research done by Garn *et al.* (1972) and Schmeling *et al.* (2006) as well as Ontell *et al.* (1996) and Schaefer and Black (2005) in which external factors such as socio-economic status have been found to have an effect on skeletal development. The results of these and other studies will be discussed further in *Chapter 5*.

The conclusions highlighted above could be verified because certain skeletal structures such as the cartilaginous growth plate found on the ends of most long bones (Winau, 1973; Nilsson and Baron, 2004) could also be viewed using radiographs. The growth plate is found between the end of the long bone shaft and epiphysis and forms an articulation between them. It was observed that this area of cartilage was gradually resorbed and replaced by bone during 'epiphyseal union'. This term describes the process of cessation of growth in length of long bones, and the fusing of the bone shaft with its epiphysis. Epiphyseal union begins when an individual attains sexual maturity (Simmons and Greulich 1943; Greulich and Pyle, 1959; Nilsson and Baron, 2004) and, according to Nilsson and Baron (2004), ends when the individual reaches adulthood. This is after the pre-pubertal growth spurt has ended and maximum height is attained (Greulich and Pyle, 1959; Nilsson and Baron, 2004).Epiphyseal union is oestrogen dependent in both males and females (Nilsson and Baron, 2004). But due to the differing concentrations of this hormone between the sexes, females having a higher level than males, it follows that females will experience epiphyseal fusion before males (Nilsson and Baron, 2004). This generally occurs between the ages of 14 and 18 with females experiencing epiphyseal union earlier than males (Nilsson and Baron, 2004). This is because females undergo the pre-pubertal growth spurt up to two years earlier than males (Mackay, 1952; Greulich and Pyle, 1959; Bogin, 1988; Tanner, 1989; 1962). This difference can be observed using hand-wrist radiographs. The wrist is reported to be an appropriate region for age estimation as a good quality image can be generated with comparatively low levels of radiation (Camerier *et al*., 2006). The wrist is also convenient in that it can be easily radiographed and there are many bones which can be analysed in this small area (Camerier *et al*., 2006).

1.3 Research Aims and Objectives

Thus with a background on what skeletal age estimation is and how it may be used to determine growth and development toward maturity, this study has attempted to fulfil the following aims:

- To determine the timing of wrist epiphyseal closure for a South African population group of African biological ancestry using current hand and wrist age estimation standards proposed by GP. This will be done by examining the state of fusion of the bones of the hand and wrist joint. By selecting individuals of ages 13 to 22 years in a cross-sectional study of this population.
- To determine whether the results obtained using these standards are consistent with those reported in Phillips and Thomson (2000). These authors found that while using GP standards, skeletal age for three population groups (Negroid, Caucasoid, and Coloured) was over-estimated by up to one year.
- To attempt to explain the reason for any differences observed between the GP age estimation and chronological age of the current sample.

CHAPTER 2: REVIEW OF THE CURRENT AGE ESTIMATION STANDARDS

2.1 Greulich and Pyle Skeletal Age Estimation Standards

GP standards are the most widely used age estimation standards all over the world. These standards were derived from a longitudinal study carried out in 1931, of children of North European ancestry, high socioeconomic status, who were born in the United States of America. The sample population comprised 1000 children (Geulich and Pyle, 1959). Children of lower socioeconomic status were included in a later stage of the study and there were some differences in skeletal development rates which were observed (Greulich and Pyle, 1959).

In their study, Greulich and Pyle (1959) took radiographs of the left shoulder, elbow, hand, hip, knee and foot of each child. This was done to assess whether the individual was developing normally with regards to sequence of epiphyseal fusion in the joints and to establish what “normal” was for this population. In other words, the developmental status of the joints other than the wrist could be used to standardize the wrist joint (Greulich and Pyle, 1959). In addition, skeletal maturation at the joints generally follows a particular sequence and overall skeletal development is uniform under normal circumstances, starting with the elbow followed by the hip, ankle, knee, wrist, and lastly the shoulder a sequence documented by Stevenson (1924) and later by Greulich and Pyle, 1959). This sequence is used in standard physical anthropological age estimation (Buikstra and Ubelaker, 1994).

To formulate a standard radiograph for a particular age, GP selected 100 radiographs of children matched for age and sex, and then designated the radiograph with the most commonly observed maturity indicators as the standard for that age group. The maturity indicators are represented as line drawings which are accompanied by a description of the characteristics which indicate the level of maturity (Greulich and Pyle, 1959). Thus a researcher would compare the wrist radiograph with the standard radiograph of individuals of the same sex and closest age (Greulich and Pyle, 1959). The relevant standards and their accompanying line drawings and explanations are provided in *Chapter 3* of this thesis.

2.2 Tanner, Whitehouse, Marshall, Healy and Goldstein (TW2) Skeletal Age Estimation Standards

The TW2 method was developed following the publication of the GP standards in 1950. TW refers to the initial method, which was formulated in 1962 by Tanner, Whitehouse and Healy, and the "2" refers to the revised version, which is described below. Tanner *et al.* (1975) had observed that due to the relatively small sample size and high socioeconomic status of the GP sample population, their standards, when applied to the Tanner *et al.* (1975) sample population, tended to suggest a delay in terms of skeletal development. Thus Tanner *et al.* (1975), drawing from a wider, more representative sample, comprising 3000 'normal' British boys and girls, formulated a standard for estimating skeletal age at the hand and wrist. This method is more flexible than the GP method because its different parts (the carpal bone scores and the radius and ulna scores) can be used for different purposes such as predicting height.

The Tanner *et al.* (1975) standards were formulated on a method which was mathematical in nature. Each bone of the hand and wrist observed on a radiograph was classified according to the stage of development, and then a score was allocated to each bone. Tanner *et al.* (1975) defined and described up to 17 developmental stages which give separate maturity ratings for the carpal bones, the radius, ulna, metacarpal and phalangeal bones. These stages were defined according to the features observed on the specific bone and the change which occurred with increasing chronological age. The amount of change had to be significant enough to distinguish it from the next stage of development (Tanner *et al.*, 1975).

Following the allocation of a stage of development, the maturity scores, which were made up of 3 sets of "biological weights", were allocated to specific groups of bones in the hand and wrist. These scores were incorporated into the "weighted scores" assigned to each bone development stage, and these were then used to read the skeletal age directly off the standard graphs published by Tanner *et al.* in 1975.

Both the Tanner *et al.* (1975) standards and the Greulich and Pyle (1959) standards are based on data from longitudinal studies of radiographs taken at regular intervals over a long period of time. However they differ in sample size and the amount of detailed analysis required to estimate skeletal age. The Greulich and Pyle (1959) method is used in the current study because of its ease of application. It presents a one step *atlas* or *inspection* method of skeletal age assessment which produces a result which is presented as an age rather than a score which is the result when using the multi-step Tanner *et al.* *bone-specific* technique (Malina, 1971). Furthermore it is noted in a recent review on the limitations of standardizing age estimation in living individuals, by Cunha *et al.* (2009) that there are more cross-populational comparative studies which have been carried out using the GP Atlas method than the TW2 method. This is a valuable advantage for a study which also aims to document development in the bones of the hand and wrist in a population of African biological origin whereas the GP sample was of European biological origin.

2.3 Other Methods for Determining Skeletal Maturity

It can be inferred that in the absence of an established or accurate skeletal age estimation standard, the actual state of development of the bone may be measured and documented and the result compared to the chronological age of an individual. From a study conducted by Moss and Noback (1958) it was found that by quantifying the actual progress toward complete epiphyseal fusion, comparisons could be made between individuals without necessarily knowing their age, sex or pattern of maturation. Thus Moss and Noback (1958) were able to study the time for complete epiphyseal union to occur in the digits of a sample of adolescents using a scoring system. The scores ranged from 0 to 3, where 0 represented an epiphysis were fusion had not begun; 1 represented an epiphysis where fusion had begun; and so on up to 3 where fusion was complete (Moss and Noback, 1958).

Similar scoring systems were used by Schmeling *et al.* (2004), Schmidt *et al.* (2008b), Cardoso (2008b), and Schulz *et al.* (2008) documenting epiphyseal fusion at the medial clavicular epiphysis, the epiphyses in hand and wrist, the upper limb and scapular girdle respectively. However Schulz *et al.* (2008) used computed tomography (CT) scanning to determine the progress toward complete epiphyseal union in the medial clavicle, while Schmeling *et al.* (2004) and Schulz *et al.* (2008) used conventional X-ray radiography, all on living individuals. The study performed by Cardoso (2008b) observed the state of fusion of skeletal material. Regardless of how or what material was examined, Cardoso (2008b), Schmidt *et al.* (2008b) and Schmeling *et al.* (2004) concur that there exists a sex difference in skeletal maturation; the scoring system is most useful in the absence of comparable age ranges or when working with skeletal remains (Cardoso, 2008b); that a minimum age for complete fusion to be observed can be found and this can be used to establish an age range for complete epiphyseal fusion to occur. It was also found that complete epiphyseal union was rarely observed below a certain age. For the medial clavicular epiphysis, that age was 25 to 27 years (Cardoso, 2008b; Schmeling *et al.*, 2004) and in the hand and wrist, that age was 18 years (Schmidt *et al.*, 2008b).

The most relevant method to the current study is the Schmidt *et al.* (2008b) method. In this method, five stages of epiphyseal union were identified. And six epiphyses in the wrist and hand were observed. This method with its numerous epiphyseal ossification stages makes it simpler to track the process of epiphyseal fusion, determining the earliest signs and enabling the researcher to relate this to the chronological ages of the individual. This is in comparison to a three stage system such as the one proposed by Cardoso (2008b). In this case it was necessary to limit the epiphyseal union stages because some of the stages in between are not as easily observed on dry bone Cardoso (2008b) and in addition there has to be a known reliable record of the date of birth and death in order to calculate chronological age. Estimating chronological age is relatively easier in living individuals, who may have birth records, or whose chronological ages can be provided by a relative. However, if there are no such records available, then it may be necessary to have an established age standard to compare their level of development with. This is where the GP standards may be useful, bearing in mind that they themselves have been subject to a number of criticisms discussed below.

2.4 Comparative Studies and Factors Affecting Skeletal Development

Greulich and Pyle (1959) reviewed the applicability of their standards to populations other than that on which their research was based. They concluded that, generally, the skeletal age standards were applicable to other populations, provided that the subjects were of corresponding chronological age and sex. This is a possible drawback of the GP method which is explored further in *Chapter 5*. Subsequent research suggests that Greulich and Pyle (1959) may have been mistaken. Some of the factors thought to have an effect on human growth and development are poor nutrition, hormonal imbalance, congenital and environmental factors including socioeconomic status, which may act to retard or accelerate skeletal development (Chan *et al.*, 1961; Mellits *et al*., 1971; Garn *et al.*, 1972; Krogman and Işcan 1986; Schmeling *et al.*, 2000, 2006; Schaefer and Black, 2005; Olze *et al.*, 2007). However, it has been observed that similar populations in different regions will develop at different rates even when they are adequately nourished (Greulich and Pyle, 1959; Chan *et al.*, 1961; Lee, 1971; Mellits *et al.*, 1971; Banerjee and Agarwal, 1998; Schmeling *et al.*, 2000, 2006; Olze *et al.*, 2007; Büken *et al.*, 2007; Schmidt *et al.*, 2007).

Some authors, although not using the GP Atlas, found that specific factors could affect the rate of skeletal growth. Cardoso (2008a), while studying epiphyseal union in the lower limb, found that socioeconomic status had an effect on skeletal maturation. So did Garn *et al.* (1972) while studying skeletal development in a sample of children of African ancestry of low-income families. It was found that this sample was in advance of children of European ancestry during the postnatal period up to 7 years (Garn *et al.* (1972). But what this study failed to adequately explain was if this advanced development was due to socio-economic status or actually due to genetics. This is a relevant question because although the samples were of similar age ranges, the ‘income/needs’ units score was lower for the group of children of African ancestry (Garn *et al.*, 1972) . Thus there were actually two variables to be controlled for, ancestry and income.

2.5 Growth and Development Studies of World Populations

Among the varied results from studies which tested the applicability of the GP standards are the apparent contradictory results of the skeletal age assessments performed on Australian Aborigines and reviewed by Schmeling *et al.* (2006), who reported that ossification rates as maturity indicators were consistent with skeletal maturity data published on European populations, yet in another study on the same population group which was also reviewed by Schmeling *et al.* (2006), it was reported that ossification rates were retarded, in comparison to European populations, in Australian Aborigines.

It is thus suggested by other researchers (Büken *et al.,* 2007; Schmidt *et al.,* 2007; Chan *et al.,* 1961; Garamendi *et al.,* 2005) that the GP age estimation standards be used with caution on populations other than those of European ancestry. Some even recommend that a standard for assessing specific populations be developed using parameters which most represent the growth and development trends of those populations (Schaefer and Black, 2005).

There are relatively few growth and maturation studies which have been carried out on African populations. In the investigation of skeletal maturation in a sample of children from East Africa, Mackay (1952) found that, in comparison to the white American children on whom the skeletal maturation standards formulated by Todd were based, the black children had skeletal maturation rates that were 1½ to 2 years later (Mackay, 1952). However the cause of this difference in timing of skeletal maturation is not specified. Singer and Kimura (1981) reported similar findings while studying growth and development in Hottentot (Khoikhoi) children, and reported that this apparent ‘delay’ may have been due to low socioeconomic status and poor environmental conditions during early childhood and later in life, and possibly to genetic factors.

Garn *et al.* (1972) looked at the timing of ossification of carpal and metacarpal bones in black children living in America. They reported advanced ossification rates in these children, who were of low income communities, in comparison to samples of children of European ancestry. It is reported that this advanced rate of ossification may not entirely be due to genetic influence but may be due to other factors (Garn *et al.*, 1972). No further information was provided.

2.6 Growth and Skeletal Development Studies on African Populations

There are few studies on skeletal maturation of the hand and wrist or any other joints in South African populations. Two studies documented general growth and nutrition patterns, using height-weight measurements as parameters (Cameron, 1984; Cameron *et al.*, 1992) and compared the pattern of growth between urban and rural populations. It was found that children in urban areas with improved socioeconomic status tended to be developing in advance of their rural counterparts (Cameron, 1984; Cameron *et al.*, 1992).

Two studies used a radiographic technique to analyse carpal ossification and carpal fusion (Beresowski and Lundie, 1952; Levine, 1972 respectively) and found these phenomena to differ in the frequency of occurrence in the various population groups which were studied. This gave an indication that skeletal development could be genetically controlled, while the urban versus rural growth and development studies (Corlett, 1986; Corlett and Woollard, 1988) could be supportive of the notion that environmental factors play a major role in growth and development.

2.6.1 Growth and Skeletal Development Studies on South African Populations

The most recent study on a South African population was performed by Phillips and Thomas with the aim of determining the applicability of GP skeletal age estimation standards for this population. Phillips and Thompson (2000) performed their research on children of similar genetic make-up and socioeconomic status in order to establish whether the developmental age determined from dental and wrist bone development was congruent with the chronological age. This study tested the applicability of two standards, the GP method for estimating skeletal age and the method proposed by Moorrees, Fanning and Hunt (1963) for dental age estimation, to populations living in the Western Cape Province of South Africa, namely the Caucasian, Negroid, Mixed population groups (Phillips and Thompson, 2000).

In their results, Phillips and Thompson (2000) found that the skeletal age estimation technique consistently under-estimated ages for children of Caucasoid, Negroid and mixed ancestry groups. They also reported a discrepancy of up to 1 year between the chronological age and the skeletal age while using the GP method. This was in contrast to the dental age estimation technique which was relatively accurate for the children of mixed ancestry, while the same technique was only relatively accurate for Caucasoid children and inaccurate for Negroid children (Phillips and Thompson, 2000). As this was a pilot study, Phillips and Thompson emphasized the need for further research to be carried out in this respect, which could be used to create a database for South African populations and African populations at large.

It is against the background of inconsistencies and the lack of a modern African reference population in general, and a black population specifically, that this project has been initiated. Phillips and Thompson (2000) demonstrated that skeletal development and maturation of South African population groups differs from that of the population used by GP to establish the skeletal age estimation standards, thus showing the need for the development of skeletal development and maturation data for South African population groups. This data will be used to generate a set of skeletal age estimation standards which are specific to these populations. This research project aims to fill this need and provide initial results on which to establish a database of skeletal age for black South Africans, information that is currently not available. For this research project, the most appropriate method is x-ray radiography, as it gives the clearest image and is the most widely used visualisation technique in this field. The study will be aimed at assessing skeletal development at the wrist for an adolescent sample

CHAPTER 3: MATERIALS & METHODS

3.1 Source of Materials

Pre-existing hand-wrist radiographs were obtained from the Martin Singer Hand Clinic at the Groote Schuur Hospital in Cape Town, South Africa (with permission from Dr. Michael Solomons the Head of Surgery of the Hand Surgery Unit). These radiographs were of trauma patients attending the Out Patient Department at the hospital. The rationale being that these individuals were developing normally with regards to growth in stature and skeletal development, prior to the injury. This is a common practice to guard against exposure of healthy individuals to unnecessary radiation. A record of the types of injury and trauma, and the skeletal anomalies observed can be found in *Appendix E* and *F* respectively.

The radiographs were stored in folders labelled with a unique folder number which is a randomly assigned computer generated eight digit numerical code. For the purposes of this study, this folder number was used only as a means of reference for the radiographs that had been analysed. The other information included on the folder was the patient name, date of birth, language spoken at home, the anatomical structure that was radiographed and the date that the radiograph was taken. For those patients who came for repeated check-ups, the subsequent radiographs were numbered sequentially. On some folders, the hospital from which the patient had been referred was also provided. Where this information was included, it was noted as a possible comparative criterion which could be used as a reasonable indicator of socio-economic status.

3.1.1 Research Sample

The radiographs of interest to this research project were the radiographs belonging to patients of ‘African’ origin. African is referring to the genetic and biological origins of these people. The main language spoken at home was used as an additional flag for this. When the language was not specified then the family name was used as a flag to reflect African genetic origin (Bernhardt, 2001; Kimenyi, 1989; Koopman, 1976).The process by which these names were selected is explained in section 3.1.2. Names which reflected traditional African genealogy were accepted as good indicators of African biological and genetic origin.

The initial search criteria were based on the age of the individual at the time the radiographs were taken, regardless of which part of the skeleton was radiographed. This proved to be tedious and continually resulted in the accumulation of many radiographs of all other joints except the wrist and hand. A new strategy was devised, which included a search according to hand, wrist, forearm or any of the phalanges and thumb radiographs. Subsequent to that the age of the individual was checked to fall roughly between 13 and 21 years.

From the potential pool of thousands of radiographs, age estimation analysis using the hand and wrist could only be performed on 190 radiographs which met the selection criteria. The initial sum of radiographs was subjected to the following selection criteria for inclusion in this study.

(i) Age: Selected age group was 13 years to 21 years. To target the termination of epiphyseal union at the wrist joint.

(ii) Biological origin: Language spoken at home and family name were used as flags for biological origin. Where family names reflective of African ancestry were included in this study. It is important to note that since the pre-existing radiographs stored at the hospital were used, there was no other way the researcher could verify biological origin.

(iii) Clarity of radiograph: If the radiographic image was blurred, over-exposed or did not include enough skeletal elements of the hand or wrist-joint then it was excluded from the study.

(iv) The view in which the radiograph was taken. Only those radiographs which were of a complete hand and wrist taken in the Anterior-posterior (AP) or Posterior-anterior (PA) view were included.

(v) Where possible the left hand was used for skeletal age analysis. However not all radiographs were of the left hand. On the advice of a registered radiologist, the right hand was used for skeletal age analysis.

(vi) If radiographs of both hands were available, the level of development for both was determined and skeletal age estimation analysis was performed on the left hand unless the image was unclear, incomplete or the hand was too extensively damaged for accurate analysis. The choice of the left hand follows the convention drawn up at the conferences of physical anthropologists in Monaco (1906) and Geneva (1912) (cited in van Rijn *et al.,* 2001).

Table 3.01 Number of cases grouped by age and sex.

Age Range (years)	Age Group (years)	Male	Female
13.0-13.4	13	4	1
13.5-14.4	14	9	6
14.5-15.4	15	8	2
15.5-16.4	16	15	6
16.5-17.4	17	21	5
17.5-18.4	18	13	2
18.5-19.4	19	22	3
19.5-20.4	20	19	4
20.5-21.4	21	15	2
21.5-22.0	22	5	1
Total		131	32

3.1.2 Determining African Origin of Study Subjects

A series of references were used for this process. An ongoing debate is raging in which researchers of ethnic studies and sociolinguistics are debating the definitions of ethnicity and ‘race’ (Fought, 2006). The bottom line is that ‘race’ as a biological construct and ethnicity as a social and cultural construct are linked (Fought, 2006). For the purposes of the current research project it is this link which is used to infer the biological origins of the research sample.

The first means of establishing the origin of the study subjects was by home language.

An individual when asked would readily report their first language or native tongue (Koopman, 1976; Fought 2006; Bayley and Schecter, 2003; Mehlwana, 1996). Taking into account the link between language and biological origin reasonably assumed that in the South African context, an individual who speaks isiXhosa or isiZulu is more likely to be of African biological origin or ‘black’. However it should be noted that there are some people of African origin who speak French, English and Afrikaans as their native tongue. In this situation the researcher referred to the individual’s family name. This was done on the understanding that an individual’s family name is an indicator of *male* biological origin (Koopman, 1976; Mehlwana, 1996; Fought, 2006). The implications of this are further discussed in *Section 5*.2. Names databases were also referred to in order to acquire a sense of the range of names of African origin and their roots and their meanings (Bernhardt, 2001; Kimenyi, 1989)

3.2 Methods

To ensure anonymity an alphanumeric code was assigned to each radiograph that was examined. It consisted of a three letter code for the hospital or institute at which the radiograph was taken, followed by the initial “M” or “F” to indicate male or female respectively, and lastly a three digit code beginning at 001 for the first record and 002 for the next one and so on. Thus the code for any record selected at random from the sample would read as follows, XYZM001 or XYZF001. The analysis results for male and female individuals were recorded separately for ease of analysis, in the view of GP having divided their skeletal age estimation standards by sex.

Once the code was assigned, the following data on the radiograph were collected in the following order: folder number (for reference purpose only); date of radiograph; research data code; language spoken; right or left hand-wrist radiograph; radiograph view (whether AP or PA views); skeletal age estimates (1, 2, 3 and final); state of epiphyseal closure; date of birth. The researcher did not know the date of birth of any of the patients whose radiographs were examined. This information was only revealed after the final skeletal age estimate was calculated. This was done to reduce bias.

3.2.1 Analysis of Hand Wrist Radiographs: Greulich & Pyle Method

A professional radiologist Dr. Weiselthaler from the Red Cross War Memorial Children's Hospital in Cape Town trained the researcher on what age indicators to look for when examining a radiograph in conjunction with the GP Atlas. Training was also given on how to interpret not only the radiographs themselves but the accompanying notes regarding the patient’s general health, any pre-existing conditions or chronic illness which might affect skeletal development, and the procedure to be performed at the Martin Singer Cape Hand Clinic. The decision to include or exclude the radiograph was made based on the information provided in the doctor’s notes which could indicate congenital abnormalities or disease in which case the radiograph was excluded. The radiograph was also excluded if the image was over-exposed, unclear or incomplete.

The researcher performed two skeletal age estimates on their own. The time interval between these results was at least 1 month. A limited number of radiographs were selected at random and were analysed by a second independent researcher who is familiar with the GP skeletal age estimation technique. This was done to ensure that repeatability and reliability of each result in the application of the technique was high. Both researchers were did not have access to the chronological age of the subjects.

The process of selection and analysis involved the following steps:

(i) Folders were drawn from a list in which they were arranged in numerical order. This is the method which best suited the manner in which these folders were stored at the Martin Singer Cape Hand Clinic.

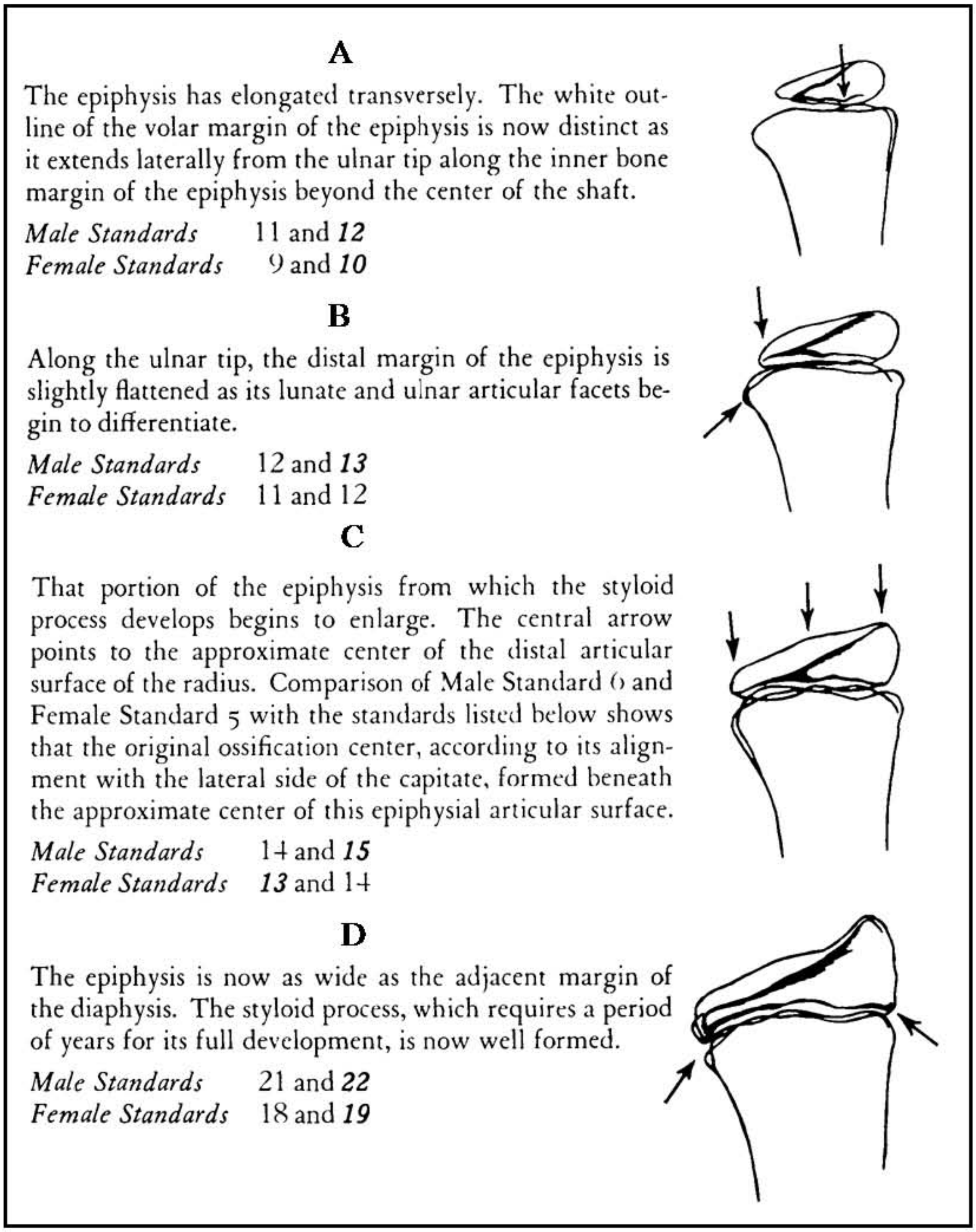
(ii) Once a folder was found it was checked for the appropriate radiograph. The image had to include the whole hand including the wrist and long bone epiphyses. It was observed in those radiographs which were excluded that the wrist was not in AP or PA orientation, while in others, the image was taken at a level at which the metacarpals and phalanges were left out or where the radius and ulna proximal ends were not included in the image.

(iii) The radiograph was viewed using a standard light box provided by the Martin Singer Cape Hand Clinic.

Upon selecting the appropriate radiograph, the researcher looked for the following features, as described by GP, which indicated progress toward skeletal maturity. It should be noted that since the termination of bone growth is the target period, it was not necessary to look at early developmental features such as the size and state of ossification of the carpal bones. This is because by the age of 14 years they have, or should have fully ossified.

When examining the hand and wrist joint in 14 to 22 year olds it is the epiphyseal union in the metacarpals, phalanges, and radial and ulnar epiphyses which is of greatest importance. (Refer to *Figures 3.01* to *3.12*., which are all adapted from Greulich and Pyle (1959). Four aspects are observed when determining the level of skeletal development: (i) width of the epiphysis; (ii) ossification of semsamoid bones; (iii) capping of epiphysis and; (iv) fusion of the epiphysis.

Figure 3.01 Radiograph depicting order of onset ossification of individual wrist and hand bones.
1. capitate; **2.** hamate; **3.** distal epiphysis of radius; **4*.** epiphysis of proximal phalanx of third digit; **5*.** epiphysis of proximal phalanx of second digit; **6*.** epiphysis of proximal phalanx of fourth digit; **7.** epiphysis of second metacarpal; **8.** epiphysis of distal phalanx of first digit; **9.** epiphysis of third metacarpal; **10.** epiphysis of fourth metacarpal; **11.** epiphysis of proximal phalanx of fifth digit; **12.** epiphysis of middle phalanx of third digit; **13** epiphysis of middle phalanx of fourth digit; **14.** epiphysis of fifth metacarpal; **15.** epiphysis of middle phalanx of second digit; **16.** triquetral; **17.** epiphysis of distal phalanx of third digit; **18.** epiphysis of distal phalanx of fourth digit; **19.** epiphysis of first metacarpal; **20*.** epiphysis of proximal phalanx of first digit; **21.** epiphysis of distal phalanx of fifth digit; **22.** epiphysis of distal phalanx of second digit; **23*.** epiphysis of middle phalanx of fifth digit; **24*.** lunate; **25*.** trapezium; **26*.** trapezoid; **27*.** scaphoid; **28.** distal epiphysis of the ulna; **29.** pisiform; **30.** sesamoid of adductor pollicis (the sesamoid of flexor pollicis brevis is visible through the head of the first metacarpal, just below the numeral 2 on the epiphysis of the proximal phalanx of the thumb).
*the timing of ossification at these centres can be highly irregular.
Image adapted from Greulich and Pyle (1959)



A

The epiphysis has elongated transversely. The white outline of the volar margin of the epiphysis is now distinct as it extends laterally from the ulnar tip along the inner bone margin of the epiphysis beyond the center of the shaft.

Male Standards 11 and ***12***
Female Standards 9 and ***10***

B

Along the ulnar tip, the distal margin of the epiphysis is slightly flattened as its lunate and ulnar articular facets begin to differentiate.

Male Standards 12 and ***13***
Female Standards 11 and 12

C

That portion of the epiphysis from which the styloid process develops begins to enlarge. The central arrow points to the approximate center of the distal articular surface of the radius. Comparison of Male Standard 6 and Female Standard 5 with the standards listed below shows that the original ossification center, according to its alignment with the lateral side of the capitate, formed beneath the approximate center of this epiphysial articular surface.

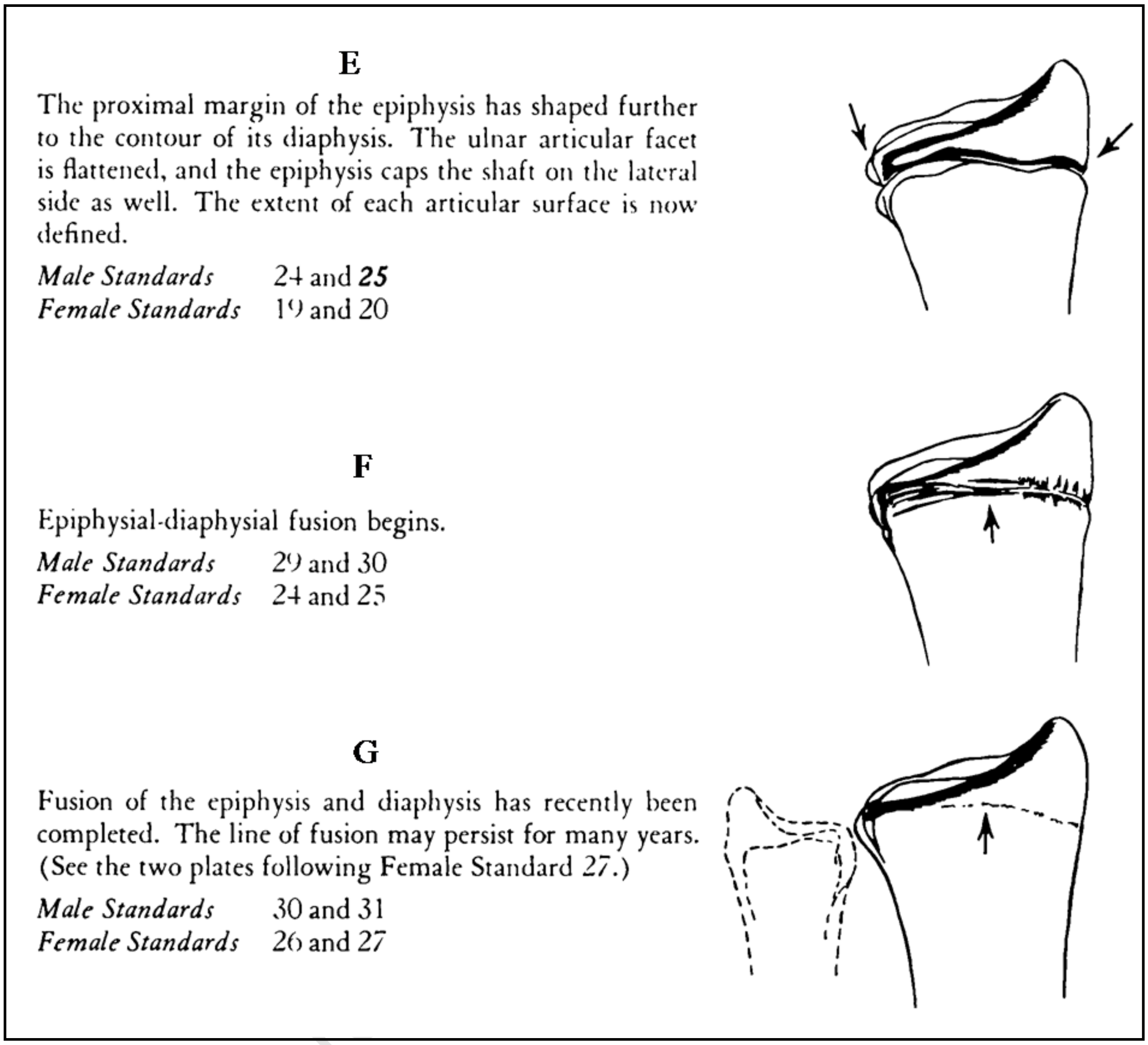
Male Standards 14 and ***15***
Female Standards ***13*** and 14

D

The epiphysis is now as wide as the adjacent margin of the diaphysis. The styloid process, which requires a period of years for its full development, is now well formed.

Male Standards 21 and ***22***
Female Standards 18 and ***19***

Figure 3.02 (a) Diagram showing age related changes in distal radial epiphysis: Males 11 years to 22 years and females 9 to 19 years.
(Image adapted from Greulich and Pyle, 1959)



E

The proximal margin of the epiphysis has shaped further to the contour of its diaphysis. The ulnar articular facet is flattened, and the epiphysis caps the shaft on the lateral side as well. The extent of each articular surface is now defined.

Male Standards 24 and ***25***
Female Standards 19 and 20

F

Epiphysial-diaphysial fusion begins.

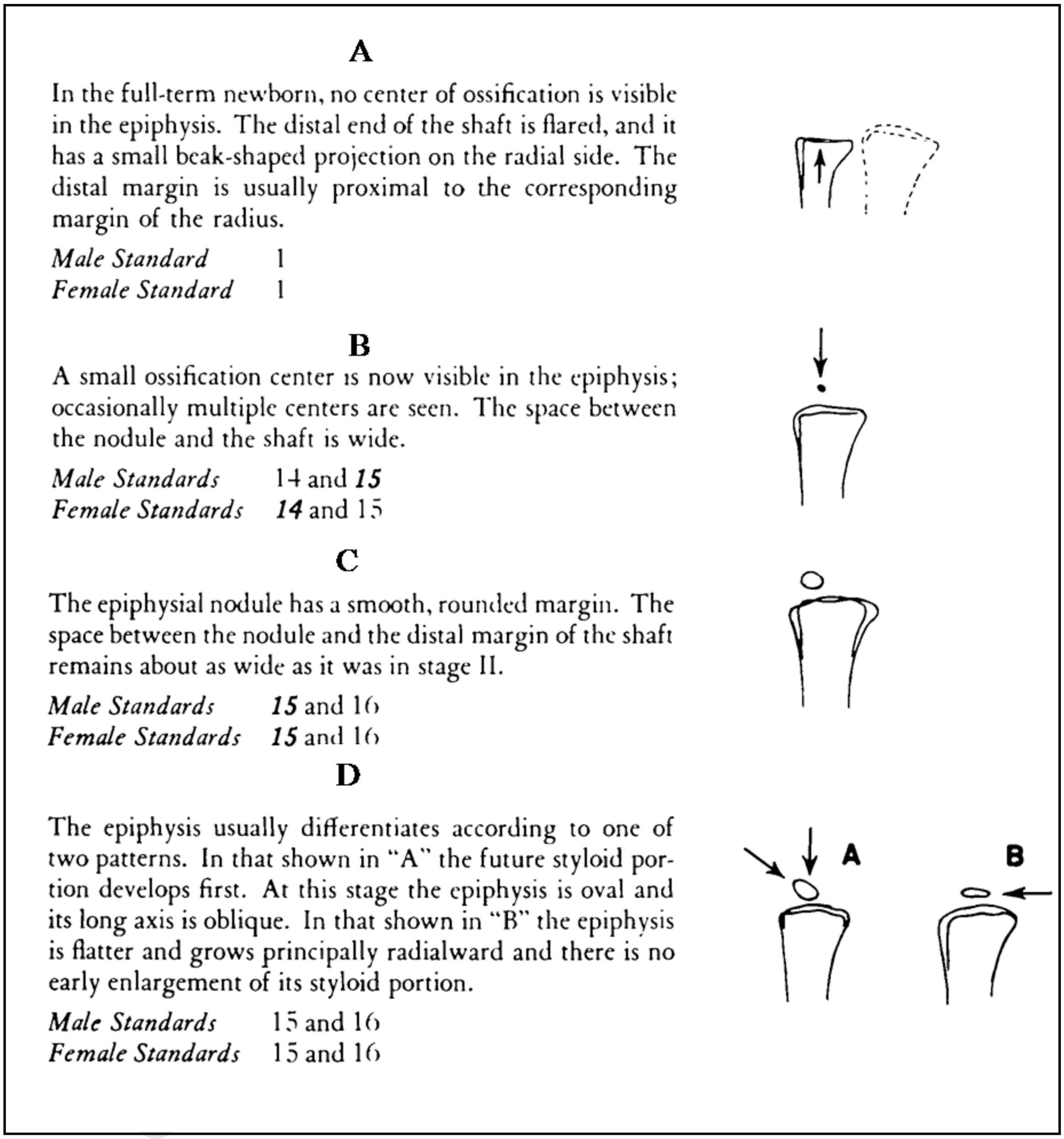
Male Standards 29 and 30
Female Standards 24 and 25

G

Fusion of the epiphysis and diaphysis has recently been completed. The line of fusion may persist for many years. (See the two plates following Female Standard 27.)

Male Standards 30 and 31
Female Standards 26 and 27

Figure 3.02 (b) Diagram showing age related changes in distal radial epiphysis: Males 24 years to 31 years and females 19 to 27 years.
(Image adapted from Greulich and Pyle, 1959)



A

In the full-term newborn, no center of ossification is visible in the epiphysis. The distal end of the shaft is flared, and it has a small beak-shaped projection on the radial side. The distal margin is usually proximal to the corresponding margin of the radius.

Male Standard 1
Female Standard 1

B

A small ossification center is now visible in the epiphysis; occasionally multiple centers are seen. The space between the nodule and the shaft is wide.

Male Standards 14 and ***15***
Female Standards ***14*** and 15

C

The epiphysial nodule has a smooth, rounded margin. The space between the nodule and the distal margin of the shaft remains about as wide as it was in stage II.

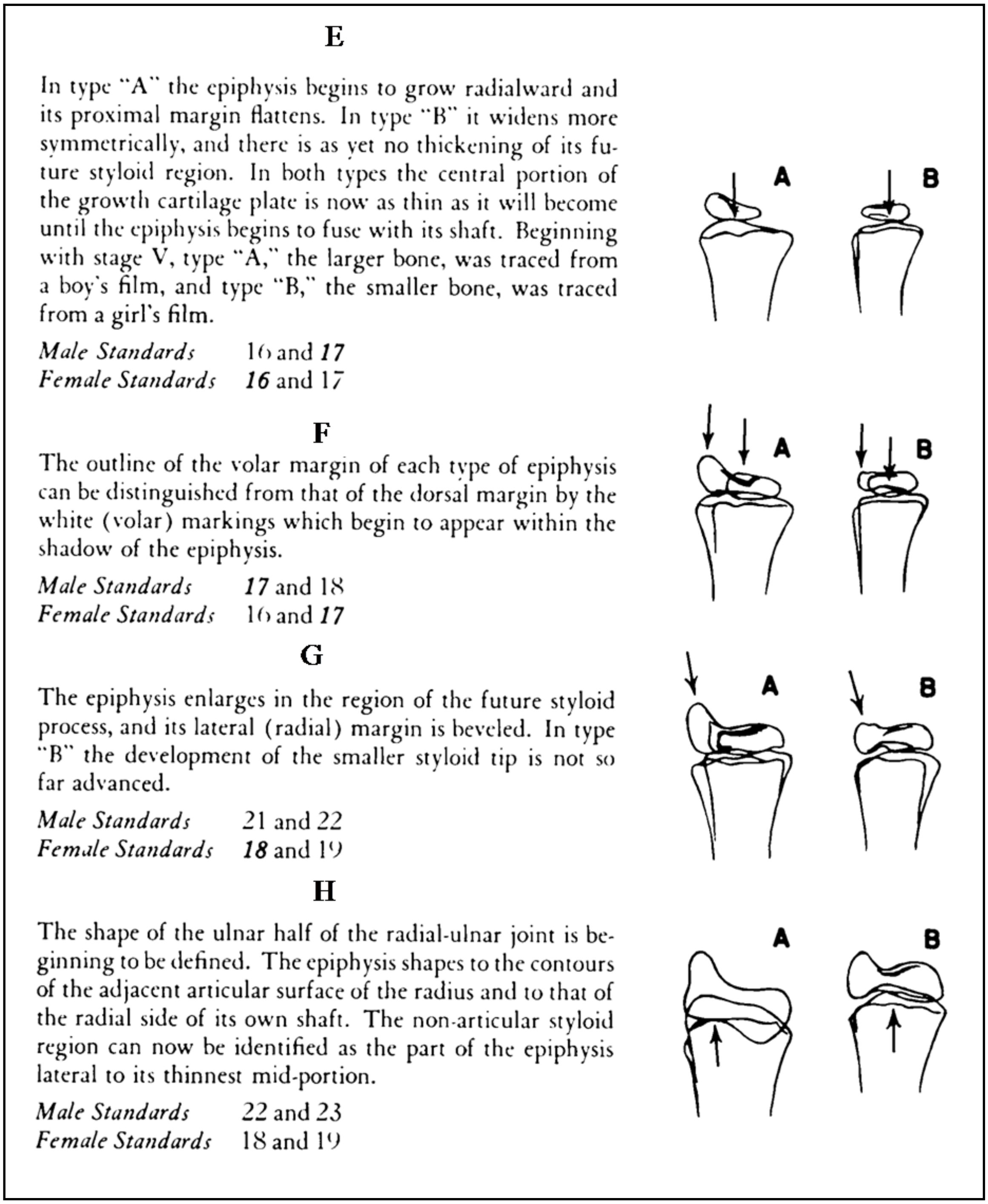
Male Standards ***15*** and 16
Female Standards ***15*** and 16

D

The epiphysis usually differentiates according to one of two patterns. In that shown in "A" the future styloid portion develops first. At this stage the epiphysis is oval and its long axis is oblique. In that shown in "B" the epiphysis is flatter and grows principally radialward and there is no early enlargement of its styloid portion.

Male Standards 15 and 16
Female Standards 15 and 16

Figure 3.03 (a) Diagram showing age related changes in distal ulnar epiphysis: skeletal age 1 year to 16 years for males for females
(Image adapted from Greulich and Pyle, 1959)



E

In type "A" the epiphysis begins to grow radialward and its proximal margin flattens. In type "B" it widens more symmetrically, and there is as yet no thickening of its future styloid region. In both types the central portion of the growth cartilage plate is now as thin as it will become until the epiphysis begins to fuse with its shaft. Beginning with stage V, type "A," the larger bone, was traced from a boy's film, and type "B," the smaller bone, was traced from a girl's film.

Male Standards 16 and ***17***
Female Standards ***16*** and 17

F

The outline of the volar margin of each type of epiphysis can be distinguished from that of the dorsal margin by the white (volar) markings which begin to appear within the shadow of the epiphysis.

Male Standards ***17*** and 18
Female Standards 16 and ***17***

G

The epiphysis enlarges in the region of the future styloid process, and its lateral (radial) margin is beveled. In type "B" the development of the smaller styloid tip is not so far advanced.

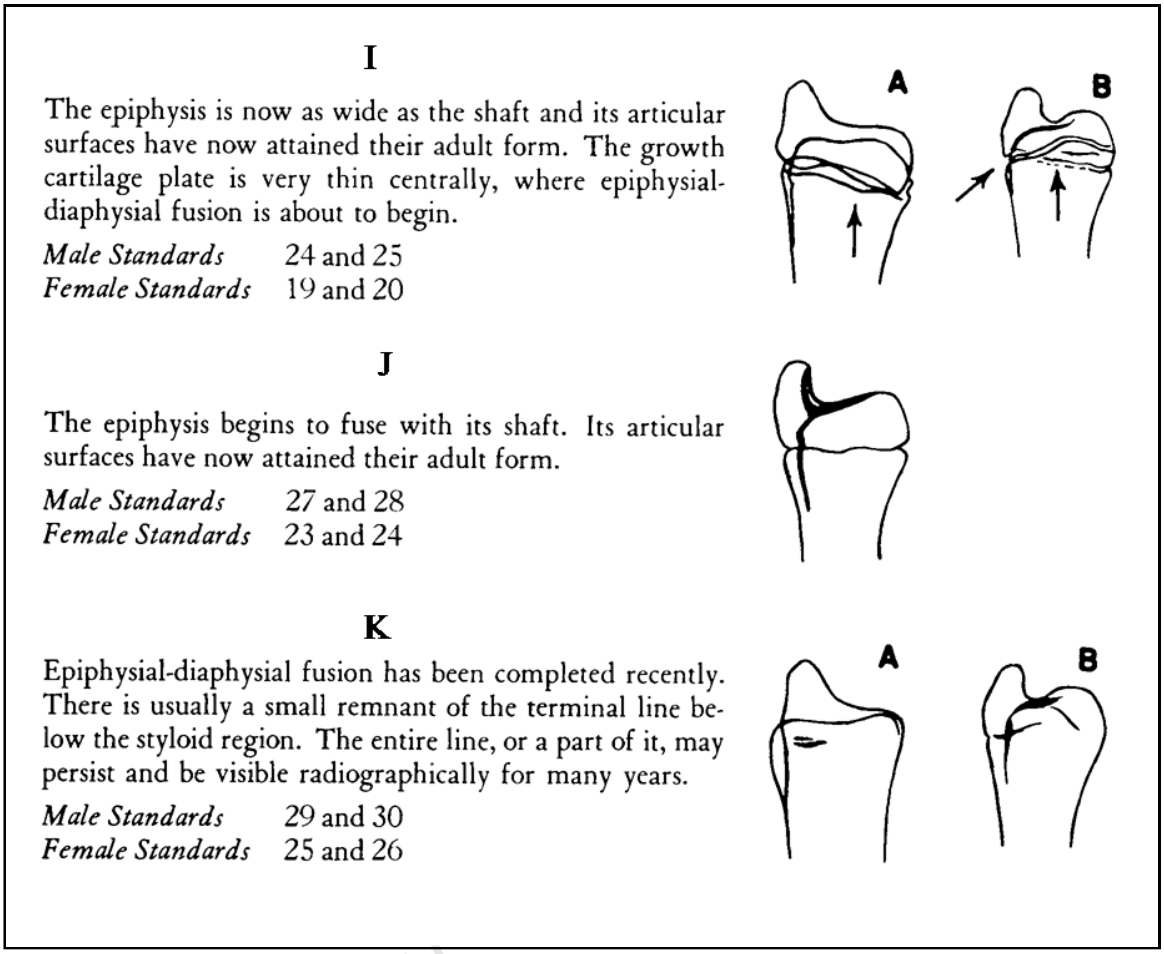
Male Standards 21 and *22*
Female Standards ***18*** and 19

H

The shape of the ulnar half of the radial-ulnar joint is beginning to be defined. The epiphysis shapes to the contours of the adjacent articular surface of the radius and to that of the radial side of its own shaft. The non-articular styloid region can now be identified as the part of the epiphysis lateral to its thinnest mid-portion.

Male Standards *22* and 23
Female Standards 18 and 19

Figure 3.03 (b) Diagram showing age related changes in distal ulnar epiphysis: skeletal age 16 years to 23 years for males and 16 to 19 years for females.
(Image adapted from Greulich and Pyle, 1959)



I

The epiphysis is now as wide as the shaft and its articular surfaces have now attained their adult form. The growth cartilage plate is very thin centrally, where epiphysial-diaphysial fusion is about to begin.

Male Standards 24 and 25
Female Standards 19 and 20

J

The epiphysis begins to fuse with its shaft. Its articular surfaces have now attained their adult form.

Male Standards 27 and 28
Female Standards 23 and 24

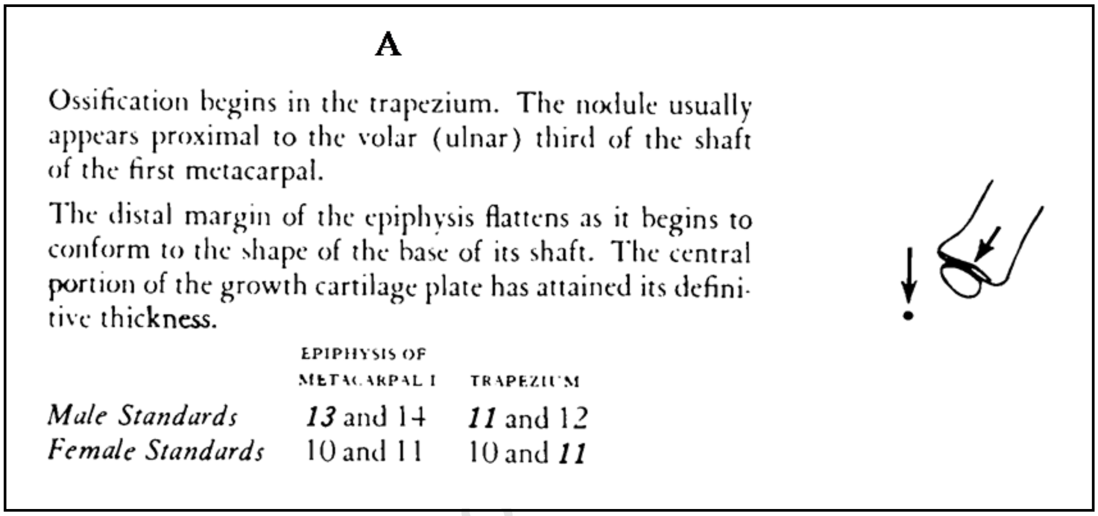
K

Epiphysial-diaphysial fusion has been completed recently. There is usually a small remnant of the terminal line below the styloid region. The entire line, or a part of it, may persist and be visible radiographically for many years.

Male Standards 29 and 30
Female Standards 25 and 26

Figure 3.03 (c) Diagram showing the age related changes in the distal epiphysis of the ulna from skeletal age 24 years to 30 years for males and 19 years to 26 for females.
(Image adapted from Greulich and Pyle, 1959)

In the metacarpals the focus is on determining whether the distal end of the metacarpal has fused to its diaphysis or not. According to GP, this feature is observed in a normally developing child, before the fusion of the proximal ends of the phalanges. Refer to figures 3.4 to 3.6 in which the relative sizes of the epiphyses are used to determine progress toward skeletal maturity. In addition the presence of the metaphyseal line as observed radiographically is also noted as a maturity indicator.



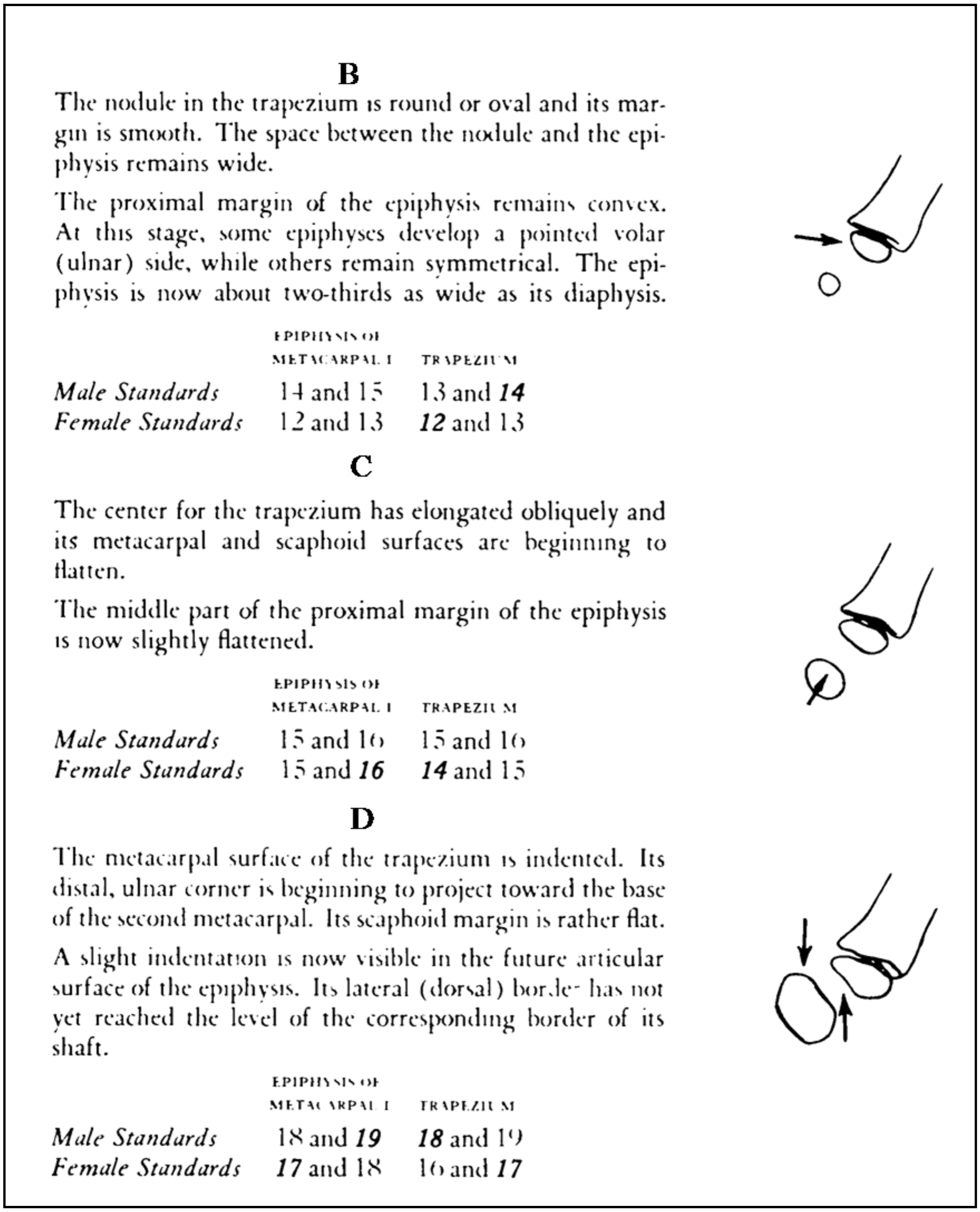
A

Ossification begins in the trapezium. The nodule usually appears proximal to the volar (ulnar) third of the shaft of the first metacarpal.

The distal margin of the epiphysis flattens as it begins to conform to the shape of the base of its shaft. The central portion of the growth cartilage plate has attained its definitive thickness.

	EPIPHYSIS OF METACARPAL I	TRAPEZIUM
Male Standards	***13*** and 14	***11*** and 12
Female Standards	10 and 11	10 and ***11***

Figure 3.04 (a) Diagram showing age related changes in proximal epiphysis of first metacarpal and trapezium for males 11 to 14 years and females 10 to 11 years.
(Image adapted from Greulich and Pyle, 1959)



B

The nodule in the trapezium is round or oval and its margin is smooth. The space between the nodule and the epiphysis remains wide.

The proximal margin of the epiphysis remains convex. At this stage, some epiphyses develop a pointed volar (ulnar) side, while others remain symmetrical. The epiphysis is now about two-thirds as wide as its diaphysis.

	EPIPHYSIS OF METACARPAL I	TRAPEZIUM
Male Standards	14 and 15	13 and ***14***
Female Standards	12 and 13	***12*** and 13

C

The center for the trapezium has elongated obliquely and its metacarpal and scaphoid surfaces are beginning to flatten.

The middle part of the proximal margin of the epiphysis is now slightly flattened.

	EPIPHYSIS OF METACARPAL I	TRAPEZIUM
Male Standards	15 and 16	15 and 16
Female Standards	15 and ***16***	***14*** and 15

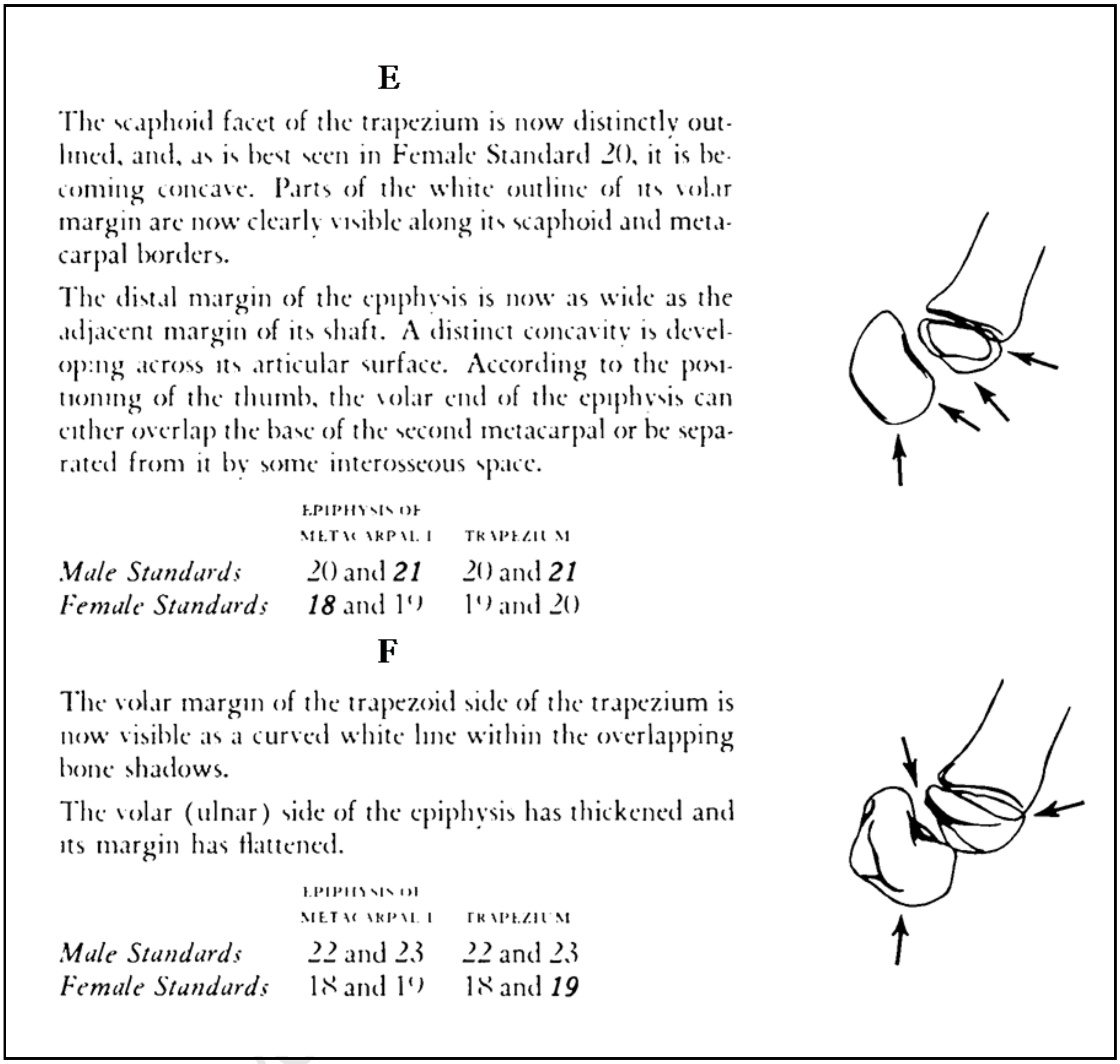
D

The metacarpal surface of the trapezium is indented. Its distal, ulnar corner is beginning to project toward the base of the second metacarpal. Its scaphoid margin is rather flat.

A slight indentation is now visible in the future articular surface of the epiphysis. Its lateral (dorsal) border has not yet reached the level of the corresponding border of its shaft.

	EPIPHYSIS OF METACARPAL I	TRAPEZIUM
Male Standards	18 and ***19***	***18*** and 19
Female Standards	***17*** and 18	16 and ***17***

Figure 3.04 (b) Diagram showing age related changes in proximal epiphysis of first metacarpal and trapezium: Males and females older than 12 and 13 years
(Image adapted from Greulich and Pyle, 1959)



E

The scaphoid facet of the trapezium is now distinctly outlined, and, as is best seen in Female Standard 20, it is becoming concave. Parts of the white outline of its volar margin are now clearly visible along its scaphoid and metacarpal borders.

The distal margin of the epiphysis is now as wide as the adjacent margin of its shaft. A distinct concavity is developing across its articular surface. According to the positioning of the thumb, the volar end of the epiphysis can either overlap the base of the second metacarpal or be separated from it by some interosseous space.

	EPIPHYSIS OF METACARPAL I	TRAPEZIUM
Male Standards	20 and **21**	20 and **21**
Female Standards	**18** and 19	19 and 20

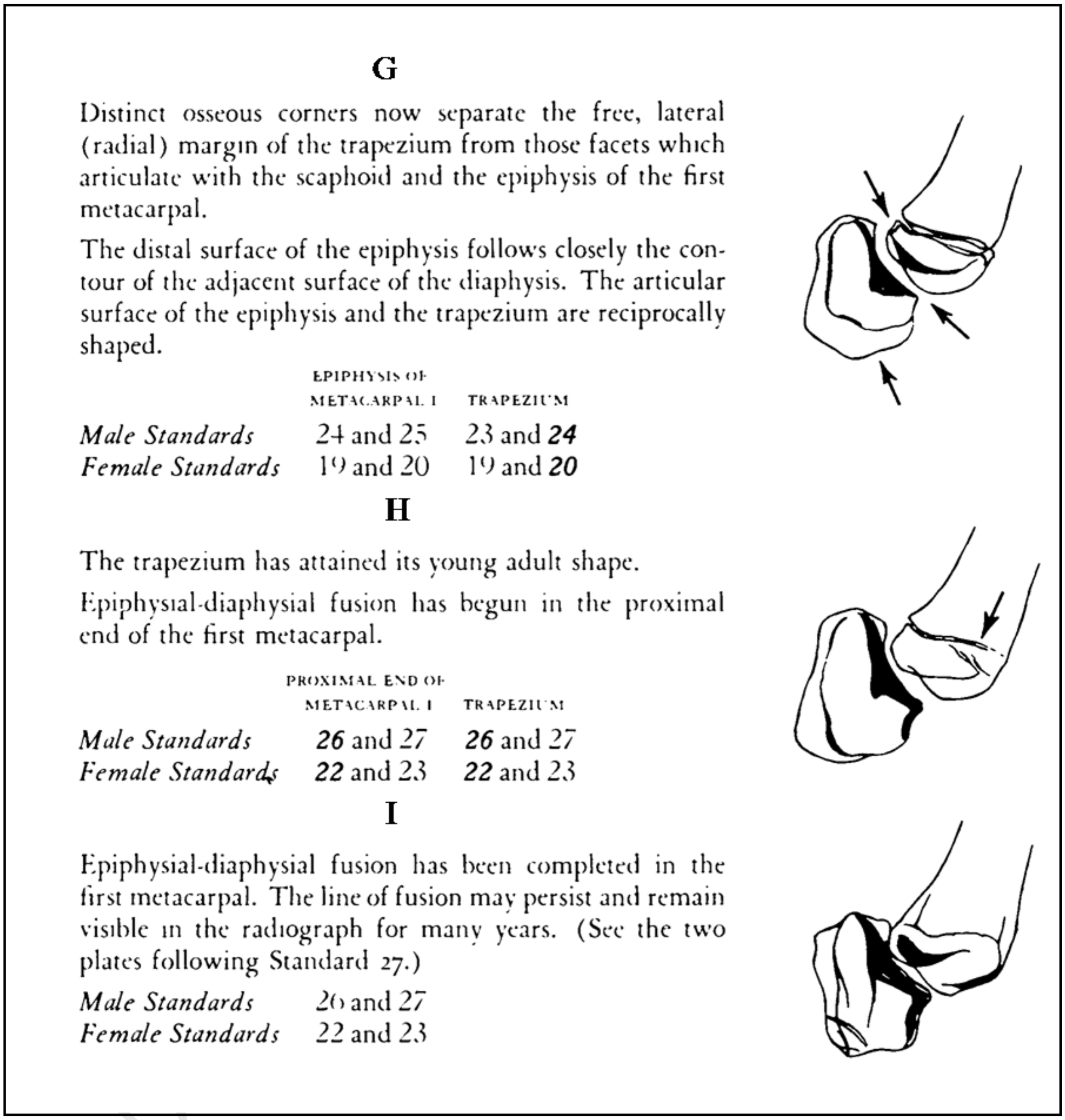
F

The volar margin of the trapezoid side of the trapezium is now visible as a curved white line within the overlapping bone shadows.

The volar (ulnar) side of the epiphysis has thickened and its margin has flattened.

	EPIPHYSIS OF METACARPAL I	TRAPEZIUM
Male Standards	22 and 23	22 and 23
Female Standards	18 and 19	18 and **19**

Figure 3.04 (c) Diagram showing age related changes in proximal epiphysis of first metacarpal and trapezium: Males 20 to 23 years and females 18 to 20 years.
(Image adapted from Greulich and Pyle, 1959)



G

Distinct osseous corners now separate the free, lateral (radial) margin of the trapezium from those facets which articulate with the scaphoid and the epiphysis of the first metacarpal.

The distal surface of the epiphysis follows closely the contour of the adjacent surface of the diaphysis. The articular surface of the epiphysis and the trapezium are reciprocally shaped.

	EPIPHYSIS OF METACARPAL I	TRAPEZIUM
Male Standards	24 and 25	23 and **24**
Female Standards	19 and 20	19 and **20**

H

The trapezium has attained its young adult shape.

Epiphysial-diaphysial fusion has begun in the proximal end of the first metacarpal.

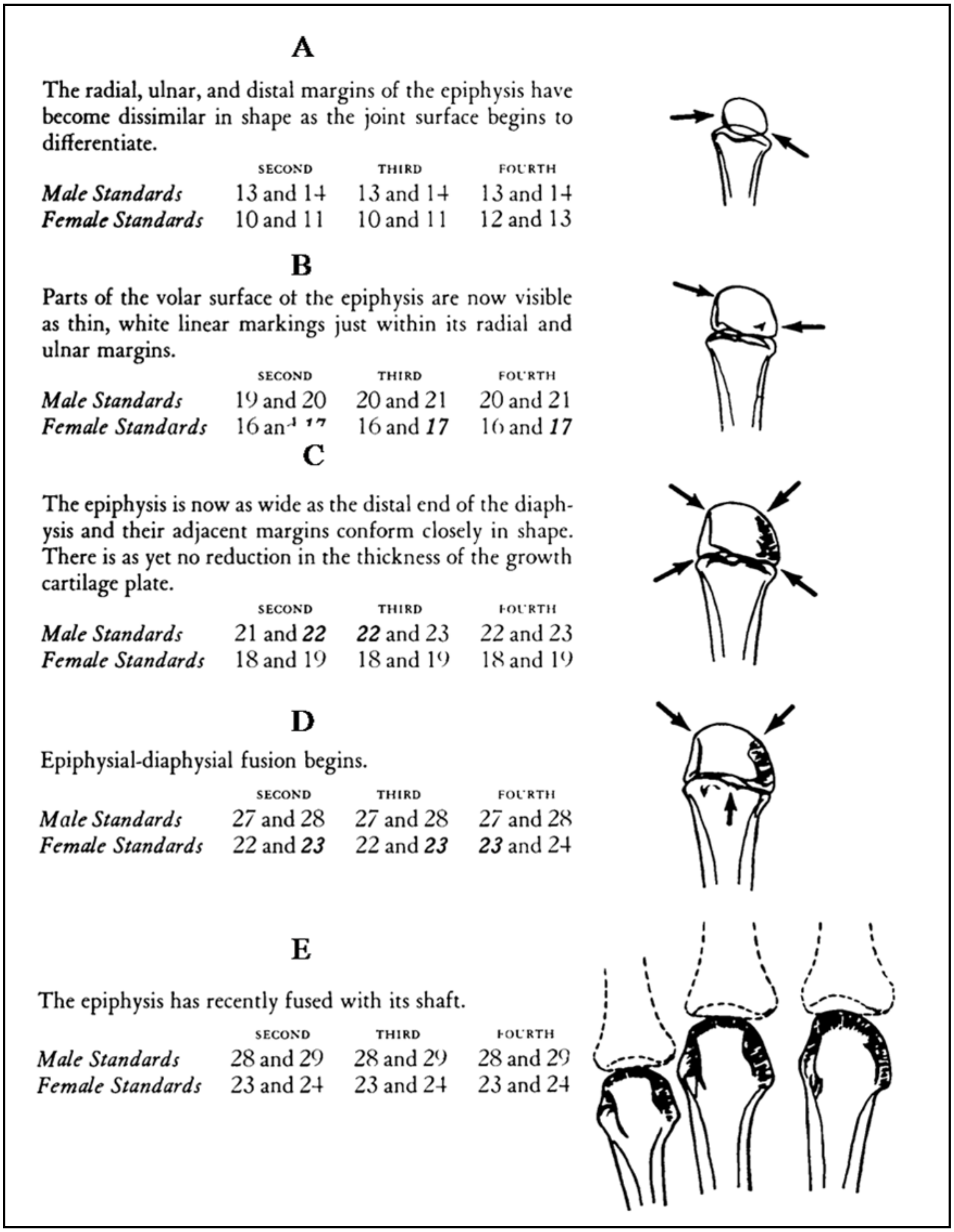
	PROXIMAL END OF METACARPAL I	TRAPEZIUM
Male Standards	**26** and 27	**26** and 27
Female Standards	**22** and 23	**22** and 23

I

Epiphysial-diaphysial fusion has been completed in the first metacarpal. The line of fusion may persist and remain visible in the radiograph for many years. (See the two plates following Standard 27.)

Male Standards	26 and 27
Female Standards	22 and 23

Figure 3.04 (d) Diagram showing termination of epiphyseal union in proximal epiphysis of the first metacarpal and adult morphology of trapezium.
(Image adapted from Greulich and Pyle, 1959)



A

The radial, ulnar, and distal margins of the epiphysis have become dissimilar in shape as the joint surface begins to differentiate.

	SECOND	THIRD	FOURTH
Male Standards	13 and 14	13 and 14	13 and 14
Female Standards	10 and 11	10 and 11	12 and 13

B

Parts of the volar surface of the epiphysis are now visible as thin, white linear markings just within its radial and ulnar margins.

	SECOND	THIRD	FOURTH
Male Standards	19 and 20	20 and 21	20 and 21
Female Standards	16 and ***17***	16 and ***17***	16 and ***17***

C

The epiphysis is now as wide as the distal end of the diaphysis and their adjacent margins conform closely in shape. There is as yet no reduction in the thickness of the growth cartilage plate.

	SECOND	THIRD	FOURTH
Male Standards	21 and ***22***	***22*** and 23	22 and 23
Female Standards	18 and 19	18 and 19	18 and 19

D

Epiphysial-diaphysial fusion begins.

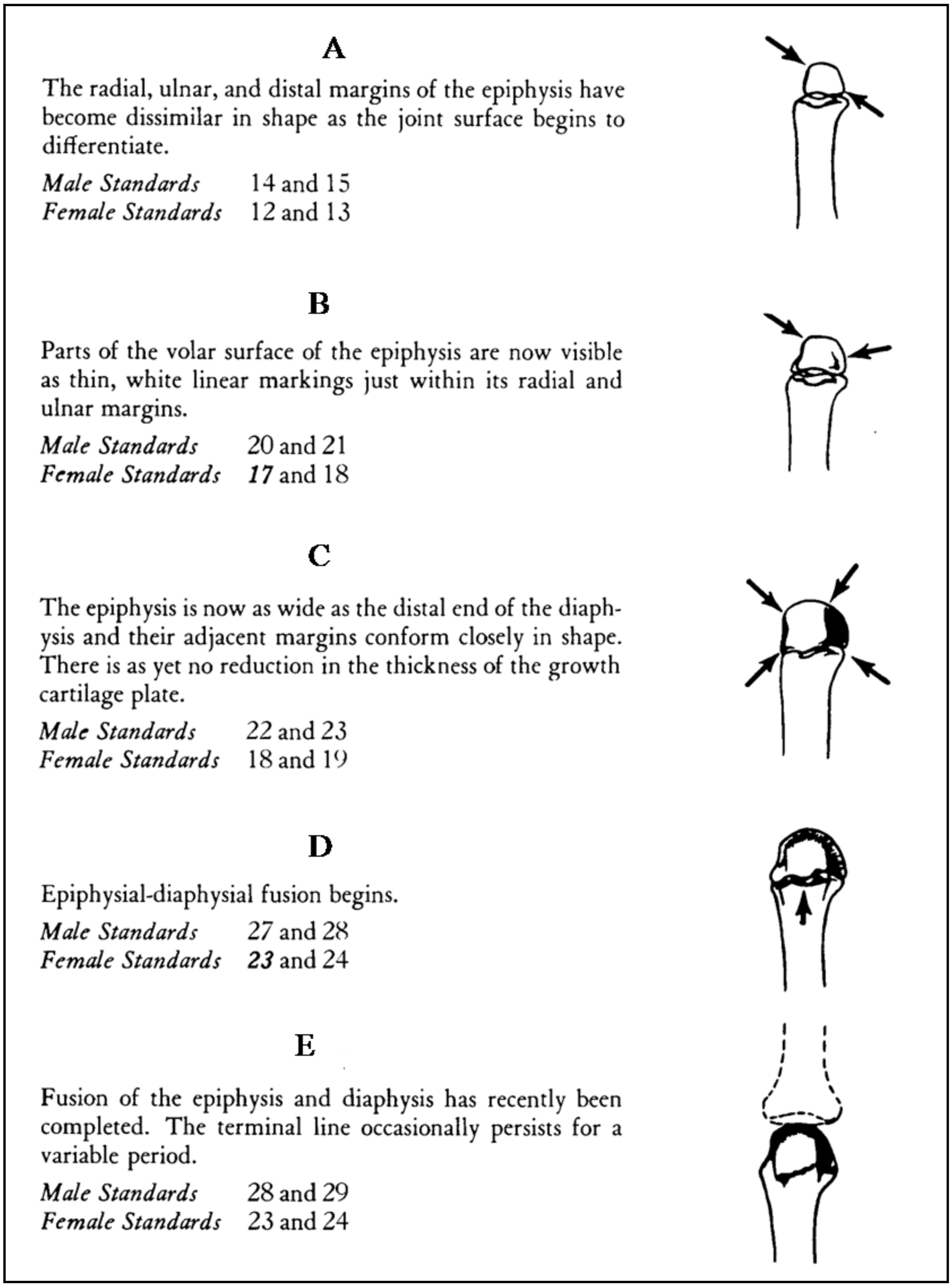
	SECOND	THIRD	FOURTH
Male Standards	27 and 28	27 and 28	27 and 28
Female Standards	22 and ***23***	22 and ***23***	***23*** and 24

E

The epiphysis has recently fused with its shaft.

	SECOND	THIRD	FOURTH
Male Standards	28 and 29	28 and 29	28 and 29
Female Standards	23 and 24	23 and 24	23 and 24

Figure 3.05 Diagram showing age related changes in distal epiphysis of second, third, fourth metacarpals: Skeletal age 10 years to 29 years for males and females.
(Image adapted from Greulich and Pyle, 1959)



A

The radial, ulnar, and distal margins of the epiphysis have become dissimilar in shape as the joint surface begins to differentiate.

Male Standards 14 and 15
Female Standards 12 and 13

B

Parts of the volar surface of the epiphysis are now visible as thin, white linear markings just within its radial and ulnar margins.

Male Standards 20 and 21
Female Standards ***17*** and 18

C

The epiphysis is now as wide as the distal end of the diaphysis and their adjacent margins conform closely in shape. There is as yet no reduction in the thickness of the growth cartilage plate.

Male Standards 22 and 23
Female Standards 18 and 19

D

Epiphysial-diaphysial fusion begins.

Male Standards 27 and 28
Female Standards ***23*** and 24

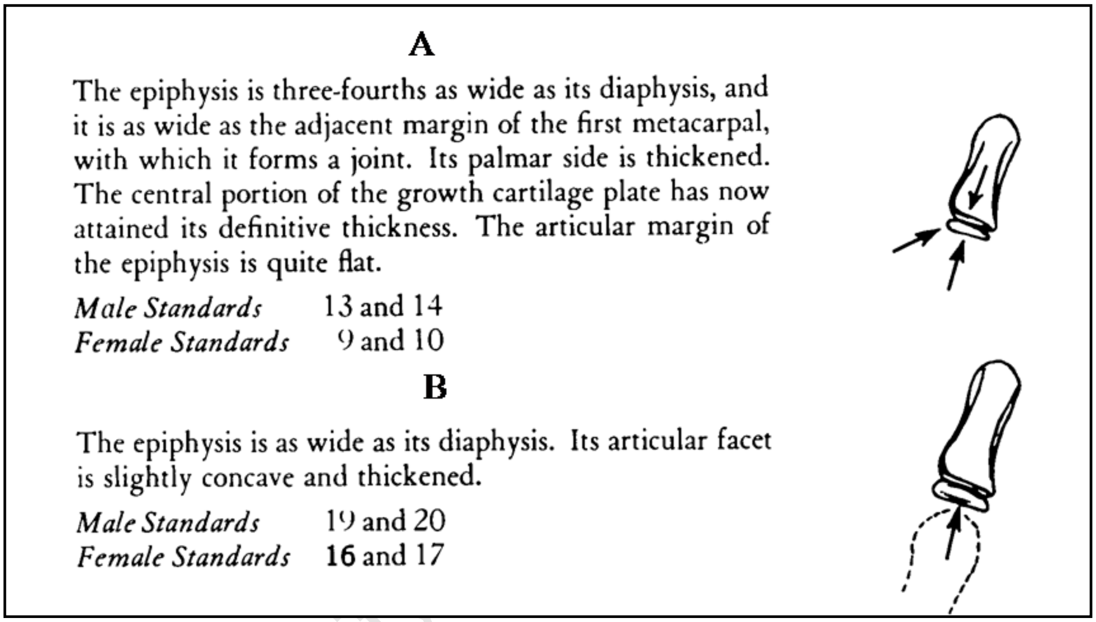
E

Fusion of the epiphysis and diaphysis has recently been completed. The terminal line occasionally persists for a variable period.

Male Standards 28 and 29
Female Standards 23 and 24

Figure 3.06 Diagram showing age related changes in distal epiphysis of fifth metacarpal: Males 14 years to 29 years and females 12 to 24 years.
(Image adapted from Greulich and Pyle, 1959)

The next feature to be examined was the size of the distal ends of the proximal phalanges in relation to their respective diaphyses. In addition the extent of fusion of these two parts was also noted. Refer to *Figures 3.07* to *3.09*. The arrows indicate the extent of these bones relative to each other and also the articular margins. The maturity indicators examined in the epiphyses of the middle phalanges (*Figure 3.10 (a)* and *(b)*) are similar to those observed when examining the proximal phalanges.



A

The epiphysis is three-fourths as wide as its diaphysis, and it is as wide as the adjacent margin of the first metacarpal, with which it forms a joint. Its palmar side is thickened. The central portion of the growth cartilage plate has now attained its definitive thickness. The articular margin of the epiphysis is quite flat.

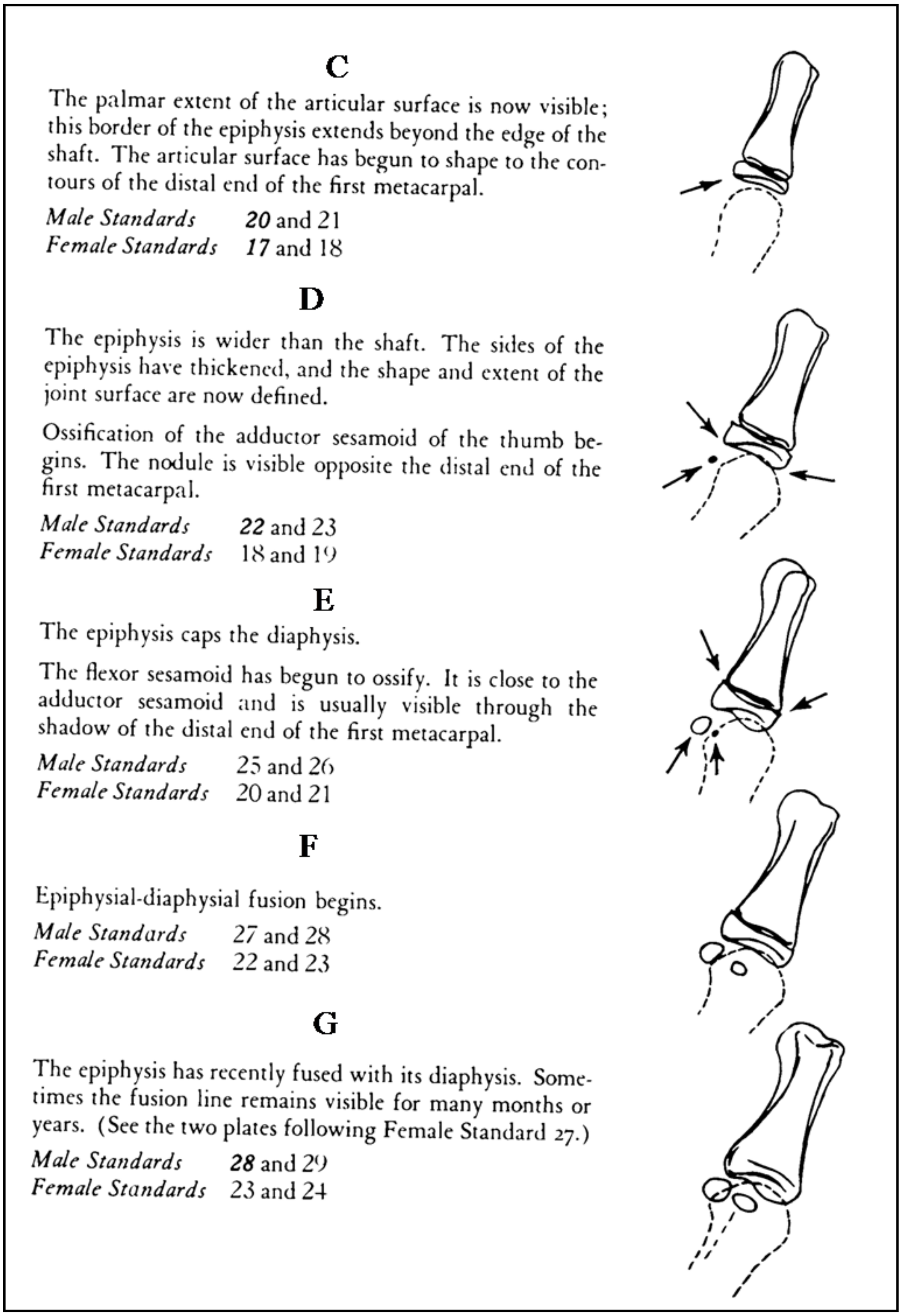
Male Standards	13 and 14
Female Standards	9 and 10

B

The epiphysis is as wide as its diaphysis. Its articular facet is slightly concave and thickened.

Male Standards	19 and 20
Female Standards	16 and 17

Figure 3.07 (a) Diagram showing age related changes in epiphysis of proximal phalanx of first digit: Males 13 years to 20 years and females 9 years to 17 years.
(Image adapted from Greulich and Pyle, 1959)



C

The palmar extent of the articular surface is now visible; this border of the epiphysis extends beyond the edge of the shaft. The articular surface has begun to shape to the contours of the distal end of the first metacarpal.

Male Standards	**20** and 21
Female Standards	**17** and 18

D

The epiphysis is wider than the shaft. The sides of the epiphysis have thickened, and the shape and extent of the joint surface are now defined.

Ossification of the adductor sesamoid of the thumb begins. The nodule is visible opposite the distal end of the first metacarpal.

Male Standards	**22** and 23
Female Standards	18 and 19

E

The epiphysis caps the diaphysis.

The flexor sesamoid has begun to ossify. It is close to the adductor sesamoid and is usually visible through the shadow of the distal end of the first metacarpal.

Male Standards	25 and 26
Female Standards	20 and 21

F

Epiphysial-diaphysial fusion begins.

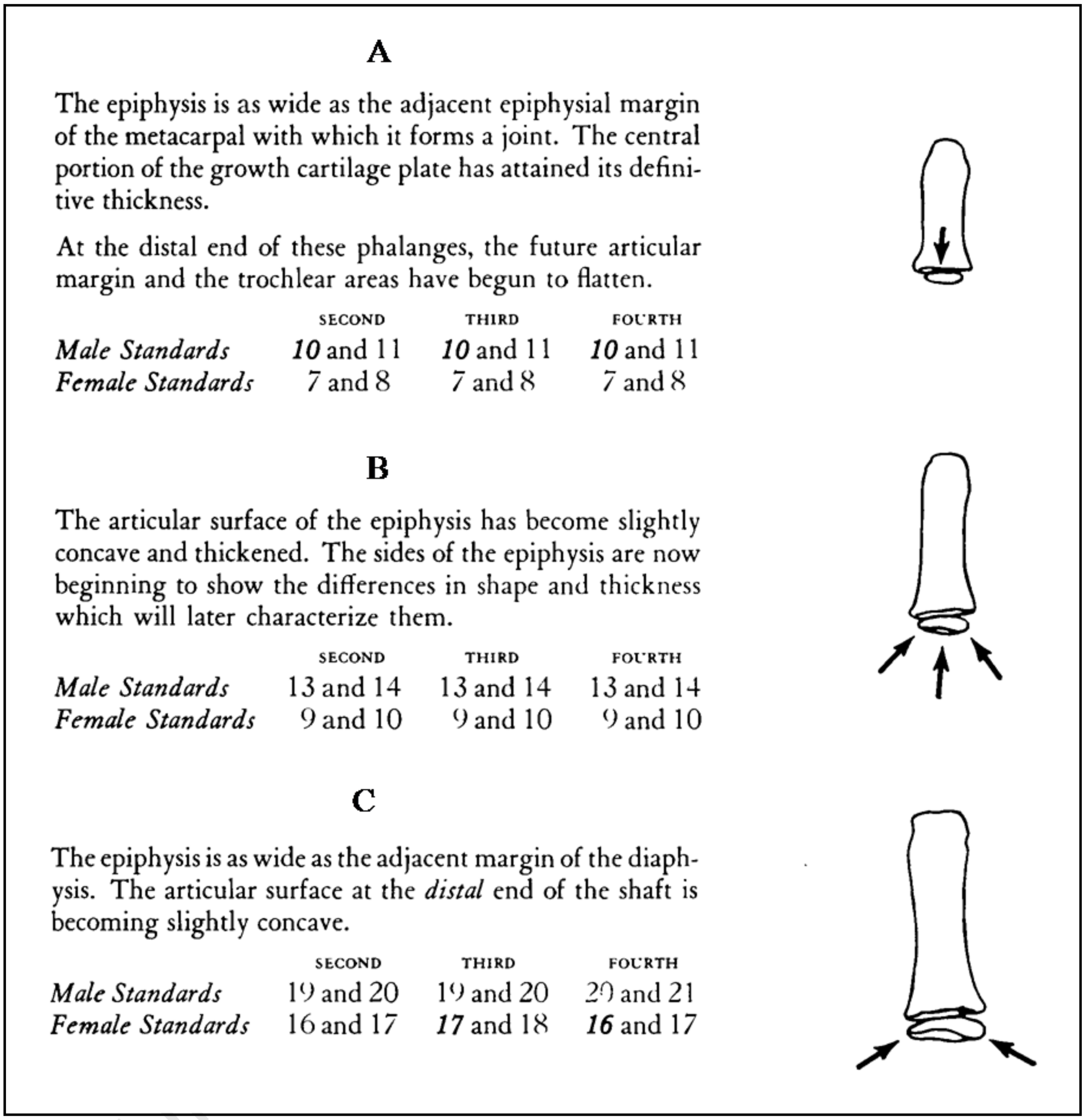
Male Standards	27 and 28
Female Standards	22 and 23

G

The epiphysis has recently fused with its diaphysis. Sometimes the fusion line remains visible for many months or years. (See the two plates following Female Standard 27.)

Male Standards	**28** and 29
Female Standards	23 and 24

Figure 3.07 (b) Diagram showing age related changes in epiphysis of proximal phalanx of first digit: Males 20 to 29 years and females 17 to 24 years.
(Image adapted from Greulich and Pyle, 1959)



A

The epiphysis is as wide as the adjacent epiphysial margin of the metacarpal with which it forms a joint. The central portion of the growth cartilage plate has attained its definitive thickness.

At the distal end of these phalanges, the future articular margin and the trochlear areas have begun to flatten.

	SECOND	THIRD	FOURTH
Male Standards	***10*** and 11	***10*** and 11	***10*** and 11
Female Standards	7 and 8	7 and 8	7 and 8

B

The articular surface of the epiphysis has become slightly concave and thickened. The sides of the epiphysis are now beginning to show the differences in shape and thickness which will later characterize them.

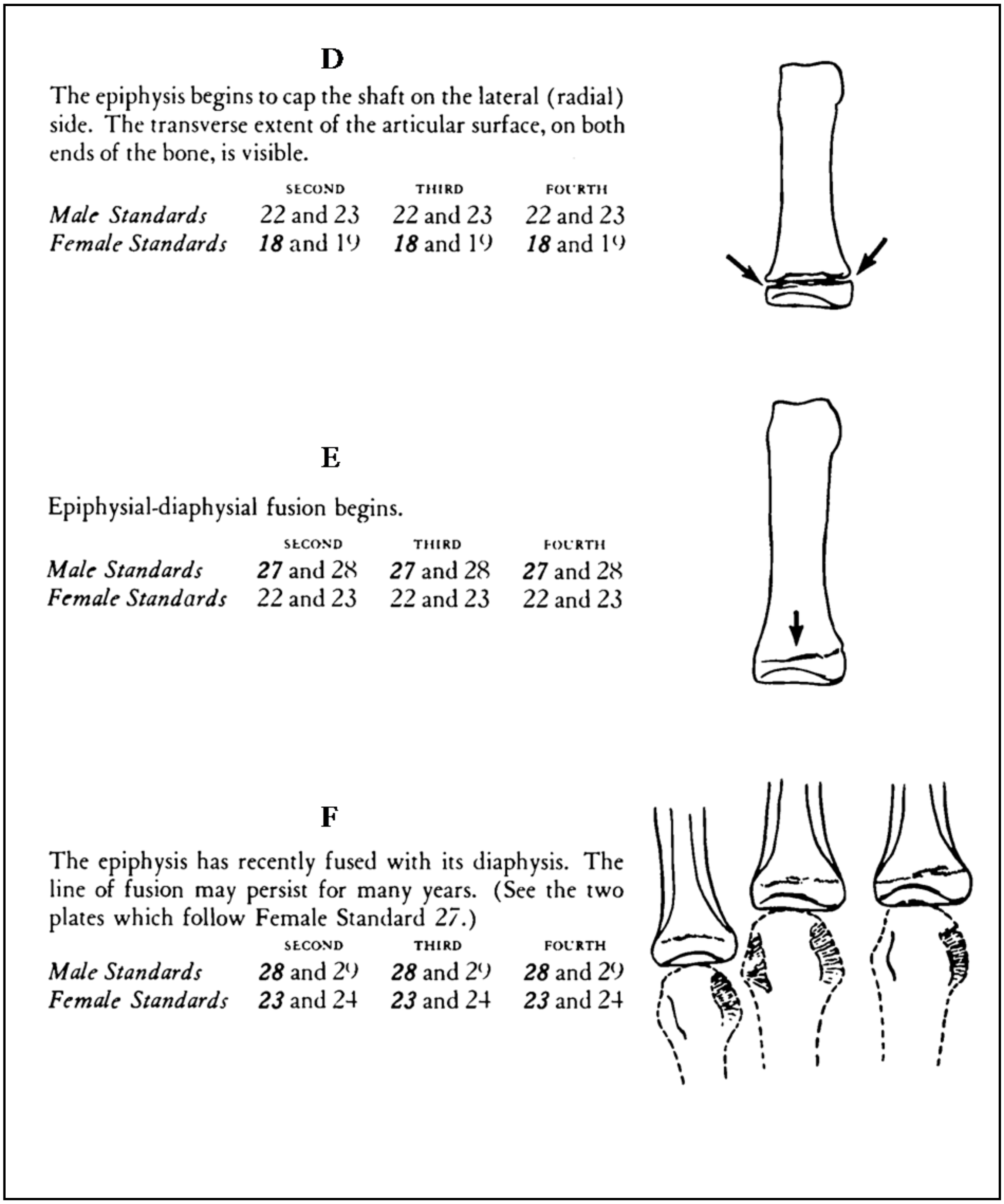
	SECOND	THIRD	FOURTH
Male Standards	13 and 14	13 and 14	13 and 14
Female Standards	9 and 10	9 and 10	9 and 10

C

The epiphysis is as wide as the adjacent margin of the diaphysis. The articular surface at the *distal* end of the shaft is becoming slightly concave.

	SECOND	THIRD	FOURTH
Male Standards	19 and 20	19 and 20	20 and 21
Female Standards	16 and 17	***17*** and 18	***16*** and 17

Figure 3.08 (a) Diagram showing early skeletal age related changes in epiphyses of proximal phalanges of the second, third, fourth digits for both males and females.
(Image adapted from Greulich and Pyle, 1959)



D

The epiphysis begins to cap the shaft on the lateral (radial) side. The transverse extent of the articular surface, on both ends of the bone, is visible.

	SECOND	THIRD	FOURTH
Male Standards	22 and 23	22 and 23	22 and 23
Female Standards	***18*** and 19	***18*** and 19	***18*** and 19

E

Epiphysial-diaphysial fusion begins.

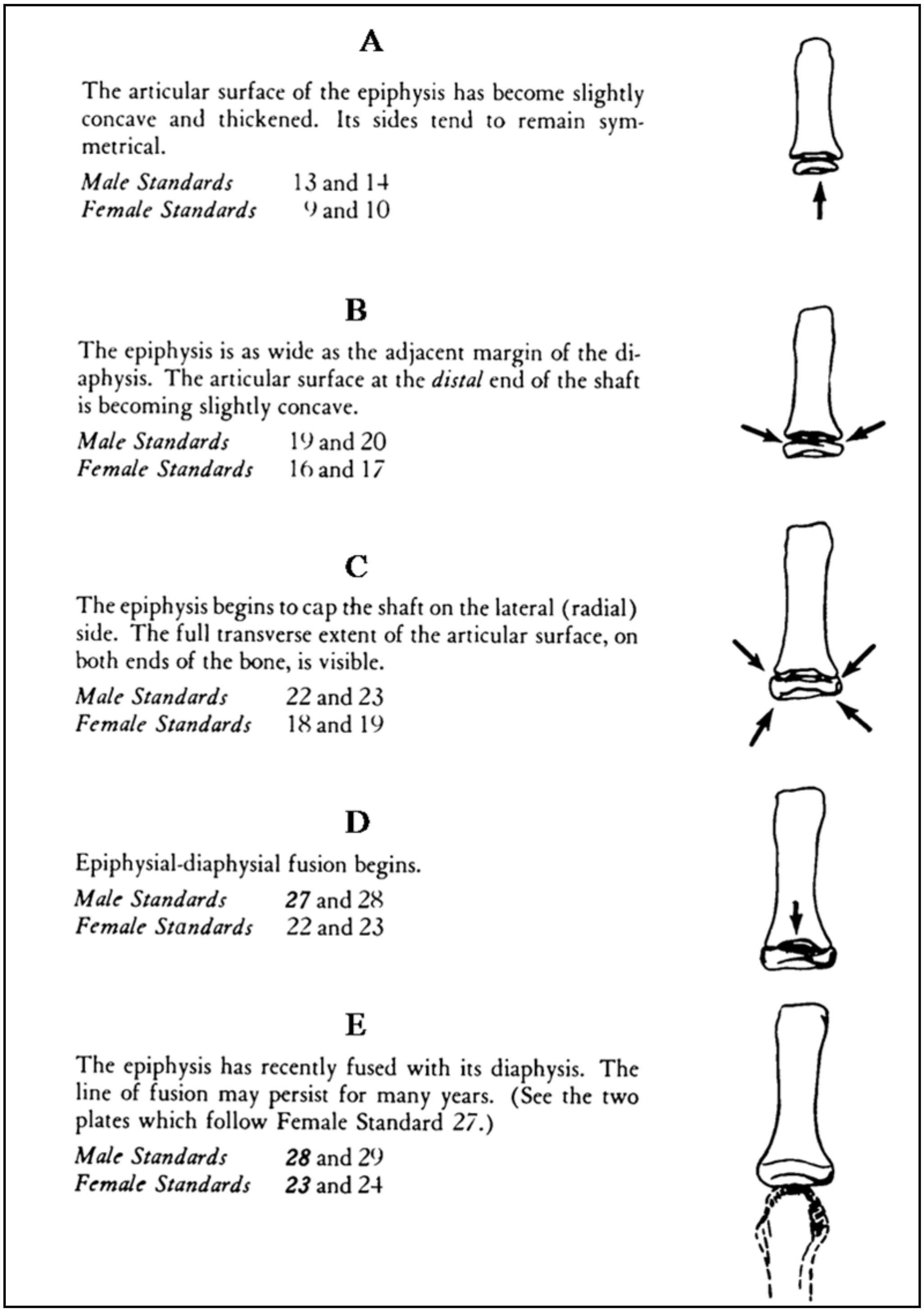
	SECOND	THIRD	FOURTH
Male Standards	***27*** and 28	***27*** and 28	***27*** and 28
Female Standards	22 and 23	22 and 23	22 and 23

F

The epiphysis has recently fused with its diaphysis. The line of fusion may persist for many years. (See the two plates which follow Female Standard 27.)

	SECOND	THIRD	FOURTH
Male Standards	***28*** and 29	***28*** and 29	***28*** and 29
Female Standards	***23*** and 24	***23*** and 24	***23*** and 24

Figure 3.08 (b) Diagram showing age related changes in epiphyses of proximal phalanges of the second, third, fourth digits for adult males and females.
(Image adapted from Greulich and Pyle, 1959)



A

The articular surface of the epiphysis has become slightly concave and thickened. Its sides tend to remain symmetrical.

Male Standards	13 and 14
Female Standards	9 and 10

B

The epiphysis is as wide as the adjacent margin of the diaphysis. The articular surface at the *distal* end of the shaft is becoming slightly concave.

Male Standards	19 and 20
Female Standards	16 and 17

C

The epiphysis begins to cap the shaft on the lateral (radial) side. The full transverse extent of the articular surface, on both ends of the bone, is visible.

Male Standards	22 and 23
Female Standards	18 and 19

D

Epiphysial-diaphysial fusion begins.

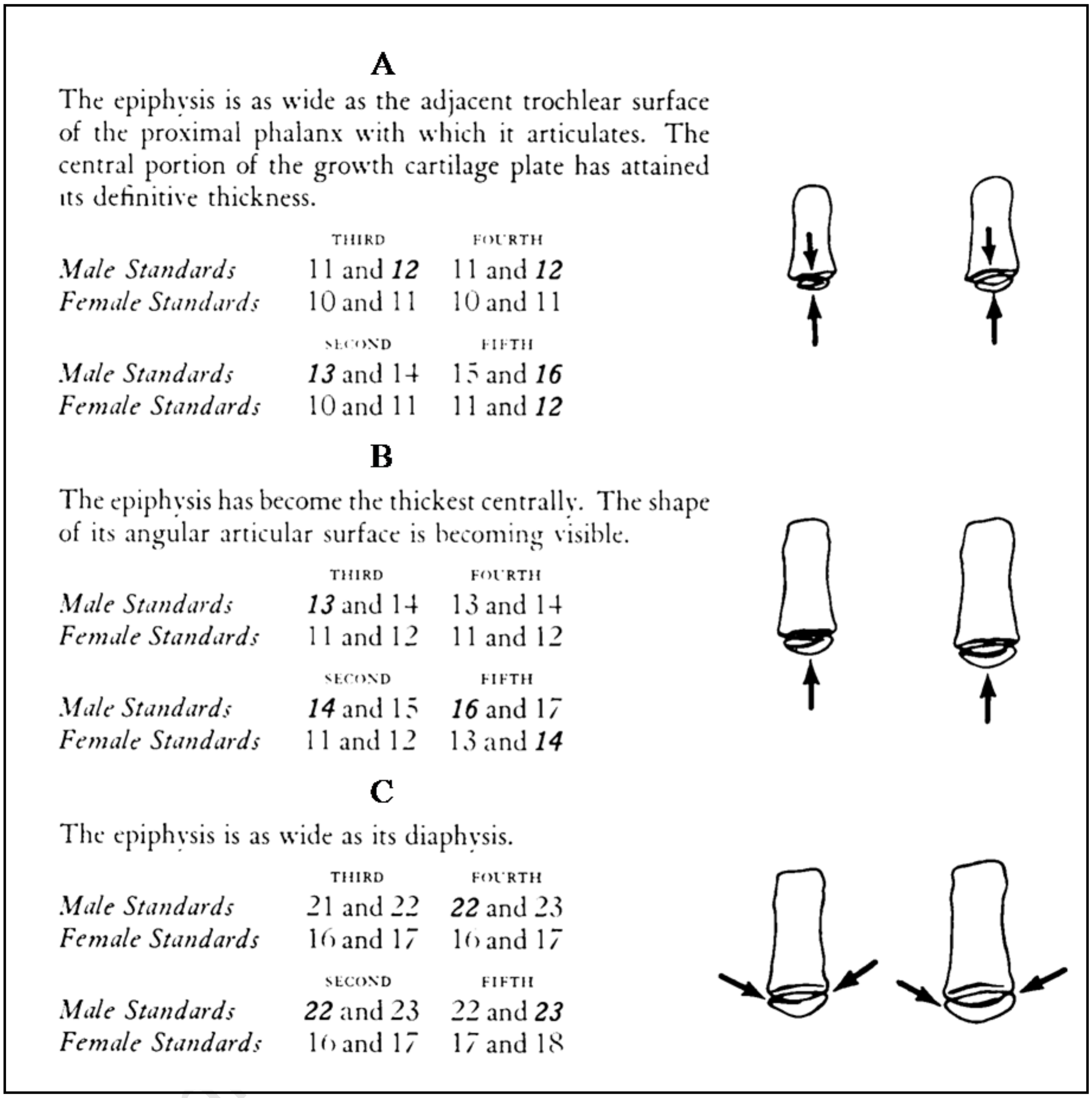
Male Standards	***27*** and 28
Female Standards	22 and 23

E

The epiphysis has recently fused with its diaphysis. The line of fusion may persist for many years. (See the two plates which follow Female Standard 27.)

Male Standards	***28*** and 29
Female Standards	***23*** and 24

Figure 3.09 Diagram showing age related changes in epiphyses of the proximal phalanx of the fifth digit: Males 13 to 29 years and females 9 to 24 years.
(Image adapted from Greulich and Pyle, 1959)



A

The epiphysis is as wide as the adjacent trochlear surface of the proximal phalanx with which it articulates. The central portion of the growth cartilage plate has attained its definitive thickness.

	THIRD	FOURTH
Male Standards	11 and ***12***	11 and ***12***
Female Standards	10 and 11	10 and 11

	SECOND	FIFTH
Male Standards	***13*** and 14	15 and ***16***
Female Standards	10 and 11	11 and ***12***

B

The epiphysis has become the thickest centrally. The shape of its angular articular surface is becoming visible.

	THIRD	FOURTH
Male Standards	***13*** and 14	13 and 14
Female Standards	11 and 12	11 and 12

	SECOND	FIFTH
Male Standards	***14*** and 15	***16*** and 17
Female Standards	11 and 12	13 and ***14***

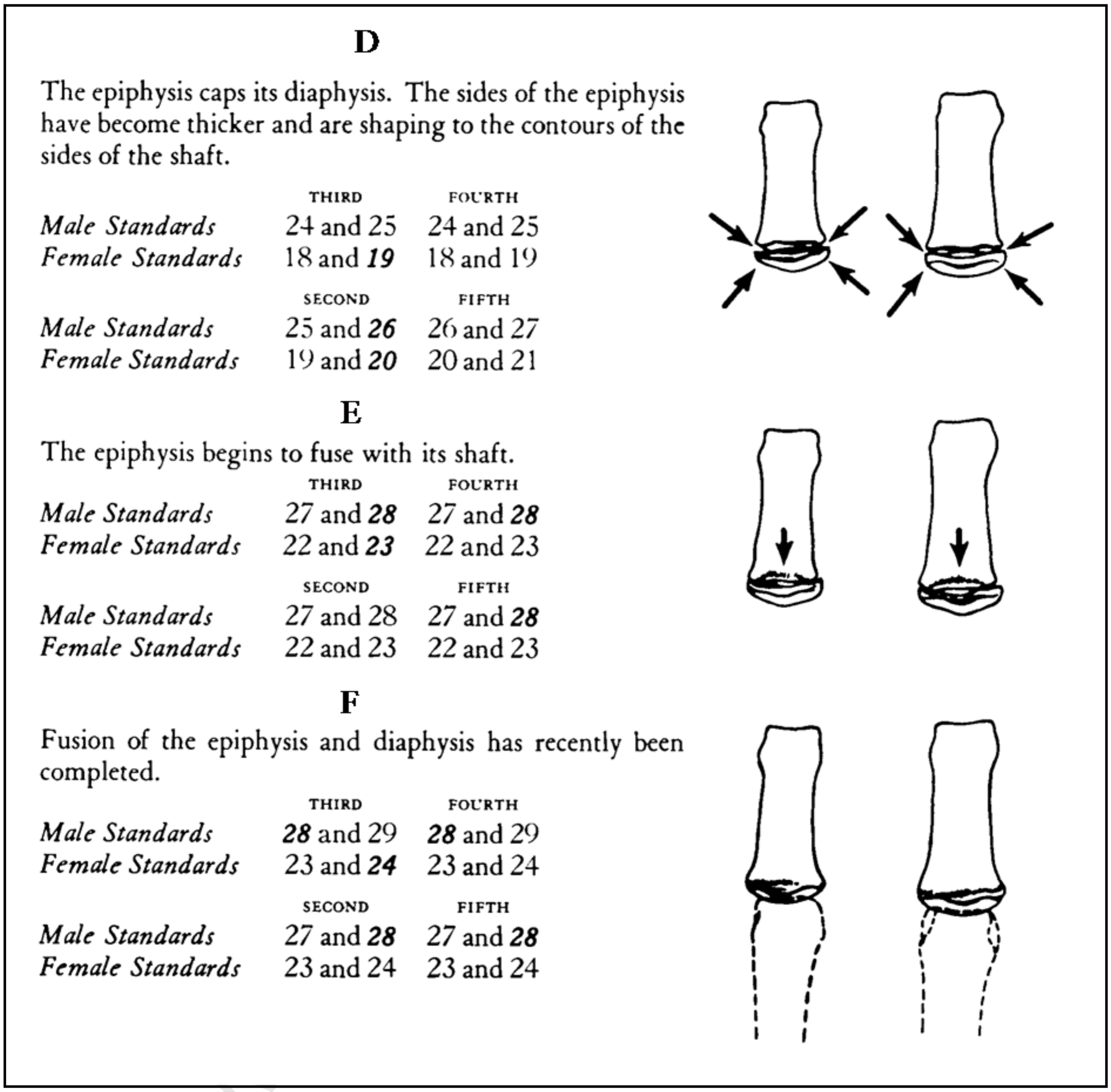
C

The epiphysis is as wide as its diaphysis.

	THIRD	FOURTH
Male Standards	21 and 22	***22*** and 23
Female Standards	16 and 17	16 and 17

	SECOND	FIFTH
Male Standards	***22*** and 23	22 and ***23***
Female Standards	16 and 17	17 and 18

Figure 3.10 (a) Diagram showing early skeletal age related changes in epiphyses of the second, third, fourth, fifth middle phalanges for both males and females.
(Image adapted from Greulich and Pyle, 1959)



D

The epiphysis caps its diaphysis. The sides of the epiphysis have become thicker and are shaping to the contours of the sides of the shaft.

	THIRD	FOURTH
Male Standards	24 and 25	24 and 25
Female Standards	18 and ***19***	18 and 19
	SECOND	FIFTH
Male Standards	25 and ***26***	26 and 27
Female Standards	19 and ***20***	20 and 21

E

The epiphysis begins to fuse with its shaft.

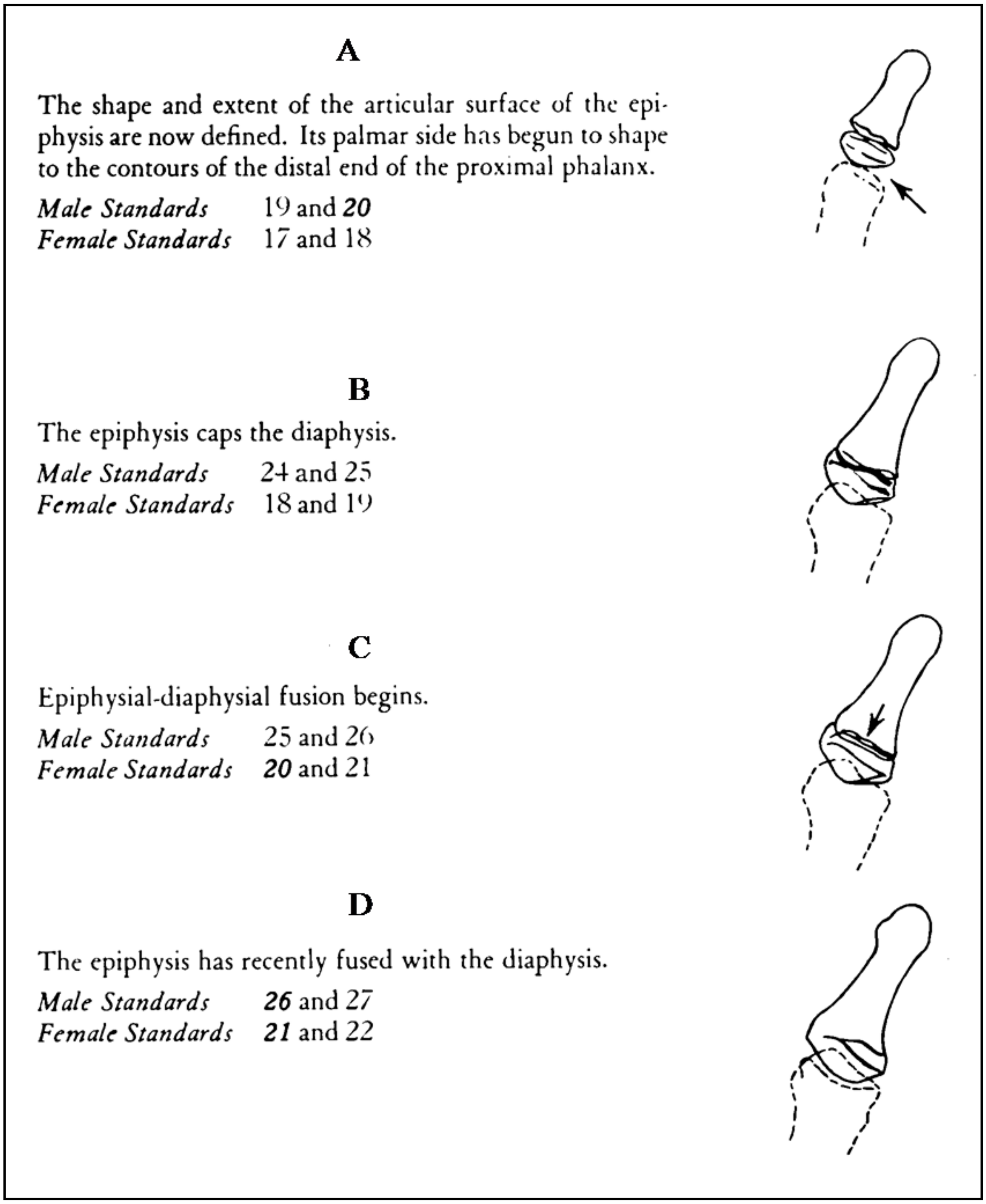
	THIRD	FOURTH
Male Standards	27 and ***28***	27 and ***28***
Female Standards	22 and ***23***	22 and 23
	SECOND	FIFTH
Male Standards	27 and 28	27 and ***28***
Female Standards	22 and 23	22 and 23

F

Fusion of the epiphysis and diaphysis has recently been completed.

	THIRD	FOURTH
Male Standards	***28*** and 29	***28*** and 29
Female Standards	23 and ***24***	23 and 24
	SECOND	FIFTH
Male Standards	27 and ***28***	27 and ***28***
Female Standards	23 and 24	23 and 24

Figure 3.10 (b) Diagram showing age related changes in epiphyses of the second, third, fourth, fifth middle phalanges of adult males and females.
(Image adapted from Greulich and Pyle, 1959)



A

The shape and extent of the articular surface of the epiphysis are now defined. Its palmar side has begun to shape to the contours of the distal end of the proximal phalanx.

Male Standards 19 and ***20***
Female Standards 17 and 18

B

The epiphysis caps the diaphysis.

Male Standards 24 and 25
Female Standards 18 and 19

C

Epiphysial-diaphysial fusion begins.

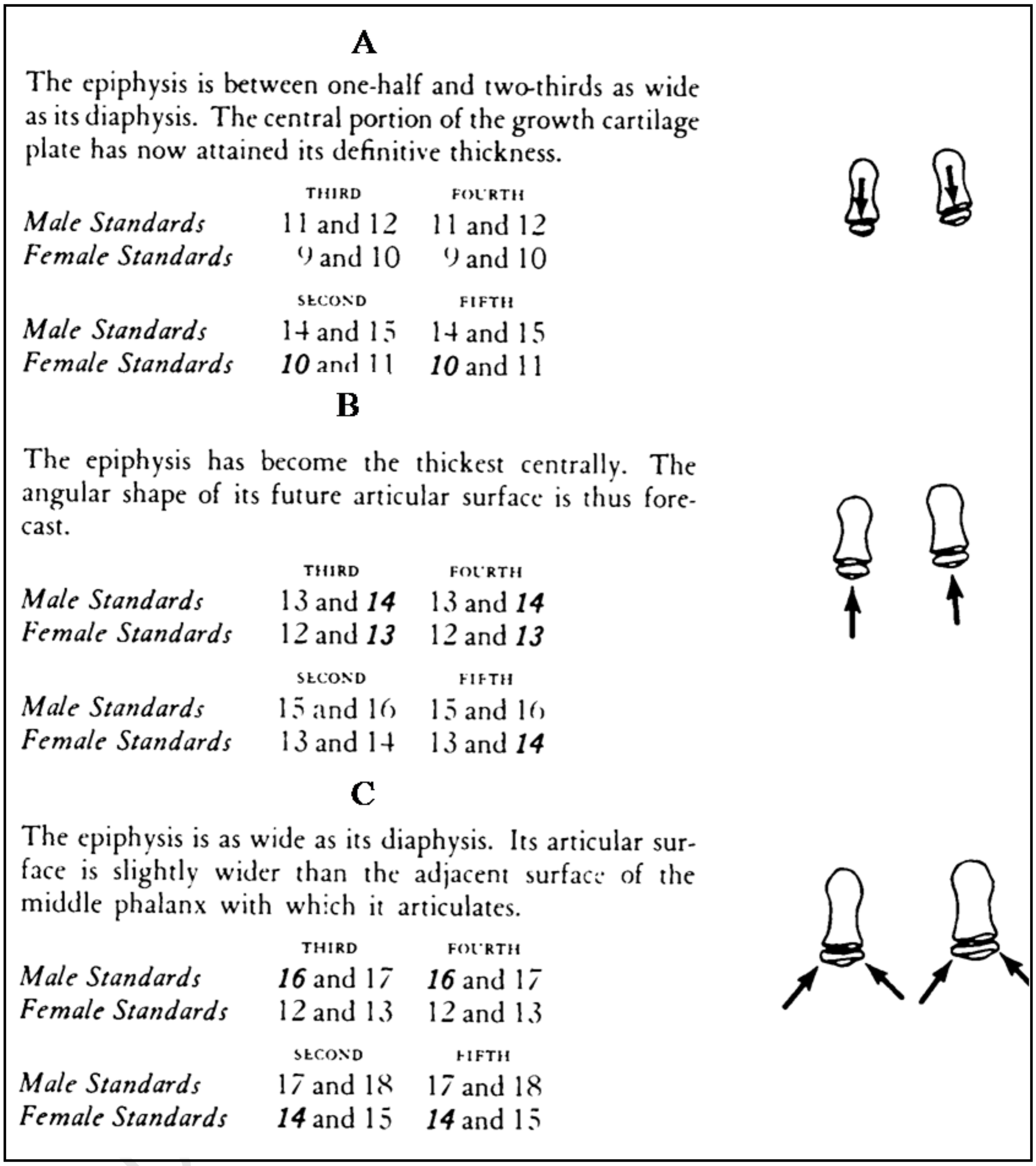
Male Standards 25 and 26
Female Standards ***20*** and 21

D

The epiphysis has recently fused with the diaphysis.

Male Standards ***26*** and 27
Female Standards ***21*** and 22

Figure 3.11 Diagram showing age related changes in epiphysis of the distal phalanx of the thumb: Males 19 to 27 years and females 17 to 22 years.
(Image adapted from Greulich and Pyle, 1959)



A

The epiphysis is between one-half and two-thirds as wide as its diaphysis. The central portion of the growth cartilage plate has now attained its definitive thickness.

	THIRD	FOURTH
Male Standards	11 and 12	11 and 12
Female Standards	9 and 10	9 and 10

	SECOND	FIFTH
Male Standards	14 and 15	14 and 15
Female Standards	***10*** and 11	***10*** and 11

B

The epiphysis has become the thickest centrally. The angular shape of its future articular surface is thus forecast.

	THIRD	FOURTH
Male Standards	13 and ***14***	13 and ***14***
Female Standards	12 and ***13***	12 and ***13***

	SECOND	FIFTH
Male Standards	15 and 16	15 and 16
Female Standards	13 and 14	13 and ***14***

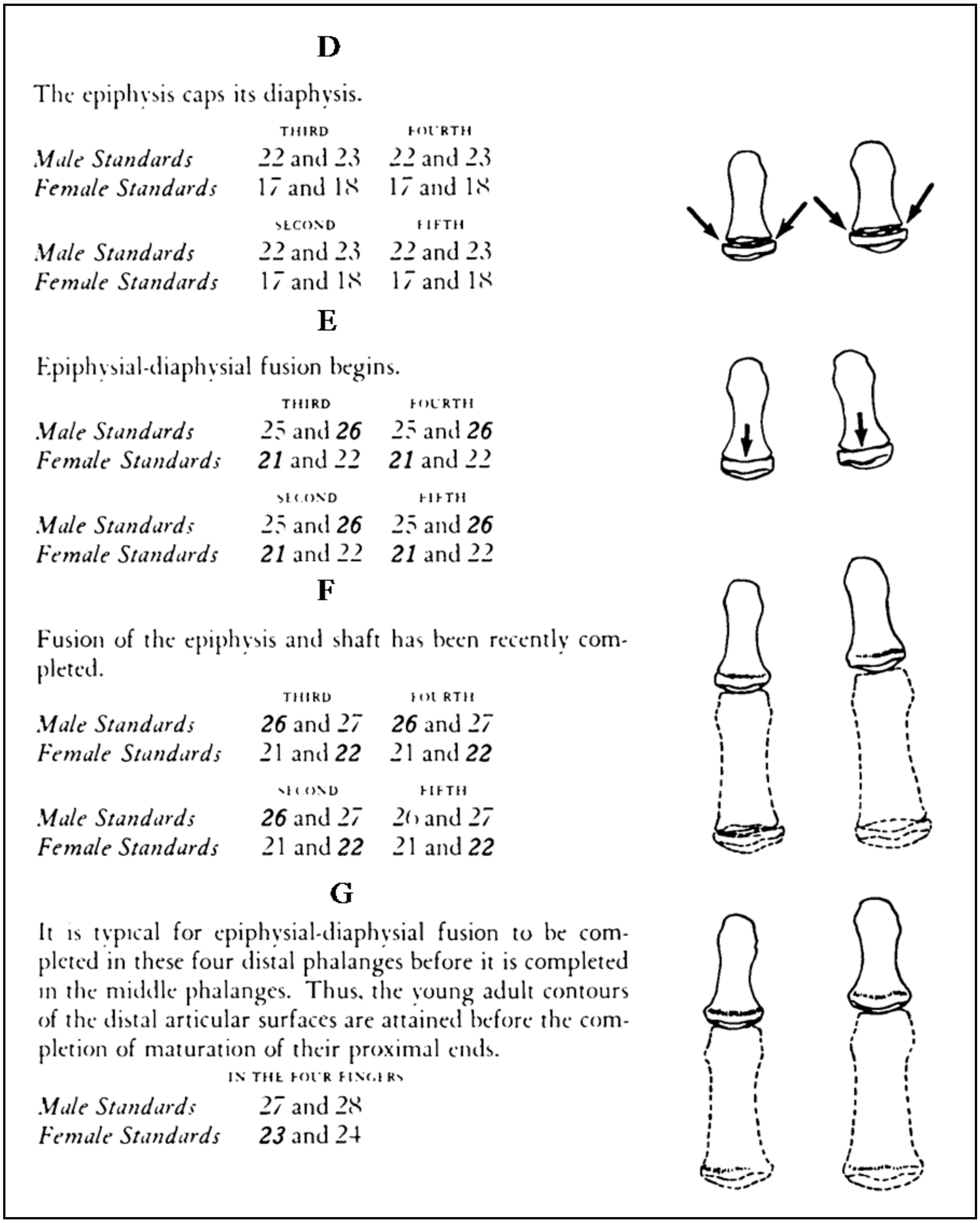
C

The epiphysis is as wide as its diaphysis. Its articular surface is slightly wider than the adjacent surface of the middle phalanx with which it articulates.

	THIRD	FOURTH
Male Standards	***16*** and 17	***16*** and 17
Female Standards	12 and 13	12 and 13

	SECOND	FIFTH
Male Standards	17 and 18	17 and 18
Female Standards	***14*** and 15	***14*** and 15

Figure 3.12 (a) Diagram showing age related changes in epiphyses of the second, third, fourth, fifth distal phalanges: Males 11 to 18 years and females 9 to 15 years.
(Image adapted from Greulich and Pyle, 1959)



D

The epiphysis caps its diaphysis.

	THIRD	FOURTH
Male Standards	22 and 23	22 and 23
Female Standards	17 and 18	17 and 18

	SECOND	FIFTH
Male Standards	22 and 23	22 and 23
Female Standards	17 and 18	17 and 18

E

Epiphysial-diaphysial fusion begins.

	THIRD	FOURTH
Male Standards	25 and **26**	25 and **26**
Female Standards	**21** and 22	**21** and 22

	SECOND	FIFTH
Male Standards	25 and **26**	25 and **26**
Female Standards	**21** and 22	**21** and 22

F

Fusion of the epiphysis and shaft has been recently completed.

	THIRD	FOURTH
Male Standards	**26** and 27	**26** and 27
Female Standards	21 and **22**	21 and **22**

	SECOND	FIFTH
Male Standards	**26** and 27	26 and 27
Female Standards	21 and **22**	21 and **22**

G

It is typical for epiphysial-diaphysial fusion to be completed in these four distal phalanges before it is completed in the middle phalanges. Thus, the young adult contours of the distal articular surfaces are attained before the completion of maturation of their proximal ends.

	IN THE FOUR FINGERS
Male Standards	27 and 28
Female Standards	**23** and 24

Figure 3.12 (b) Diagram showing age related changes in epiphyses of the second, third, fourth, fifth distal phalanges in relation to the middle phalanges for adult males and females.
(Image adapted from Greulich and Pyle, 1959)

3.2.2 Analysis of Hand Radiographs: Schmidt *et al.* Method

The authors of this method devised a scale of ossification which was divided into 5 stages. The original application was to the medial epiphysis of the clavicle. This grading system was later applied to the ossification of the wrist and hand bones. Schmidt *et al.* (2008) described the following stages of ossification:

Stage 1: Non-ossified epiphysis
Stage 2: Discernable ossification centre of epiphysis
Stage 3: Partial fusion of epiphysis
Stage 4: Complete fusion
Stage 5: Complete fusion with no evidence of metaphyseal line.

The figures below (*Figures 3.13* to *3.16*) illustrate the appearance of the stages of ossification as defined and described in original paper by Schmeling *et al.* (2004) in part "a" of each figure and accompanied by what it would look like in a hand radiograph part "b" of each figure. The illustrations in part "b" are radiographs used in the current study.

Figure 3.13 (a) Plain chest radiograph showing stage 2 ossification of the right medial clavicular epiphysis: Male of chronological age 17.9 years. The arrow shows the non-ossified epiphyseal cartilage. (Image adapted from Schmeling et *al.,* 2004)

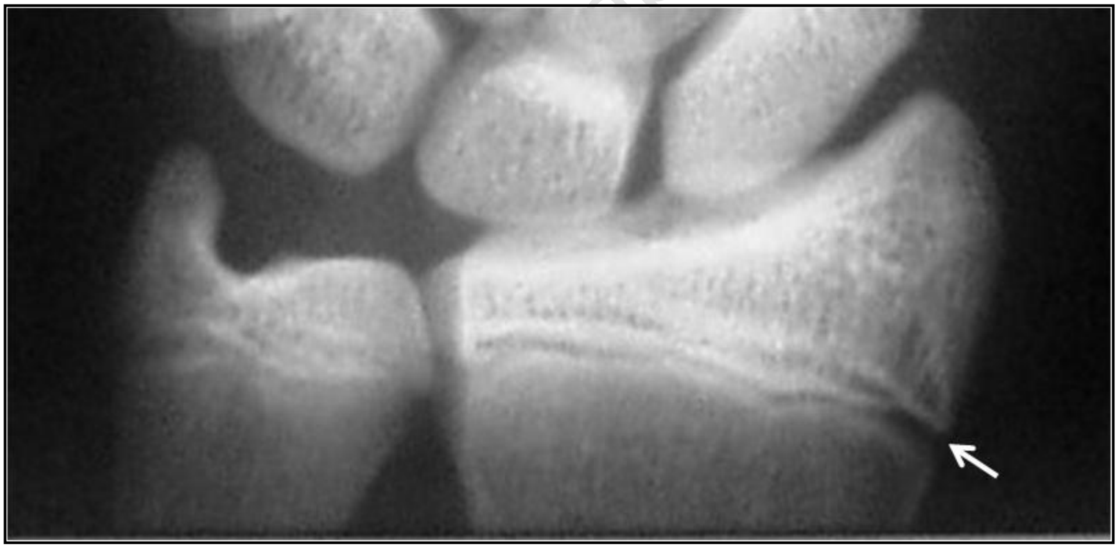


Figure 3.13 (b) Radiograph showing stage 2 ossification of left wrist: Male (GSM151) chronological age 18.9 years. Arrow shows the non-ossified epiphyseal cartilage of the radius.

Figure 3.14 (a) Plain chest radiograph showing stage 3 ossification of a right medial clavicular epiphysis: Female chronological age 20.3 years. The arrow shows the partially ossified epiphyseal cartilage. (Image adapted from Schmeling et *al.,* 2004)

Figure 3.14 (b) Radiograph showing stage 3 ossification of the left wrist: Male (GSM118) chronological age 17.3 years. The arrow shows the partially ossified epiphyseal cartilage of the radius.

Figure 3.15 (a) Plain chest radiograph showing stage 4 ossification of the medial clavicular epiphysis: Male of chronological age 30.0 years. The arrow shows the epiphyseal scar.
(Image adapted from Schmeling et *al.*, 2004)

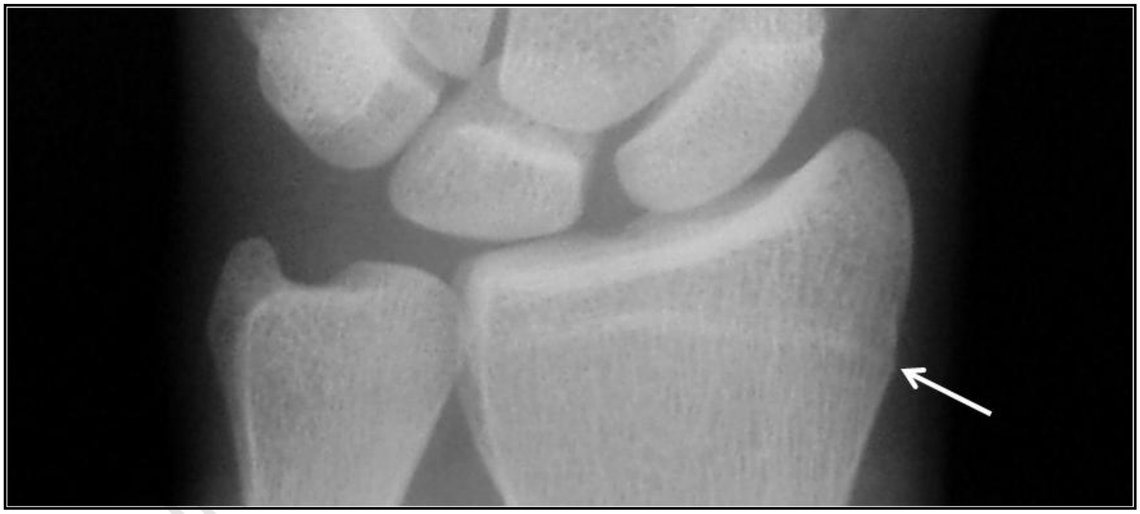


Figure 3.15 (b) Radiograph showing stage 4 ossification of the wrist: Male (GSM071) chronological age 16.3 years. The arrow shows the epiphyseal scar on the radius.

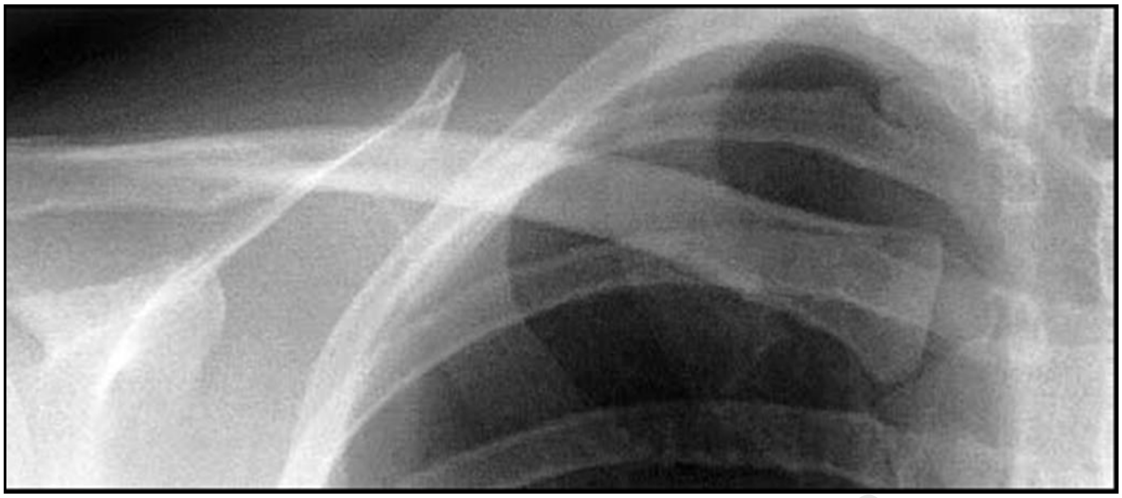


Figure 3.16 (a) Plain chest radiograph showing stage 5 ossification of the medial clavicular epiphysis: Female chronological age 30.3 years. The epiphyseal scar has disappeared.
(Image adapted from Schmeling et *al.,* 2004)

Figure 3.16 (b) Radiograph showing stage 5 ossification at the wrist: Male (GSM122) of chronological age 19.2 years. The arrow with the dashed line indicates where the epiphyseal scar has disappeared.

This method was used in conjunction with the GP atlas method, to establish the youngest age at which epiphyseal non-fusion was observed and the oldest age at which partial fusion and complete fusion could be observed.

3.3 Statistical Analysis

3.3.1 Inter- and Intra- observer Error Analysis

Skeletal age estimates using the Greulich and Pyle Atlas Method were performed three times, twice by the primary researcher and once by a second researcher, familiar with the technique. The time difference between the first and second estimates was one month. The services of the second researcher were employed during that month. At each reading, the results of the previous estimate were not made available to any of the researchers to prevent bias in their estimates.

The first level analysis was to test for significant difference between the first set of skeletal age estimates and the second set made by the primary researcher. This required non-parametric analysis as the sample distribution did not follow a normal distribution pattern. The next level analysis involved testing for a significant difference between the primary researcher's estimates and the second researcher. The Mann-Whitney test was used to analyze the first and second estimates and the Kruskal-Wallis test was used to analyze the difference between all three estimates. All the sets of estimates were treated as independent groups.

The estimates generated by the primary researcher were tested for any significant difference. A third estimate was generated by an independent researcher, referred to in this study as the second researcher. A randomly selected sample of 27 female subjects and 57 male subjects were re-analysed by the second researcher and a test for significance was applied to all three estimates. Where there was a high difference, the radiograph in question was re-examined and the age estimate was based on a consensus.

3.3.2 Analysis of Difference between Skeletal Age and Chronological Age

In terms of analysis of the age estimates, the mean chronological ages of the subjects were compared to the mean skeletal ages as determined while using the GP technique. Results were grouped according to sex and age for this analysis. Then the differences between the chronological age and the skeletal age (mean chronological age – mean skeletal age) was calculated. A Mann-Whitney test was performed on these results to test for significance.

A correlation between the chronological age and the GP skeletal age was performed using a non-parametric Spearman Rank Analysis which analyses the association between two variables.

The strength of agreement between the chronological age and skeletal ages was tested using the Bland and Altman plot (Bland and Altman, 1986). In this case it was used to determine whether the GP method is measuring ‘age’ as accurately as the chronological age. This is in addition to the association analysis which is used to detect whether two variables are related but does not necessarily determine if they are measuring the same thing. That is to say that the Bland-Altman plot indicates a good agreement between chronological age, determined from the date of birth, and skeletal age as determined by the GP method. The results of all the analyses were summarized and then compared to the results from other populations on which the GP method was applied.

CHAPTER 4: RESULTS

4.1 General Distribution of the Sample

The results of the various analyses are presented in this chapter and arranged from the more basic analyses to more complex ones.

The sample was made up of 131 male subjects and 32 female subjects the general distribution of which is shown in *Table 4.01* in which the sample is grouped according to the radiographs which were analysed.

It can be seen that there were more radiographs of the right hand and wrist than of the left hand but testing using the *Chi*-Square (χ^2) values for proportions revealed that the result was not significant at the 0.05 level (χ^2=0.026; degrees of freedom = 1). Greulich and Pyle (1959) specify the use of the left hand for age estimation analysis. Therefore individuals represented by both left and right hand radiographs were counted as single individuals and age estimation analysis was performed on the left hand unless it was too damaged or the radiographs were unclear or incomplete.

Table 4.01 Distribution Profile of the sample by sex and side.

Side	Male	Female
Left	61	16
Right	81	20
Total number of hands	142	36
Paired	11	4
Total number of individuals*	131	32

**value includes only one side of pairs.*

4.1.1 Age and Sex Distribution of the Sample

Table 4.02 below shows the age distribution of the sample. The age groups used follow those used in the Greulich and Pyle Radiographic Atlas of Skeletal Development of the Hand and Wrist. This is because GP used whole year categories from the age of 5 years as it was observed that skeletal development was not proceeding rapidly enough to warrant half-year categories. However at puberty, skeletal development tends to proceed quite rapidly that much is changed in the space of one year. Thus GP in the 1959 edition, found it necessary to introduce half-year categories between the ages 12 and 13, 13 and

14, 15 and 16 years in order to give more precise estimations of age during this phase of development. However there were no 12 year olds included in the current sample.

From the table it is evident that there were notably more male than female research subjects in this study. This is a phenomenon that may be related to the higher frequency of visits to the Hand Clinic by male individuals compared to female individuals over a specific period of time. It may also be reflective of the higher number of traumatic incidents that males encounter compared to females (See Record of Trauma in Appendix E). When tested for significance using the χ^2 Test for Proportions it was found that the proportion of males compared to females in this sample, was significant at the 0.05 level (χ^2=60.13; degrees of freedom =1) meaning that there were significantly more males than females in this research sample.

Table 4.02 Age Distribution of the Sample using Greulich & Pyle Age Groups.

Greulich & Pyle Age (years)	Male	Female	Total
13	4	1	5
13.5	4	4	8
14	9	3	12
15	4	1	8
15.5	6	3	6
16	16	5	21
17	20	4	24
18	19	3	22
19	22	4	26
20	13	2	15
21	14	2	16
Total	131	32	163

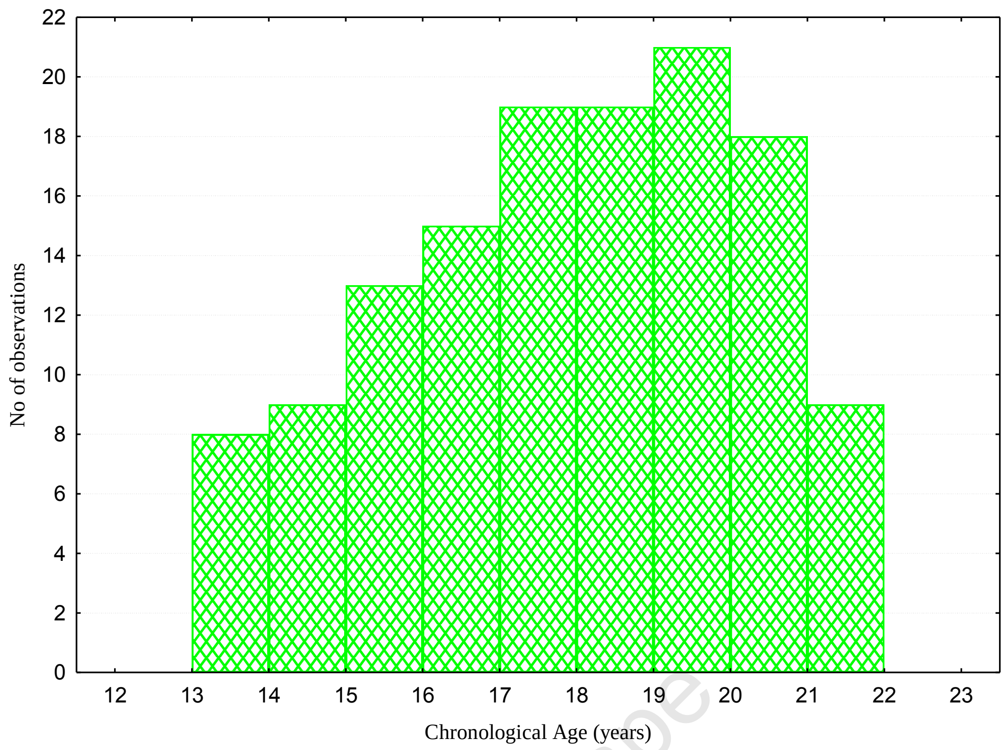


Figure 4.01 Age distribution histogram of the male sample. Youngest age was 13.0 years and the oldest age was 21.9 years.

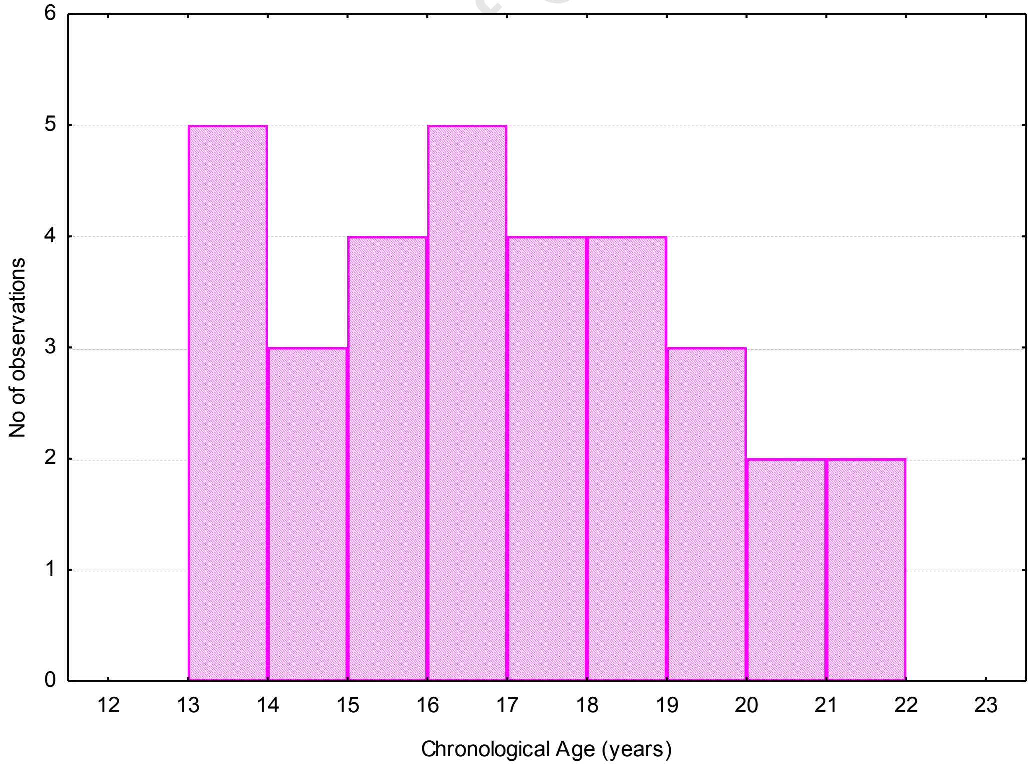


Figure 4.02 Age distribution histogram for the female sample. The youngest individual had a chronological age of 13.1 years and the oldest, 21.6 years.

4.2 Skeletal Age Analysis 1: Greulich & Pyle Results

4.2.1 Whole Hand Analyses

In this section, the results of the skeletal age analysis of the whole hand using the GP Atlas method are presented.

4.2.1.1 Intra- and Inter- observer Error Analysis

As mentioned in *Chapter 3 section 3.3.1*, the skeletal age estimates were carried out three times. Twice by the primary researcher and a small sample was chosen at random and examined once more by an independent second researcher, Ms Belinda Roff. Ms Roff is familiar with the application of the GP atlas method to estimate skeletal age. The two sets of estimates taken by the primary researcher were tested for significance using the Mann-Whitney test and the resulting *p*-values of 0.875 and 0.969 for the female and male samples respectively was reported. These values show that there are no significant differences between the first estimate and the second estimate. This result is consistent with a low intra-observer error in the evaluation of skeletal age on consecutive analyses made by the primary researcher.

In order to evaluate the degree of inter-observer error, the Kruskal-Wallis test was applied to the two estimates taken by the primary researcher together with the random sample of estimates taken by the second researcher. 27 radiographs from the female sample and 57 from the male samples were selected for analysis by the independent researcher. A *p*-value of 0.909 was recorded for the skeletal age estimates recorded for the male sample and the estimates for the female sample was *p*-value 0.913. Both values reflect a low level of inter-observer bias at the 0.05 level.

The mean skeletal age estimation values per chronological age group for each researcher are not shown as the sample sizes of these age groups did not satisfy the conditions required to perform a t-test. It is advised that a large sample size will give a more reliable result when applying the t-test (Howell, 2004). Thus a more valid result was obtained when the t-test was performed on the male and female samples as a whole.

The final skeletal age estimate was generated by using the average of the first and second estimates and will, from this point forward, be referred to as the Skeletal Age or SA while the chronological age will be referred to as CA.

4.2.1.2 Difference between Skeletal Age and Chronological Age for the Whole Hand

Once the radiographs had been aged using the GP method, the estimated Skeletal Age (SA) was compared to the known chronological age (CA). This was done for the samples grouped according to the SA as determined by the GP method which records a maximum age of 18 years for females and 19 years for males using the bones of the hand and wrist. The known CA's for each of the SA single year categories were averaged and the results are presented below in *Table 4.03*.

Table 4.03 Chronological Age Grouped by Skeletal Age

CA	SA				Difference (CA-SA)	
	N	Mean	SD	CV	Years	Months
Males						
13	4	12.3	1.6	13.3	0.7	8.4
13.5	4	13.3	2.0	14.9	0.2	2.4
14	9	14.4	1.9	12.9	-0.4	-4.8
15	4	14.5	0.7	4.6	0.5	6.0
15.5	6	15.1	1.1	7.1	0.4	4.8
16	16	16.5	1.4	8.4	-0.5	-6.0
17	20	17.3	1.2	6.8	-0.3	-3.6
18	19	17.6	1.2	6.9	0.4	4.8
19	22	18.0	1.0	5.5	1.0	12.0
20	13	18.6	0.7	3.8	1.4	16.8
21	14	18.2	1.0	5.5	2.8	33.6
Total	104	15.4	1.3	8.4	0.6	6.8
Females						
13	1	12.0	*	*	1.0	12.0
13.5	4	15.0	0.7	4.9	-1.5	-18.0
14	3	12.5	0.8	6.4	1.5	18.0
15	1	13.0	*	*	2.0	24.0
15.5	3	15.3	1.3	8.2	0.2	2.4
16	5	15.7	1.3	8.0	0.3	3.6
17	4	16.1	1.5	9.3	0.9	10.8
18	3	16.9	0.1	0.9	1.1	13.2
19	4	17.6	0.7	4.0	1.4	16.8
20	2	17.0	0.1	0.6	3.0	36.0
21	2	18.0	*	*	3.0	36.0
Total	24	15.4	0.6	3.8	1.0	12.0

No individuals in the sample with CA less than 13.0 years; values not available due to single observation; CA Chronological Age; SD Standard Deviation; CV Coefficient of Variation; SA Skeletal Age*

It can be observed from *Table 4.03* above that the mean SA values are generally less than the corresponding CA. Thus the GP method is underestimating age for all age groups except 14, 16, 17 years in the male sample and 13.5 years in the female sample. In these cases the GP method was over-estimating age by between 3.6 and 6.0 months. But this value was 18.0 months for the group of four individuals in the 13.52 year age category. For the rest of the sample, the amount by which the GP method is underestimating age ranged from 2.4 to 8.4 months between the ages of 13 years and 18 years for the males. The underestimated values fell between 2.4 and 24 months in the female sample between the ages of 13 and 17 years. Again the values for the female sample must be treated with caution due to the small sizes of each age category. However it was observed that after the CA of 18 years and 17 years in the male and female samples respectively, the GP method became inaccurate by 1 year and this under estimation increased as CA increased. The mean under-estimation was 12 months in the female sample and 6 months in the male sample.

Also shown in the table above are the measures of variability. These are indicated by the coefficient of variation (CV) which is relatively consistent for the female sample taking note of the small sample sizes in each age group. In the male sample it is the younger age groups, ages 13 to 14 years, which display a higher variability compared to the older age groups which show a more consistent level of variation in the average SA. It should be noted however, that in the male sample, the 13 to 14 year age groups are very small. A comparison of the variability of the two samples confirms that the females show more consistency in the under estimation of SA than the male sample.

Significant correlations were found to exist between Skeletal Age (SA) estimated using the GP method, and the Chronological Age (CA). The correlation coefficients as measures of association between the two samples were recorded using the Spearman Rank Order Correlation and the following values produced: 0.819 for the female sample and 0.679 for the male sample. These correlations were found to be significant at α level 0.05 showing a positive linear correlation which indicates that CA varies as SA varies. It can be said that these two parameters are both measuring an increase in age. But the SA underestimates the CA and this difference is consistent in the female sample and in age groups 15 to 21 years in the male sample as shown in *Table 4.03* above.

The Mann-Whitney test was used to establish if there was a significant difference between the CA and SA as determined by the GP age estimation method. The following results were obtained. For the female sample a *p*-value of 0.066 was recorded, indicating no significant difference between CA and SA. This should however, be treated with caution as a sample size of 32 is small. The male sample recorded a significant difference between CA and SA with a *p*-value <0.00 which demonstrates that there is a mismatch between SA and CA. A multiple comparison performed for each age group showed that the significant age differences occurred at 19, 20 and 21 years, as determined using the Kruskal-Wallis test. This is expected as the GP skeletal age estimation method identifies the attainment of maturity as age 19 years for males and does not continue beyond this age.

Thus where the two methods are both measuring age and that CA varies with SA, the SA underestimates the CA. The Spearman Rank test shows that a linear relationship exists between CA and SA while the Mann-Whitney test identifies any significant differences between the two variables and a multiple comparison identifies where this significant difference lies. Further analyses to investigate the extent of the difference in SA and CA were performed.

The following scatter plots in *Figures 4.03* and *4.04* show the magnitude of the difference, in years between CA and SA for individuals in the male and female sample respectively. The scatter plots also reflect whether this difference results in an over- or under- estimation of age according to the GP skeletal age estimation. It can be seen from the plots that for the majority of the individuals in both samples, SA tended to be less than the CA which is shown by the points lying above the y=0 line. This is the line on which all the points would lie if SA was accurately estimating CA at all ages. Points falling below the y=0 line signify an over-estimation of chronological age by using the GP skeletal age estimation. For more than three quarters of each sample CA was under estimated recording scores of 78.1% and 74.0% for the female and male samples respectively. This is in comparison to 21.9% and 26.0% for female and male samples respectively for which CA was over estimated.

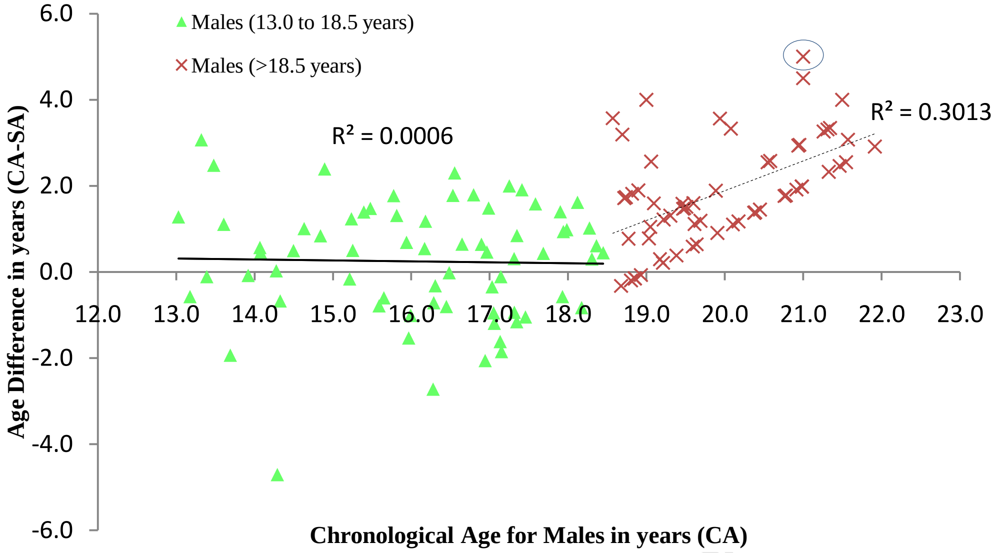


Figure 4.03 Scatter plot illustrating the difference between CA and SA for the male data. The trend line is depicting how the two variables are related up to age 18.5 years (solid line r²=0.0006) and from age 18.6 to 21.9 years (dashed line r²=0.30).The majority of the points lie above the *y*=0 line. This indicates that the SA is less than the CA. The case circled is the only specimen that falls beyond 2 SD from the base line. Although it is an outlier it is still included in the analysis

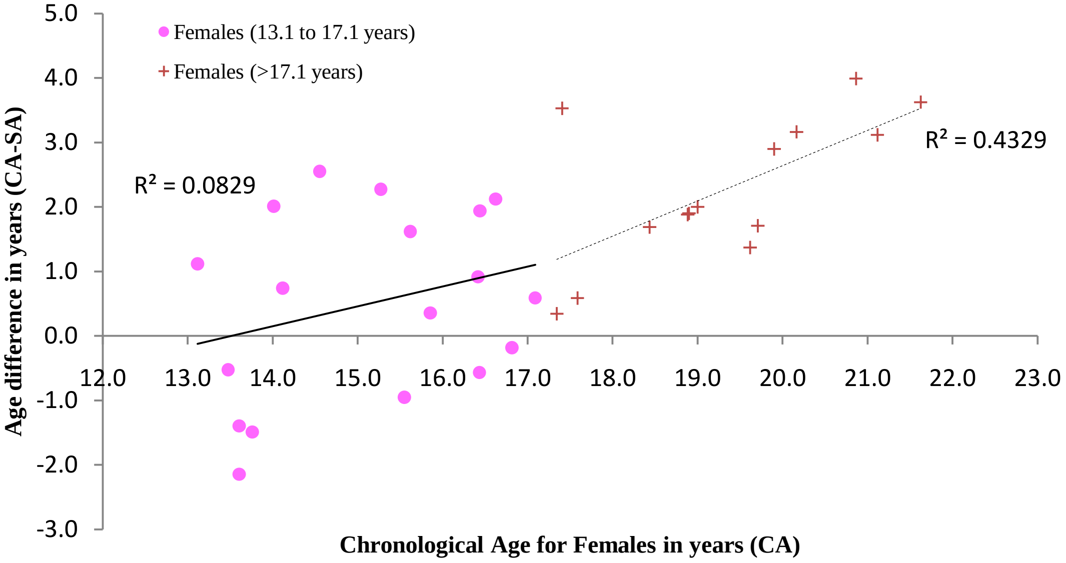


Figure 4.04 Scatter plot showing the difference between CA and SA for the female data. The trend line to indicate the relationship between the two variables, one for ages below 17.1 years (solid line r²=0.08) and one for ages 17.2 years to 21.9 years (dashed line r²=0.43). The majority of the points lie above the *y*=0 line. This is an indication of under estimation of CA by SA.

From the scatter plots shown above, it can be seen that the GP skeletal age estimation method becomes less accurate in older individuals. This is illustrated by the trendlines and the increased magnitude of the difference between CA and SA in individuals between the chronological ages of 13 years and 18.5 years for the male sample and those between 13 years and 17.1 years in the female sample. For the male sample the difference between CA and SA is fairly consistent compared to the female sample. This is indicated by the slope in the trendline (solid line). There after as indicated by the second trendline (dashed line), the difference between CA and SA notably increases, and this is characterised by the vast change in gradient.

This is due to the fact that the GP skeletal age estimation method concludes that full skeletal maturity is attained at age 18 for females and 19 for males. The point at which the gradient changes indicates the age at which the GP age estimation assumes that maturity is attained, the point where growth stops in the hand and wrist bones while chronological age continues to increase. As indicated by the points lying above the y=0 line, the chronological age of the current population may indicate maturity but skeletal maturity has not been reached yet. Further investigations were carried out in order to establish the exact age at which the termination of growth was reached for the current sample.

4.2.1.3 Termination of Growth and Attainment of Maturity

It would be expected that the current research sample would show development similar to that reported by GP. However the figures recorded in *Table 4.04* show that in the male sample those individuals who are 19 chronologically and skeletally represent only 23% of the 19 year old sample. It is at this age that GP conclude that a male individual has reached full skeletal maturity, which is characterised by complete epiphyseal fusion in the hand and wrist. The remaining individuals had not yet attained maturity and had skeletal ages less than 19 years according to the GP method. Of the total number of 22 male individuals of CA 19 years, two had a SA of 15 years, one was 16 years, five were 17 years and six were 18 years chronologically. This implies that there is a delay in the skeletal maturation of this group.

This apparent delay is illustrated graphically in *Figure 4.03* where it can be seen that the GP method is under-estimating age for more individuals. This is represented by the points lying above the y=0 line, confirming that SA is under estimating CA for this sample. Similar results were recorded for the female sample as shown in *Figure 4.04*. There was an increase in the difference between the CA and SA after the age of 18 years. In the younger age groups the GP method is fairly consistent, giving values of the SA which are approximately 1 year less than the CA. But there is a slight increase in the error as the CA approaches 18 years.

It was also noted is that in the younger age groups of the male sample, one individual was assessed as being 19 years skeletally while their chronological age was 14. While two 16 year old individuals had already attained skeletal maturity as seen in *Table 4.04*. Although these results may indicate early maturity in these individuals, the sample still shows an overall delay in completing maturation as shown by the low percentages of individuals with completely fused epiphyses shown in *Table 4.04*.

The females in the sample are maturing earlier than the males with at least one individual undergoing the first phase of termination of growth as seen in *Table 4.04* compared to the male sample. This is consistent with normal human skeletal development. According to GP female skeletal maturation is attained at CA 17 years. The current research sample reflects that at the age 17 years where 50% individuals recorded SA consistent with CA and termination of growth. The other two individuals were still developing. Of the total number of female individuals of CA 18 years, two of these recored SA of 17 years having undergone termination of growth and attainment of maturity, while one individual recorded SA of 16.5 years. All individuals of 19 years had completed skeletal maturation but there are very small sample sizes for these age groups.

The following figures (*Figures 4.05* to *4.08*) present illustrations of the process of matching a radiograph to the closest representative in the GP Atlas. The figures show the result of this process and how the GP estimates differed from chronological age of the individual in question. The two examples of an under estimation of CA by SA presented below in *Figures 4.06* and *4.08,* while the radiographs showing instances where CA was over estimated by SA are show in *Figures 4.05* and *4.07*. In all cases, the radiographs marked “a” and those marked “c” are adapted from the Greulich and Pyle Atlas (1959).

Figure 4.05 Female individual whose skeletal age was over estimated. Radiograph (a) is GP Standard radiograph for a 14 year old female. Radiograph (b) is the radiograph for individual GSF036. This individual's chronological age was 13.8 years. Radiograph (c) is GP Standard radiograph for a 15 year old female. Notice that in (b) epiphyseal fusion is complete in the distal metacarpals and in the phalanges and fusion is more advanced in the radius making radiograph (c) more representative of the level of skeletal development

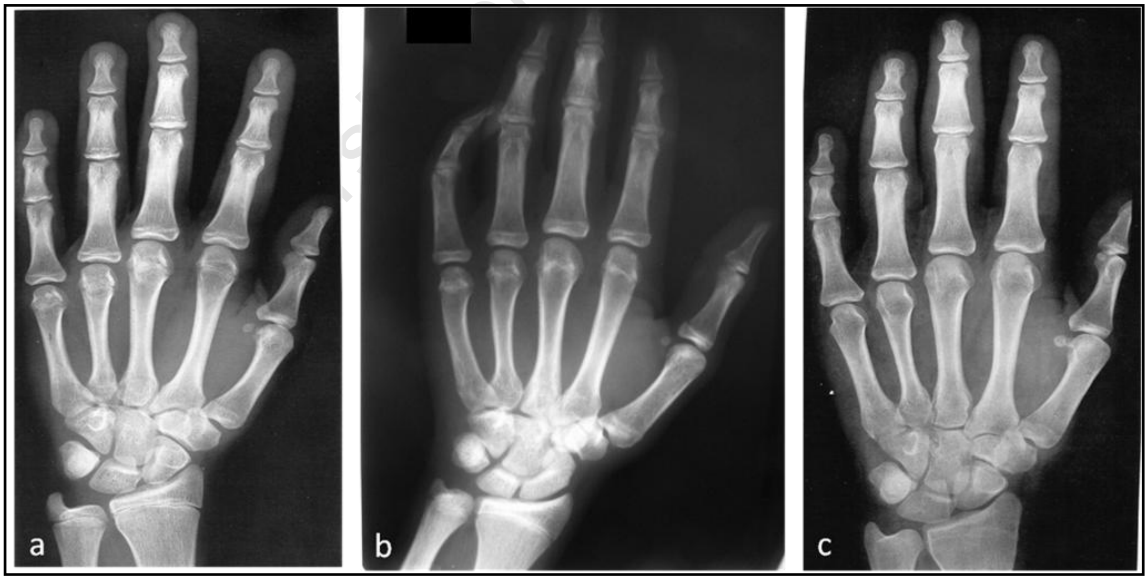

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Figure 4.06 Female individual whose skeletal age was under estimated. Radiograph (a) is GP Standard radiograph for a 14 year old female. Radiograph (b) is the radiograph for individual GSF022. This individual's chronological age was 17.4 years. Radiograph (c) is GP Standard radiograph for a 17 year old female. Notice that in (b) epiphyseal fusion is still in progress in all epiphyses but is complete in radiograph (c) which is of the same chronological age as GSF022. Thus skeletal age was better represented by radiograph (a).

Figure 4.07 Male individual whose skeletal age was over estimated. Radiograph (a) is GP Standard radiograph for a 16 year old male. Radiograph (b) is the radiograph for individual GSM071. This individual's chronological age was 16.3 years. Radiograph (c) is GP Standard radiograph for a 19 year old male. Notice that in (b) epiphyseal fusion is complete in all epiphyses and that the epiphyseal scar is still visible on the distal radius in radiograph. Therefore skeletal age was better represented in radiograph (c).

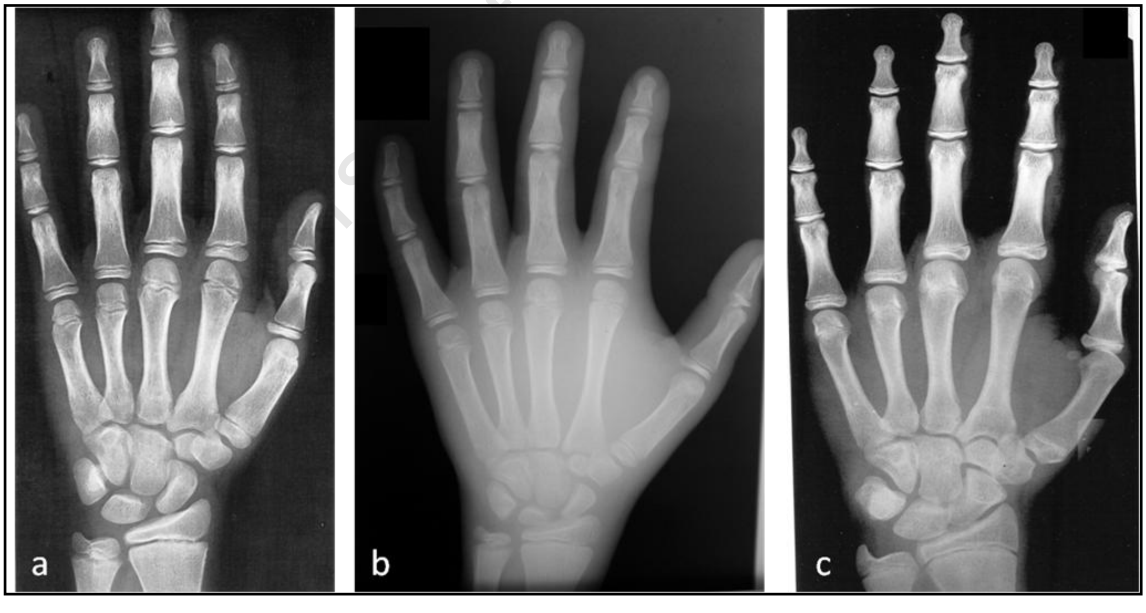

Figure 4.08 Male individual whose skeletal age was under estimated. Radiograph (a) is GP Standard radiograph for a 12.5 year old male. Radiograph (b) is the radiograph for individual GSM071. This individual's chronological age was 14.9 years. Radiograph (c) is GP Standard radiograph for a 15 year old male. Notice that in (b) epiphyseal fusion has not begun in any of the epiphyses. Radiograph (a) is the closest match for skeletal age.

From the data presented in *Table 4.04*, the age of termination of growth and attainment of maturity is at the point at which 100% of the sample have complete fusion of all the epiphyses in the hand and wrist. The expectation being that all individuals at or older than the age of maturity in the GP Atlas to have undergone complete epiphyseal fusion and skeletal growth ceased. This was not observed in the male sample, but the female sample seemed consistent with the GP prediction that females mature at age 17, it is essential to take note that the sample size is very small. Thus in the current sample, males are maturing later than age 17 years chronologically. Thus the point of maturity is older than what is recorded in GP and this is more so in the males than in the females. The Schmidt *et al.* analysis was used to determine the exact age for this point (see *Section 4.3*).

Table 4.04 Percentage of Skeletally Mature Individuals per Chronological Age Group

Skeletally Mature Individuals per Age Group			Individuals with Complete Epiphyseal Fusion	
Male	CA	N	n	%
	14	9	1	11
	16	16	2	13
	17	20	1	5
	18	19	6	32
	19	22	5	23
	20	13	9	69
	21	14	6	43
Females				
	16	5	2	40
	17	4	2	50
	18	3	2	67
	19	4	4	100
	20	2	1	50
	21	2	2	100

only the age groups in which mature individuals were found are represented.
N is the total number of individuals per CA group;
n is number of mature individuals

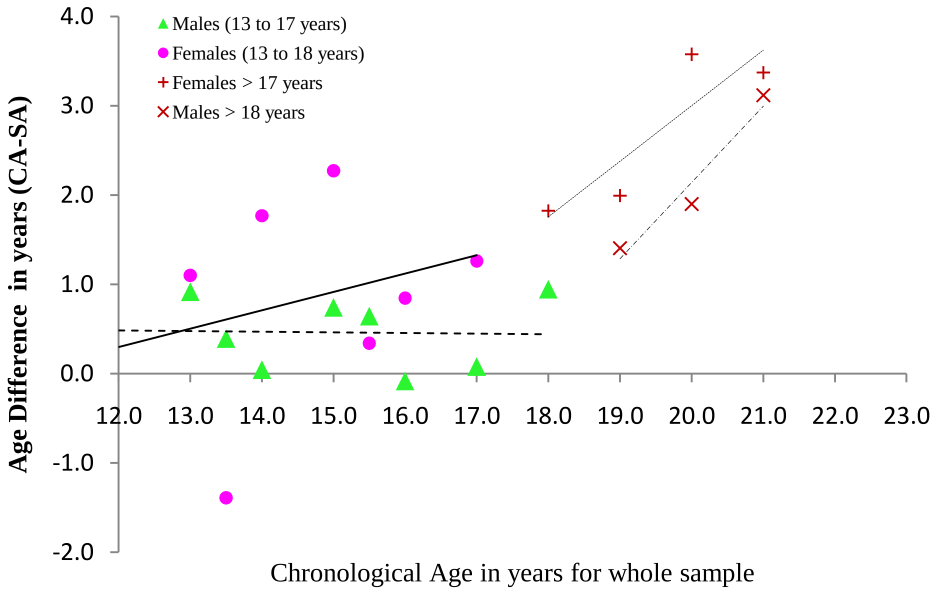

Figure 4.09 Scatter plot showing the distribution of the average discrepency between CA and SA for both male and female samples per age group. Note that the female sample points are shifted to the left. The dashed trendline is for the male sample and the solid line is for the female sample.

Figure 4.09 above, shows that the points indicating the difference between CA and SA for the female sample are shifted to the left. This is an indicator that the CA for the females are lower than those of the males. This is consistent with the literature (Greulich and Pyle, 1959) which states that females mature earlier than males in terms of sexual, and skeletal development during puberty. From the slopes of the two trendlines it can be seen that generally the difference between CA and SA for the female sample there were greater differences between the two parameters, compared to the male sample where this difference was consistent between the age groups younger than 18 years.

What this suggests is that at a given chronological age, the difference between CA and SA will be greater for the females than for the males. But it must be noted that the female sample size is small. Also shown in *Figure 4.09* are a second set of trendlines, those indicating age differences after the age of 17 for the female sample and 18 for the male sample. It can be noted that the CA to SA difference is much greater. This is because GP assumes the cessation of growth to occur at age 18 in the females and 19 in the male while chronological age continues to increase and incidentally so does skeletal development for the current sample

4.2.2 Age Difference between Radius and Ulna Skeletal Age and Chronological Age

Comparisons were made to assess whether the SA recorded for the whole hand differed from the SA for the radius and ulna using the GP method were significantly different to the CA. Multiple Mann-Whitney tests were performed and the level for significance was $p<0.05$. The male sample recorded a p-value <0.001. The SA for the radius was therefore significantly different from the CA. Similar results were recorded for the ulna. However no significant differences were reported for the female sample where p-values for the radius and ulna were 0.091 and 0.063 respectively.

The tables below show the differences between CA and SA for the radius and ulna. It is evident from the relevant p-values that the age groups where the CA to SA differences were significant were ages 18 to 21 years for the male sample shown in *Table 4.05* for the radius. The differences recorded for the ulnar epiphysis were significant at ages 15 and 18 to 21 years. At ages 14, 16 and 17 years, a negative result was recorded, indicating that the SA was in advance of the CA showing an over-estimation of CA by SA in this sample using the radial epiphysis. Similarly a negative difference was recorded for age 14 and 16 years in the ulna. But the overall results were positive meaning that the skeletal age is underestimating the chronological age. Once again it should be noted that the increase in difference between the CA and SA from age 19 years and older is due to individuals growing older chronologically but GP only measuring bone development up to age of 18 and 19.

Table 4.05 Difference between CA and SA for the Ulna and Radius for Males

	Average Greulich & Pyle Skeletal Age Estimates for Males								
CA	N	Radius Mean SA	Difference (years)	Difference (months)	*p*-value	Ulna Mean SA	Difference (years)	Difference (months)	*p-value*
13	4	12.3	0.8	9.0	0.166	12.0	1.0	12.0	0.109
13.5	4	13.3	0.3	3.0	0.242	13.3	0.3	3.0	0.339
14	9	14.5	-0.5	-6.0	0.459	14.4	-0.4	-5.3	0.494
15	4	14.5	0.5	6.0	0.500	14.4	0.6	7.5	0.027
15.5	6	15.2	0.3	4.0	0.144	14.9	0.6	7.0	0.058
16	16	16.5	-0.5	-5.6	0.429	16.5	-0.5	-5.6	0.430
17	20	17.4	-0.4	-5.1	0.391	17.0	0.0	0.0	0.103
18	19	17.6	0.4	5.1	0.001	17.6	0.4	5.1	0.001
19	22	18.0	1.0	12.0	0.000	17.9	1.1	13.1	<0.001
20	13	18.5	1.5	17.5	0.000	18.6	1.4	16.6	<0.001
21	14	18.2	2.8	33.9	0.000	18.1	2.9	34.3	<0.001

**these values were not applicable as only one reading existed for this CA*

The results for the female sample are shown in *Table 4.06*. It is evident from the relevant *p*-values that at ages 14 and 18 to 21 years the SA is significantly different from the CA in the radial epiphysis. This difference is negative at age 14 and 15.5 years meaning that for these age groups, SA over estimates the CA. The differences recorded for the other age groups are positive, which is consistent with an under estimation of CA by SA. For the ulna significant differences were found in the 14 year age group and from 18 to 21 years where an over estimation of CA by SA was observed. However it was only in age group 14 years where the skeletal age was in advance of the chronological age, as characterised by the negative difference. A similar pattern to that of the results of the whole hand analyses recorded in *Table 4.03* shows that the magnitude of the difference between CA and SA is fairly consistent up to age 18 years in both the male and female sample.

Table 4.06 Difference between CA and SA for the Ulna and Radius for Females

CA	Average Greulich & Pyle Skeletal Age Estimates for Females								
	N	Radius Mean SA	Difference (years)	Difference (months)	*p*-value	Ulna Mean SA	Difference (years)	Difference (months)	*p-value*
13	1	12.0	1.0	12.0	*	12.0	1.0	12.0	*
13.5	4	15.0	-1.5	-18.0	0.008	14.9	-1.4	-16.8	0.021
14	3	12.7	1.3	16.0	0.013	12.7	1.3	16.0	0.042
15	1	13.0	2.0	24.0	*	13.0	2.0	24.0	*
15.5	3	15.8	-0.3	-4.0	0.372	15.5	0.0	0.0	0.374
16	5	15.8	0.2	2.4	0.086	15.4	0.6	7.2	0.066
17	4	16.1	0.9	10.5	0.070	16.1	0.9	10.5	0.070
18	3	17.0	1.0	12.0	<0.001	16.7	1.3	16.0	0.002
19	4	17.5	1.5	18.0	0.001	17.8	1.3	15.0	0.006
20	2	16.8	3.3	39.0	0.006	17.0	3.0	36.0	0.005
21	2	18.0	3.0	36.0	0.003	18.0	3.0	36.0	0.003

**these values were not applicable as only one reading existed for this CA*

4.3 Skeletal Age Analysis 2: Schmidt *et al.* Method Results

The results for the skeletal development analysis method proposed by Schmidt *et al.* (2008b) are presented in this section. This method assessed progress toward complete epiphyseal closure or fusion of six skeletal epiphyses in the hand and wrist. This method used categorical data and the relevant statistical analyses were applied. There was no intra-observer bias reported (*p*-value = 0.072) using the χ^2 test for independence.

4.3.1 Basic Statistics for the Schmidt *et al.* Analysis

The table below (*Table 4.07*) shows the frequencies for the epiphyseal fusion scores obtained for the radius, ulna, and third metacarpal together with the proximal, middle and distal phalanges of the third finger, as recorded using this method. It can be seen that the epiphyseal stages 4 and 5 have relatively higher frequencies in both the male and female samples compared to the earlier epiphyseal fusion stages. This is expected for individuals who are undergoing the process of skeletal maturation and termination of growth. The Schmidt et al. Stages 4 and 5 indicate the termination of growth.

Although high frequencies were recorded for ossification stages 4 and 5, stage 1 also recorded high frequencies compared to the other stages for the male sample. This is an expected result as stage 1 signifies the commencement of epiphyseal fusion. The individuals included in the research sample were already undergoing this stage of development; hence the relatively high frequencies compared to ossification stages 2 and 3. The intervening stages, stage 2 and 3, varied in the proportions of individuals going through those stages of development. This is what is expected from the epiphyseal fusion process which has a distinct beginning and end, and from a sample population of a specific age range.

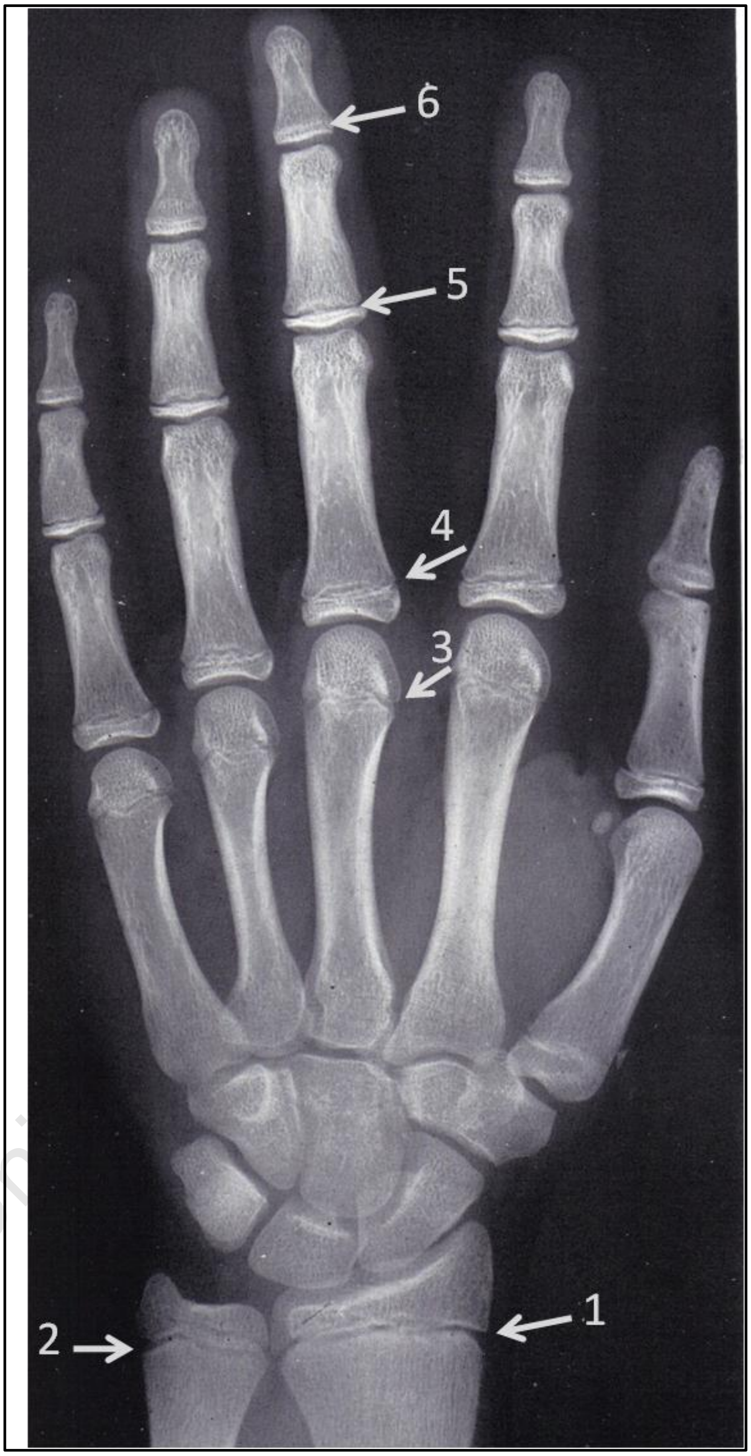

Figure 4.10 Radiograph indicating epiphyses of the hand and wrist used in the Schmidt *et al.* method. Arrows indicate the epiphyses of the third digit and wrist bones in the order proposed by Schmidt *et al.* (2008b): 1. Distal radial epiphysis; 2. Distal ulnar epiphysis; 3. Distal metacarpal epiphysis; 4. Proximal epiphysis of proximal phalanx; 5. Proximal epiphysis of middle phalanx; 6. Proximal epiphysis of distal phalanx. (*Image adapted from Greulich and Pyle, 1959)*

Table 4.07 Frequency Table for Schmidt *et al.* Epiphyseal Fusion Stages

Skeletal Element	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	N
Female						
Radius	3	6	7	9	7	32
Ulna	4	5	7	2	14	32
Metacarpal III	2	3	2	1	24	32
Proximal Phalanx III	3	1	1	10	17	32
Middle Phalanx III	5	2	2	2	21	32
Distal Phalanx III	5	1	*	2	24	32
Male						
Radius	24	29	20	28	30	131
Ulna	30	18	20	9	54	131
Metacarpal III	20	13	6	7	85	131
Proximal Phalanx III	26	6	5	37	57	131
Middle Phalanx III	34	4	4	7	82	131
Distal Phalanx III	24	3	3	10	91	131

*N number of observations; *no individuals in the female sample recorded a stage 3 epiphyseal closure for the distal phalanx*

The next level of analysis involved statistical analysis of the entire sample. And the results are presented in the table below (*Table 4.08*). The statistical parameters shown in the table include the mean and the median (as this is categorical data), as well as the standard deviation (SD). The SD is relatively high but consistent between the different epiphyses of the hand and wrist in both the male and female samples. The values range between 1.3 and 1.8. This means that the sample scores for each epiphysis differ from the mean by relatively the same amount. Also shown in the table are the mean stages of ossification, which illustrate that the epiphyses in the palm and fingers are fusing earlier than those in the radius and ulna. The mean values of 3.4 and 3.1 were recorded for the wrist in the female and male samples respectively while mean scores of 4.2 and 3.9 were recorded for the palm and fingers in the female and male samples respectively. This is consistent with normal bone development in the hand and wrist, according to the literature.

Table 4.08 Statistical Data for Ossification Scores Grouped by Sex

Epiphysis	Mean		Median		SD	
	Female	Male	Female	Male	Female	Male
Radius	3.3	3.1	4	3	1.3	1.5
Ulna	3.5	3.3	4	3	1.5	1.6
Metacarpal III	4.3	3.9	5	5	1.3	1.6
Proximal Phalanx III	4.2	3.7	5	4	1.3	1.5
Middle Phalanx III	4.0	3.8	5	5	1.6	1.8
Distal Phalanx III	4.2	4.1	5	5	1.5	1.6

SD Standard Deviation

4.3.2 Comparisons between the Various Skeletal Elements

The results of these comparisons are presented in the following tables (*Table 4.09, 4.10 and 4.11*). In the first and second tables the comparison between the Schmidt *et al.* epiphyseal closure scores for each skeletal element were compared to each other and tested for significant differences. *Table 4.09* shows the results for male sample. Significant differences were found to exist between the radius and third metacarpal, middle and distal phalanges (p <0.01 for all comparisons). Significant differences were also observed between the ulna and third metacarpal and distal phalanx (p=0.02, p<0.01 respectively). In *Table 4.10* the analysis for the female sample yielded significant difference between the radius and third metacarpal and distal phalanx only (p=0.02 and 0.03 respectively).

The same comparisons were performed between the epiphyseal closure scores for the male sample and those of the female sample and the results are presented in *Table 4.11* below. A significant outcome was found between the female third metacarpal and male radius scores and between the female distal phalanx and male radius scores (p<0.01 for both results). This result confirms what was observed in *Table 4.08*, that the palmar and phalangeal epiphyses are maturing in advance of the ulnar and radial epiphyses. Significant differences were recorded in the male sample but the small sample sizes may be affecting the results for the significance test in the female sample.

Table 4.09 Schmidt *et al.* Kruskal-Wallis Multiple Comparison of Ossification Scores for Male Sample

		Radius	Ulna	Metacarpal III	Proximal Phalanx III	Middle Phalanx III	Distal Phalanx III	
p-values	Radius	-	1.703	4.939*	2.905	4.134*	5.508*	z' values
	Ulna	>0.999	-	3.216*	1.196	2.422	3.794*	
	Metacarpal III	<0.001*	0.020*	-	2.023	0.795	0.579	
	Proximal Phalanx III	0.056	>0.999	0.646	-	1.229	2.603	
	Middle Phalanx III	<0.001*	0.231	>0.999	>0.999	-	1.374	
	Distal Phalanx III	<0.001*	0.002*	>0.999	0.139	>0.999	-	

** indicates statistically significant results. Z-values are presented on the right and P-values on the left*

Table 4.10 Schmidt *et al.* Kruskal-Wallis Multiple Comparison of Ossification Scores for Female Sample

		Radius	Ulna	Metacarpal III	Proximal Phalanx III	Middle Phalanx III	Distal Phalanx III	
p-values	Radius	-	1.002	3.210*	2.261	2.442	3.084*	z' values
	Ulna	>0.999	-	2.208	1.259	1.440	2.082	
	Metacarpal III	0.020*	0.409	-	0.949	0.768	0.126	
	Proximal Phalanx III	0.357	>0.999	>0.999	-	0.181	0.823	
	Middle Phalanx III	0.219	>0.999	>0.999	>0.999	-	0.642	
	Distal Phalanx III	0.031*	0.560	>0.999	>0.999	>0.999	-	

** indicates statistically significant results. Z-values are presented on the right and P-values on the left*

Table 4.11 Schmidt *et al.* Kruskal-Wallis Multiple Comparison of Ossification Scores between Male and Female Samples showing *p*-values.

		Radius	Ulna	Metacarpal III	Proximal Phalanx III	Middle Phalanx III	Distal Phalanx III	
Male	Radius	-		0.002*	0.139	0.073	0.004*	Female
	Ulna		-	0.116			0.239	
	Metacarpal III	0.455		-				
	Proximal Phalanx III				-			
	Middle Phalanx III					-		
	Distal Phalanx III	0.137					-	

** indicates statistically significant results. Note in this table only the most relevant values are shown all other values were >0.999. Female data on the right and Male data on the left.*

Table 4.12 and *Table 4.13* below present the statistical data relating to progress toward complete epiphyseal closure of the various skeletal elements of the hand and wrist, and the respective ages at which each ossification stage is attained. From these tables it can be seen that the mean chronological age and median ages increase with each stage of epiphyseal closure for all the skeletal elements analysed. This is expected as progress from un-ossified epiphyses to complete ossification and fusion is age related.

Comparing the male and female samples, it can be seen in the radial epiphyses that the difference between median ages for the two samples decreases with increasing ossification stage. This pattern is not as obvious for the other epiphyses. This is indicative of the “catch-up growth” referred to in Schmidt *et al.* (2008b) which males undergo following the initial lag at the start of puberty. This refers to the increase in growth which occurs after the initial lag often observed at the onset of puberty (Schmidt *et al.*, 2008b). In other words, the delay in growth spurt in males is made up for around the time of skeletal maturation.

The sex independent differences were observed in the minimum age at which complete epiphyseal fusion was recorded. This was found in the third metacarpal and distal phalanges. This is in comparison to the distal radial and ulnar epiphyses which reached ossification stages 4 and 5 at an older age.

The chronological sequence in which stage 5 ossification is reached is first in the distal phalangeal epiphysis, followed by the middle phalanx and metacarpal followed by the proximal phalanx and then the epiphyses of the wrist joint. Although sex-independent, for the current sample, this pattern was better illustrated in the female sample than the male sample.

Table 4.12 Statistical Parameters of Chronological Age for the Male Sample in years

Skeletal Element Stage	N	Mean	SD	LQ	Median	UQ	Minimum	Maximum
Radius								
Stage 1	24	15.5	2.0	14.0	15.1	16.4	13.0	21.0
Stage 2	29	16.9	1.8	15.8	17.0	18.1	13.2	20.1
Stage 3	20	18.0	1.8	16.6	17.5	19.5	15.7	21.5
Stage 4	28	19.1	1.7	17.9	19.1	20.5	14.3	21.6
Stage 5	30	19.8	1.4	19.1	19.9	20.9	16.3	21.9
Ulna								
Stage 1	24	15.5	2.0	14.0	15.5	16.4	13.0	21.0
Stage 2	29	16.9	1.8	15.8	17.3	18.1	13.2	20.1
Stage 3	20	18.0	1.8	16.6	17.4	19.5	15.7	21.5
Stage 4	28	19.1	1.7	17.9	17.5	20.5	14.3	21.6
Stage 5	30	19.8	1.4	19.1	19.6	20.9	16.3	21.9
Metacarpal III								
Stage 1	20	14.9	1.6	13.5	14.7	15.8	13.0	19.0
Stage 2	13	16.8	1.8	15.4	16.2	18.1	14.3	21.0
Stage 3	6	15.3	1.4	14.1	15.3	16.5	13.7	16.6
Stage 4	7	18.2	1.9	17.1	17.9	19.9	15.6	21.5
Stage 5	85	18.9	1.7	17.5	19.1	20.4	14.3	21.9
Proximal Phalanx III								
Stage 1	26	15.3	1.6	13.9	15.2	16.2	13.0	19.0
Stage 2	6	16.0	1.8	14.3	15.9	17.3	14.1	18.7
Stage 3	5	16.7	3.0	14.3	16.2	18.1	13.7	21.0
Stage 4	37	18.5	1.8	17.1	18.8	20.2	15.6	21.6
Stage 5	57	19.1	1.7	18.2	19.2	20.1	14.3	21.9
Middle Phalanx III								
Stage 1	34	15.4	1.6	14.1	15.2	16.5	13.0	19.0
Stage 2	4	19.2	1.6	17.9	19.0	20.5	17.6	21.0
Stage 3	4	16.0	1.6	15.2	16.8	16.9	13.7	17.0
Stage 4	7	17.4	2.1	15.7	16.4	19.7	15.6	21.0
Stage 5	82	19.0	1.6	17.9	19.1	20.4	14.3	21.9
Distal Phalanx III								
Stage 1	24	15.0	1.6	13.8	14.7	15.6	13.0	19.0
Stage 2	3	16.7	3.0	14.1	16.2	19.9	14.1	19.9
Stage 3	3	16.7	1.1	15.4	17.3	17.4	15.4	17.4
Stage 4	10	17.4	2.0	16.5	17.0	18.8	13.7	21.0
Stage 5	91	18.8	1.7	17.3	18.9	20.4	14.3	21.9

N number of observations; SD Standard Deviation; LQ Lower Quartile; UQ Upper Quartile

Table 4.13 Statistical Parameters of Chronological Age for the Female Sample in years

Skeletal Element Stage	N	Mean	SD	LQ	Median	UQ	Minimum	Maximum
Radius								
Stage 1	3	13.9	0.7	13.1	14.0	14.6	13.1	14.6
Stage 2	6	15.7	1.3	15.3	15.7	16.4	13.5	17.4
Stage 3	7	14.9	1.5	13.6	14.1	16.4	13.6	16.6
Stage 4	9	18.1	1.4	17.3	18.4	18.9	15.6	20.2
Stage 5	7	20.0	1.6	19.6	19.9	21.1	16.8	21.6
Ulna								
Stage 1	4	14.2	0.9	13.6	14.3	14.9	13.1	15.3
Stage 2	5	15.4	1.7	13.8	15.9	16.4	13.5	17.4
Stage 3	7	15.1	1.3	13.6	15.6	16.4	13.6	16.6
Stage 4	2	18.0	1.3	17.1	18.0	18.9	17.1	18.9
Stage 5	14	19.1	1.6	17.6	19.3	20.2	16.4	21.6
Metacarpal III								
Stage 1	2	14.3	0.4	14.0	14.3	14.6	14.0	14.6
Stage 2	3	14.7	1.4	13.1	15.3	15.6	13.1	15.6
Stage 3	2	15.4	2.8	13.5	15.4	17.4	13.5	17.4
Stage 4	1	14.1		14.1	14.1	14.1	14.1	14.1
Stage 5	24	17.7	2.3	16.4	17.5	19.7	13.6	21.6
Proximal Phalanx III								
Stage 1	3	13.9	0.7	13.1	14.0	14.6	13.1	14.6
Stage 2	1	15.3		15.3	15.3	15.3	15.3	15.3
Stage 3	1	15.6		15.6	15.6	15.6	15.6	15.6
Stage 4	10	17.2	2.2	15.9	17.5	18.9	13.5	20.2
Stage 5	17	17.6	2.6	16.4	17.1	19.7	13.6	21.6
Middle Phalanx III								
Stage 1	5	14.5	1.0	14.0	14.6	15.3	13.1	15.6
Stage 2	2	15.4	2.8	13.5	15.4	17.4	13.5	17.4
Stage 3	2	13.9	0.4	13.6	13.9	14.1	13.6	14.1
Stage 4	2	15.1	2.1	13.6	15.1	16.6	13.6	16.6
Stage 5	21	18.2	2.1	16.4	18.4	19.7	13.8	21.6
Distal Phalanx III								
Stage 1	5	14.5	1.0	14.0	14.6	15.3	13.1	15.6
Stage 2	1	14.1		14.1	14.1	14.1	14.1	14.1
Stage 3	0							
Stage 4	2	17.0	0.8	16.4	17.0	17.6	16.4	17.6
Stage 5	24	17.6	2.5	16.1	17.4	19.7	13.5	21.6

N number of observations; SD Standard Deviation; LQ Lower Quartile; UQ Upper Quartile

The statistical parameters presented in the tables above illustrate the pattern of the distribution of ages for each stage of ossification. The range of the distribution is given by the minimum and maximal ages. While the inter-quartile range which represents 50% of the population is indicated by the boundaries created by the lower quartile and upper quartile values, the median represents the middle of the age range for each ossification stage.

Referring to *Table 4.12* and *4.13* it is evident that complete epiphyseal fusion as characterised by stage 4 and stage 5 occurred earliest in the middle and distal phalanges where the females attained stage 4 at age 15.1 years and the males at 16.4 years in the middle phalanx. The result for the distal phalanx showed males and females reaching stage 4 at 17.0 years. The distal radial epiphysis attained stage 4 and stage 5 at later ages in both males and females and this is consistent with the sequence of development detailed in the literature as the distal radius is the last epiphysis in the wrist to attain complete fusion. This result is also consistent with that reported for the Schmidt *et al.* (2008b) sample.

The age at which complete epiphyseal fusion in hand and wrist is attained is important forensically, as this level of development and the corresponding chronological age at which it is reached is used to confirm whether an individual has attained adulthood or not. In this respect, the radial epiphysis being the last epiphysis to fuse upon reaching skeletal maturity recorded the following age ranges for reaching ossification stage 4. Age ranges of 15.6 to 20.2 years were recorded by the female sample and 14.3 to 21.6 years were recorded for the male sample. This gives an indication as to the length of time taken for epiphyseal fusion to occur from beginning to end.

Table 4.14 Percentage of Male Individuals Undergoing Termination of Growth

CA	Skeletal Element	N	Mature Individuals		CA	Skeletal Element	N	Mature Individuals	
			n	%				n	%
13	Radius	4	0	0	17	Radius	20	7	35
	Ulna	4	0	0		Ulna	20	8	40
	Metacarpal III	4	0	0		Metacarpal III	20	17	85
	Proximal Phalanx III	4	0	0		Proximal Phalanx III	20	17	85
	Middle Phalanx III	4	0	0		Middle Phalanx III	20	15	75
	Distal Phalanx III	4	0	0		Distal Phalanx III	20	18	90
13.5	Radius	4	0	0	18	Radius	19	10	52.6
	Ulna	4	0	0		Ulna	19	9	47.4
	Metacarpal III	4	0	0		Metacarpal III	19	16	84.2
	Proximal Phalanx III	4	0	0		Proximal Phalanx III	19	16	84.2
	Middle Phalanx III	4	0	0		Middle Phalanx III	19	16	84.2
	Distal Phalanx III	4	1	25		Distal Phalanx III	19	18	94.7
14	Radius	9	1	11.1	19	Radius	22	15	68.2
	Ulna	9	1	11.1		Ulna	22	18	81.8
	Metacarpal III	9	1	11.1		Metacarpal III	22	21	95.5
	Proximal Phalanx III	9	1	11.1		Proximal Phalanx III	22	21	95.5
	Middle Phalanx III	9	1	11.1		Middle Phalanx III	22	20	90.9
	Distal Phalanx III	9	1	11.1		Distal Phalanx III	22	20	90.9
15	Radius	4	0	0	20	Radius	13	12	92.3
	Ulna	4	1	25		Ulna	13	12	92.3
	Metacarpal III	4	0	0		Metacarpal III	13	13	100
	Proximal Phalanx III	4	0	0		Proximal Phalanx III	13	13	100
	Middle Phalanx III	4	0	0		Middle Phalanx III	13	13	100
	Distal Phalanx III	4	0	0		Distal Phalanx III	13	13	100
15.5	Radius	6	0	0	21	Radius	14	11	78.6
	Ulna	6	0	0		Ulna	14	11	78.6
	Metacarpal III	6	2	33.3		Metacarpal III	14	13	92.9
	Proximal Phalanx III	6	2	33.3		Proximal Phalanx III	14	13	92.9
	Middle Phalanx III	6	2	33.3		Middle Phalanx III	14	13	92.9
	Distal Phalanx III	6	3	50.0		Distal Phalanx III	14	14	100
16	Radius	16	2	12.5					
	Ulna	16	3	18.8					
	Metacarpal III	16	9	56.3					
	Proximal Phalanx III	16	11	68.8					
	Middle Phalanx III	16	9	56.3					
	Distal Phalanx III	16	13	81.3					

CA is Chronological Age group in years; N is the total number of individuals in that age group; n is the number of individuals at Ossification Stage 4 and 5 per element

Table 4.15 Percentage of Female Individuals Undergoing Termination of Growth

CA	Skeletal Element	N	Mature Individuals		CA	Skeletal Element	N	Mature Individuals	
			n	%				n	%
13	Radius	1	0	0	17	Radius	4	4	100
	Ulna	1	0	0		Ulna	4	4	100
	Metacarpal III	1	0	0		Metacarpal III	4	4	100
	Proximal Phalanx III	1	0	0		Proximal Phalanx III	4	4	100
	Middle Phalanx III	1	0	0		Middle Phalanx III	4	4	100
	Distal Phalanx III	1	0	0		Distal Phalanx III	4	4	100
13.5	Radius	4	0	0	18	Radius	3	3	100
	Ulna	4	0	0		Ulna	3	3	100
	Metacarpal III	4	2	50		Metacarpal III	3	3	100
	Proximal Phalanx III	4	3	75		Proximal Phalanx III	3	3	100
	Middle Phalanx III	4	1	25		Middle Phalanx III	3	3	100
	Distal Phalanx III	4	3	75		Distal Phalanx III	3	3	100
14	Radius	3	0	0	19	Radius	4	4	100
	Ulna	3	0	0		Ulna	4	4	100
	Metacarpal III	3	2	66.7		Metacarpal III	4	4	100
	Proximal Phalanx III	3	2	66.7		Proximal Phalanx III	4	4	100
	Middle Phalanx III	3	1	33.3		Middle Phalanx III	4	4	100
	Distal Phalanx III	3	1	33.3		Distal Phalanx III	4	4	100
15	Radius	1	0	0	20	Radius	2	2	100
	Ulna	1	0	0		Ulna	2	2	100
	Metacarpal III	1	0	0		Metacarpal III	2	2	100
	Proximal Phalanx III	1	0	0		Proximal Phalanx III	2	2	100
	Middle Phalanx III	1	0	0		Middle Phalanx III	2	2	100
	Distal Phalanx III	1	0	0		Distal Phalanx III	2	2	100
15.5	Radius	3	0	0	21	Radius	2	2	100
	Ulna	3	0	0		Ulna	2	2	100
	Metacarpal III	3	2	66.7		Metacarpal III	2	2	100
	Proximal Phalanx III	3	2	66.7		Proximal Phalanx III	2	2	100
	Middle Phalanx III	3	2	66.7		Middle Phalanx III	2	2	100
	Distal Phalanx III	3	2	66.7		Distal Phalanx III	2	2	100
16	Radius	5	1	20					
	Ulna	5	1	20					
	Metacarpal III	5	4	80					
	Proximal Phalanx III	5	5	100					
	Middle Phalanx III	5	4	80					
	Distal Phalanx III	5	5	100					

CA is Chronological Age group in years; N is the total number of individuals in that age group; n is the number of individuals at Ossification Stage 4 and 5 per element

The two tables above (*Table 4.14* and *4.15*) present the data relating to the distribution of individuals per ossification stage grouped by age. The pattern that can be observed is that as individuals get older, higher percentages of the sample are undergoing the final stages of ossification and attaining adulthood. This is characterised by Stage 4 in which the epiphyseal fusion has ended and the epiphyseal scar is still visible and at Stage 5 which is characterised by the eventual disappearance of this scar.

As is expected in younger individuals, in both the male and female samples, very few individuals are undergoing the termination of growth. There were almost none between the ages of 13 and 14 years in both samples. However in the female sample just over two thirds of 14 year old individuals had undergone complete epiphyseal fusion in their palm and fingers (metacarpal, proximal, middle and distal phalanges). This is not the case in the male sample though, which may be due to the early onset of puberty in females compared to males, a result which is consistent with normal development.

In older individuals, by age 18 years in the female sample, all individuals show complete epiphyseal fusion at the wrist, palm and in the fingers. This indicates that all individuals have undergone termination of growth and attained adulthood in terms of skeletal development. This is in advance of the male sample in which the highest proportion of individuals with complete fusion in the wrist and hand is at age 20 with only 92.3% of individuals with complete fusion at the wrist joint but all individuals having complete epiphyseal fusion in the hand. This result shows that skeletal development is still continuing at the wrist in this sample even at this mature age.

When working with categorical data the median is often used as a measure of central tendency. Presented below are the results of various comparisons using the median chronological age as a statistical parameter. The Mann-Whitney test was used to compare sex differences for the overall sample median ages and there were no significant differences found, meaning that males and females were developing similarly except at stage 3 of the radial epiphysis where epiphyseal fusion for the females was at an advanced state at an earlier age than the males. This suggests an advanced rate of ossification in females compared to males.

The table below (*Table 4.16*) presents the difference between the male and female median ages for each ossification stage and skeletal element. It can be seen that the difference between male and female median ages decreased with increasing ossification stages, and this is conflicting with Schmidt *et al.* (2008b) results. This was true in all cases, yet there were instances where the female median age was higher than the male median age and resulted in a negative value for the difference between the two ages. This was in stage 4 for the ulna and stage 3 for the third metacarpal epiphysis. This suggests that the females are reaching these ossification ages at a later age than their male counterparts are. However, the decrease in the difference between male and female median ages in the higher ossification stages (stage 4 and stage 5) may be as a result of the males catching up with females who initially develop earlier than males at the onset of puberty.

It should be noted that the particularly large age difference observed for the middle phalanx of the third digit at ossification stage 2, is due to the very small number of observations made in the female sample. This is as opposed to a large difference resulting from an actual discrepancy in the ossification rates between males and females.

Table 4.16 Difference between Male and Female Median Ages per Ossification Stage and Skeletal Element

Skeletal Element Stage	Median Chronological Ages			
	Male	Female	Difference (months)	Difference (years)
Radius				
Stage 1	15.1	14.0	12.7	1.1
Stage 2	17.0	15.7	15.0	1.2
Stage 3	17.5	14.1	40.8	3.4
Stage 4	19.1	18.4	8.0	0.7
Stage 5	19.9	19.9	0.0	0.0
Ulna				
Stage 1	15.5	14.3	15.0	1.3
Stage 2	17.3	15.9	17.3	1.4
Stage 3	17.4	15.6	22.8	1.9
Stage 4*	17.5	18.0	-6.5	-0.5
Stage 5	19.6	19.3	3.4	0.3
Metacarpal III				
Stage 1	14.7	14.3	5.5	0.5
Stage 2	16.2	15.3	10.9	0.9
Stage 3*	15.3	15.4	-1.5	-0.1
Stage 4	17.9	14.1	45.4	3.8
Stage 5	19.1	17.5	19.2	1.6
Proximal Phalanx III				
Stage 1	15.2	14.0	14.6	1.2
Stage 2	15.9	15.3	7.4	0.6
Stage 3	16.2	15.6	6.6	0.6
Stage 4	18.8	17.5	15.7	1.3
Stage 5	19.2	17.1	25.0	2.1
Middle Phalanx III				
Stage 1	15.2	14.6	8.3	0.7
Stage 2	19.0	15.4	43.1	3.6
Stage 3	16.8	13.9	34.9	2.9
Stage 4	16.4	15.1	16.0	1.3
Stage 5	19.1	18.4	7.7	0.6
Distal Phalanx III				
Stage 1	14.7	14.6	2.2	0.2
Stage 2	16.2	14.1	24.8	2.1
Stage 3	17.3	**	n/a	n/a
Stage 4*	17.0	17.0	-0.6	0.0
Stage 5	18.9	17.4	18.7	1.6

**negative result due to females being older than males at this particular ossification stage*
***no observations made for this stage in the female sample.*

CHAPTER 5: DISCUSSION

5.1 Introduction to the Discussion

The measurement of skeletal age (SA) is a means of assessing development and the process of skeletal maturation in children and adolescents for various clinical and forensic purposes (Schmidt *et al.*, 2008b and 2007; Garamendi *et al.*, 2005; Lynnerup *et al.*, 2008). These assessments are carried out by comparing the SA of a selected test population against established standards. The most widely used skeletal age estimation standards are those published by Greulich and Pyle (1959). The applicability of such standards to populations, which differ from the reference population from which the standards were derived, is often questioned. This is because by its nature, a standard is based on the results of a specific study performed on a specific population at a specified point in time. In the case of the GP Atlas, that reference population is from the Brush Foundation study which was carried out in the 1940's.

The applicability of the GP standards to modern day populations has been tested over the past few decades. This is following evidence that secular trends in growth rate and height, differing genetic origin, health and economic status (Loder *et al.*, 1993; Zhang *et al.*, 2009; Schmeling *et al.*, 2006) which affect growth and skeletal development. Thus it was believed that the above-mentioned factors have varying effects on different populations this might in turn affect the direct applicability of GP standards to populations of different origin to the GP reference population. The present study examines these issues in a modern African sample.

5.2 The Sample: Biological Origin, Age and Sex Distribution

The sample was chosen on the basis of biological origin as indicated on the patient folder. As mentioned in the *Section 3.1*, family name was used as an indicator of African genealogy, using the meanings and the roots of these names. Home language was also used as a flag for African descent. Individuals, who indicated isiXhosa, isiZulu, seSotho, seTswana and other African languages as the language spoken at home, were assumed not to have been of European descent. However, it is acknowledged that some individuals could have indicated any of the above languages as their home language but still been of non-African descent. Nevertheless, the numbers of these individuals would be far out-weighed by individuals who met the inclusion criteria.

The same problem applies to the name because it reflects familial relation along patriarchal lines. The mother might not be of African descent, a contemporary example being Ian Khama, the current president of Botswana whose mother is of English origin. Thus Ian Khama is actually of mixed biological origin yet fully accepted as MoTswana by the people of Botswana. However it can be reasonably assumed that such cases are the exception rather than the rule.

The age range for the current sample was approximately 14 years to 22 years. This was chosen as it encompasses the adolescent growth spurt, which is characterised by changes in body shape and size, at the onset of puberty and culminates in the termination of growth of most long bones to attain the adult skeletal form. Greulich and Pyle (1959) traced skeletal development from birth to 18 years and determined adolescence to be the period between 14 and 18 years. However, due to the lack of data on the present sample in terms of termination of growth and epiphyseal union, the ages of 13 and 19 to 22 years were included. This was done in order to ascertain the earliest age at which full skeletal maturity characterised by complete epiphyseal closure could be observed and the latest age at which incomplete epiphyseal fusion was observed. The oldest age at which non-fusion was observed was 21 years in the male sample and earliest age at which complete fusion was observed was 14.6 years in the female sample at the radial epiphysis.

A brief note on the sex distribution of the current sample is that it was observed that more males of the appropriate age group, presented at the clinic than females. However, there were more, older females visiting the clinic than young ones. A possible explanation may be that men tend be employed in industries where they are more likely to suffer work related injuries and men are more likely to participate in violent behaviour. In the South African context, men tend to be the primary bread winners and are thus more likely to seek medical attention in order to get treated and return to work. In addition, the types of work in which males engage in versus those that females tend to engage in are socially regulated. Thus the current sample, although not reflective of the sex distribution in the general population, was a reflection of the patients attending the hand clinic. All the patients whose radiographs were examined were coming in for trauma to the hand or forearm. The surgeons attended to more males in the age range 13 to 22 years than females.

5.3 Discussion of Skeletal Age Analysis Results

5.3.1 Intra- and Inter Observer Error Analysis

These measurements are recorded as a means of checking the accuracy and reliability of the skeletal age estimates based the GP standards. This is a recognized practice in anthropometric studies as the quantification of growth and development is subjective in nature (Groell *et al.*, 1999). It is often stated that experience increases the accuracy of bone age estimation (Malina *et al.*, 1971; Büken *et al.*, 2007). It was proposed by Malina *et al.* (1971) that the GP Atlas method has low systematic error which suggests that the application of the method is more straightforward compared to individual bone methods. In the current study, a general observation was that the precision of the skeletal age estimate (SA) improved when the radiographs were re-examined after a brief hiatus of approximately one month where it was noted that the time taken to examine a single radiograph was reduced and specific patterns of development were more easily discernable.

The concepts of repeatability and reproducibility can be interpreted as measures of the degree of ‘accuracy’ of the SA estimation method and its ‘precision’, respectively, terms used by Vignolo *et al.* (1992). In this paper, ‘accuracy’ is described as the ability to give figures close to the actual value of a given variable, where the variable has a specific pattern and rate relating to bone growth (Vignolo *et al.*, 1992). This trait when observed and measured in any sample may vary from the reference population on which the method was originally formulated. Vignolo *et al.* (1992) go on to define ‘precision’ as the degree of similarity between measurements performed on a sample population on two or more occasions, whether by the same observer or by a different one.

A similar method of checking precision and accuracy was followed in the present study as was done by Vignolo *et al.* (1992), where three age estimation assessments were carried out, twice by one researcher with a short break between estimates, and once by a second researcher. This is the recommended practice when applying age estimation methods to a population other than the reference population on which the method was based. This is further supported by van Rijn *et al.* (2009) who regard intra- and inter-observer error as ‘random effects’ which can be minimised by taking many estimates and using the average between these, thereby producing a combined reading rather than one gained through consensus. Both the precision and accuracy for the data in this study were satisfactory.

5.3.2 Difference between Skeletal Age and Chronological Age for the Whole Hand

The overall results were that skeletal age (SA) as determined using the GP Atlas was less than the chronological age (CA) for a large proportion of the sample. For females the mean difference was 12 months and for the males it was about 6.8 months when using the CA as the “gold standard”, a term used in Groell *et al.* (1999). Below are the Bland-Altman (1986) plots for the male and female samples. This plot measures the agreement between the two methods by plotting the average of the two measurements (SA and CA) against the difference between them (CA-SA). These plots show the number of individuals for whom the difference between CA and the GP skeletal age estimate differed by more than 2 standard deviations. Also visible are the ages at which

GP can no longer be applied with any confidence to the sample. This is indicated by the vertical line.

In the few cases where age was overestimated it has been suggested that this result may be due to the position in which the hand was placed on the radiographic plate. Patients who have been injured may be unable to place the hand flat against the radiographic plate as is indicated in the GP standard radiographs due to pain. The resulting image may be distorted due to the wrist and hand being at an angle to each other and thus the extent of epiphyseal fusion may be misinterpreted (personal communication, Phillips, 29 June 2010).

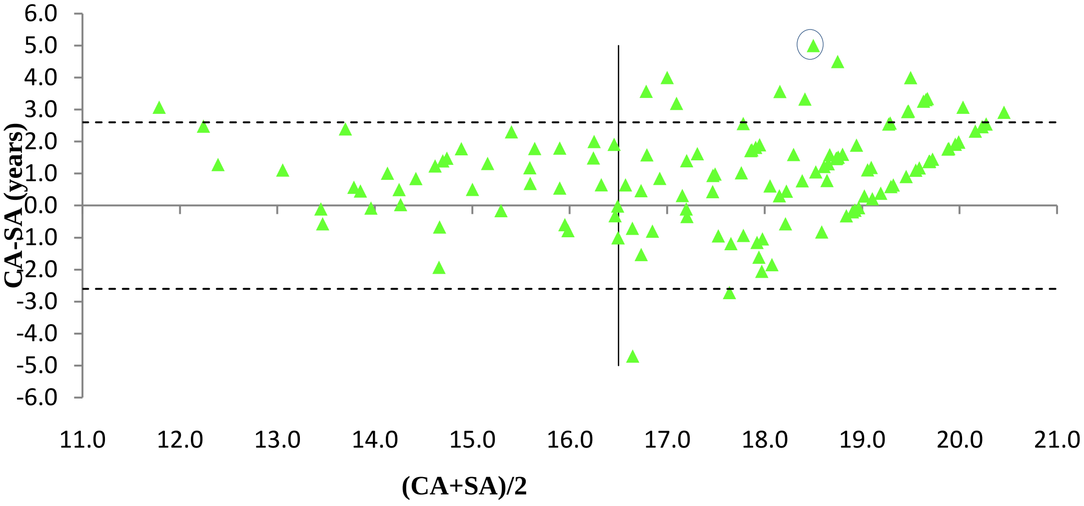

Figure 5.01 Bland-Altman (1986) Plot showing the difference between SA and CA for the male sample plotted against the average age given by the two methods. The dashed lines indicate the 2 standard deviation limits for skeletal age. The solid line indicates the point at which the reliability for GP to predict chronological age is lost. At approximately 16.5 years for the male sample. It should be noted that there is an outlier (indicated by circle) which has been included as it is a valid observation.

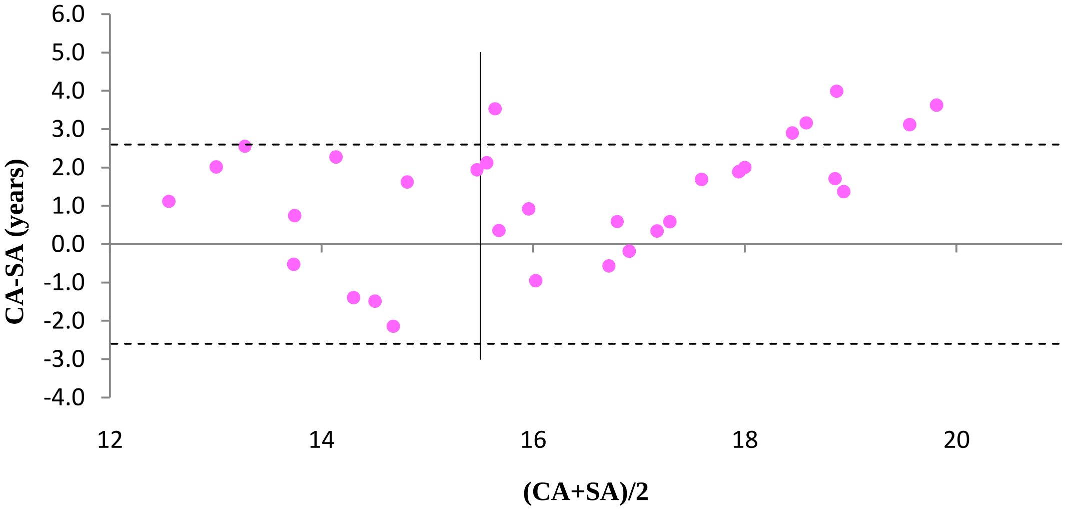

Figure 5.02 Bland-Altman (1986) Plot showing the difference between SA and CA for the female sample plotted against the average age given by the two methods. The dashed lines indicate the 2 standard deviation limits for skeletal age. The solid line indicates the point at which the reliability for GP to predict chronological age is lost. This is approximately 15.5 years for female sample.

The results of the above plots are comparable to those published in van Rijn *et al.* (2009). In this paper, it was found that at ages 17 years for the male sample and 15 years for the female sample, GP became inapplicable as characterised by the increased number of estimates falling outside of the two standard deviation limits. For the current South African sample of African descent, these points are at age 16.5 for the male sample and 15.5 for the female sample. However since the female sample is not representative of the distribution in the general population, this result should be treated with caution.

As expected the maximum age for GP method in the male sample was greater than that of the female sample as seen in van Rijn *et al.* (2009). This pattern is congruent with the normal sex differences in skeletal maturation. However, the expected two-year age difference was not observed in the current sample, a possible reason being that the female sample size is very small. The increased number of individuals with CA to SA age differences greater than two standard deviations is the main criticism for GP method (Garamendi *et al.*, 2005; van Rijn *et al.*, 2009). The GP method assumes that epiphyseal fusion in the wrist is complete by the age of 17 years in females and age 19 in males (Greulich and Pyle, 1959) whereas skeletal maturation and termination of growth is continuing in the present sample. This is further confirmed by the number of points falling above the y=0 line showing that the SA was indeed less than CA.

The underestimation of age by SA reported here can be interpreted as a delay in maturation of the current sample compared to the GP reference population. A result found in Schmidt *et al.* (2007); Groell *et al.* (1999); Lewis *et al.* (2002) and E. Andersen (1971). It was E. Andersen (1971) in particular who noted a delay in skeletal maturation in the Danish population on which that study was performed. Reports of delays of between 4 and 6 months (Schmidt *et al.*, 2007) and 1.5 to 2.7 months in Groell *et al.* (1999) were recorded when GP Standards were applied to populations of European descent while Lewis *et al.* (2002) reported a discrepancy of up to 20 months in a Malawian sample.

Other studies on South African populations were performed by Roff (2008) and Phillips and Thompson (2000) and both tested the applicability of GP on South African populations. Their samples consisted of “Negroid”, “Mixed” and “Caucasian” or “white” South Africans and both reported under estimation of SA. Roff (2008) reported an increasing tendency to underestimate SA in males as CA increased which is similar to the results of the current study. Phillips and Thompson (2000) reported an under estimation of SA of up to 1 year for their entire sample in all of the groups studied.

Thus, delayed skeletal maturity is not unique to the African context but is found in other populations as well. The question then is what could be the reason for this apparent delay? Many possible reasons have been given for the delay in skeletal maturity ranging from biological origin, often referred to as ‘race’ or ‘ethnicity’, to secular trends in growth, to economic status etc (Loder *et al.*, 1993; Zhang *et al.*, 2009; Schmeling *et al.*, 2006 respectively). For the current sample, it is likely that biological origin is the dominant factor. This is in consideration of how the sample was generated.

It is not likely that socioeconomic status or level of health care would be influential as the higher socioeconomic status sample was too small for a comparison to be made. To begin with, the sample was made up of individuals attending the hand clinic for trauma to the hand or wrist and would have been of reasonably good health up to that point. The Martin Singer Hand Clinic is one of the best hand surgery units in the city and draws patients from all sectors of society with a wide range of incomes. It was observed however that some patients were noted as ‘State’ or ‘Free’ upon admission and others were noted as ‘Private’. According to the administrative staff at the Hand Clinic, the billing system is such that patients are charged according to their income. Thus patients listed as ‘state’ patients are either sponsored by the state or charged the minimum fee for treatment while those listed as ‘private’ are billed by their respective health insurance provider. There were relatively few ‘private’ patients, only 15 out of a total sample 163 (0.92%) compared to 148 ‘state’. It should be acknowledged the ‘state’ patients include students, elderly, disabled persons who may not necessarily be of low economic standing, making the current sample a relatively homogenous one.

However socioeconomic status does have an impact on the state of nutrition of a developing individual. Thus bone development is also affected by poor nutrition which is closely related to socioeconomic status (personal communication Phillips 2010).

5.3.3 Population Differences in Skeletal Development: Genetics or Environment based.

Although the current study is based on a single population of African biological origin, the results are comparable to populations from America, specifically the African Americans. *Table 5.01* below shows the results for each study. Studies by Loder *et al.* (1993); Ontell *et al.* (2006); Mora *et al.* (2001) and Zhang *et al.* (2009) showed that there was a difference between SA and CA. The current sample was developmentally delayed, having SA less than CA. Compared to the above studies, this population would be described by Schmidt *et al.*(2007) as being ‘accelerated’ relative to the samples of the afore mentioned authors. The acceleration refers to the fact that the CA is in advance so to speak, of the SA (Schmidt *et al.*, 2007).

A further comparison can be made between the results of populations of European and other biological origin. In comparison to a “white” population (Loder *et al.*, 1993), Hispanic and Asian populations (Ontell *et al.*, 2006), even European American population (Mora *et al.*, 2001), this population was found to be more advanced than the current sample in terms of skeletal development. A difference of up to 1 year was reported although this figure may be high, it is still within the margin of error given in Greulich and Pyle (1959) (See Appendix D). However, a significant difference in SA was found between Asian and Hispanic populations who matured earlier than the African American and “white” as reported in Zhang *et al.* (2009).

Despite the differences in the skeletal development rates of populations of varying ethnicities and biological origins reported by the above authors, Schmeling *et al.* (2000 and 2006) reported that the apparent retardation in skeletal development in the non-European populations was influenced mainly by low socio-economic status and that the genetics played a lesser role. However, one criticism of these two studies is that they were performed retrospectively and the populations being so diverse would come from various SES and heath conditions. Thus, it can be surmised that the results may differ if these variables were actually controlled for.

Socio-economic status is reported to have minimal effects on skeletal age (Roche, 1979 as cited in Loder *et al.*, 1993). This is in contrast to studies conducted by Cameron *et al.* (1992) and Henneberg and Louw (1995) who found there to be differences in growth and physiological development between population groups of varying socio-economic status. Cameron *et al.* (1992) found that 'black' children of farm labourers in South Africa tended to weigh less and were shorter than their urban counterparts. This was found using height-weight measurements yet earlier work suggests that these variables were unreliable when it came to determining maturation (Simmons and Greulich, 1943). Simmons and Greulich proposed that since maturation was a physiological process different from growth resulting in increased height, a better indicator of maturation was the occurrence of menarche and the tracking of skeletal development (Simmons and Greulich, 1943). In this regard, Henneberg and Louw (1995) did indeed find that middle-class 'Cape Coloured' girls' age at menarche was lower than the 'white' girls and lower still than the 'black' girls, but provided no data on skeletal maturation.

Van Rijn *et al.* (2009) recognised that diversity exists among all world populations and that ideally the use of locally formulated standards for specific populations and by determining the average deviation of the SA using GP Atlas, the estimates can be adjusted accordingly. Van Rijn *et al.* (2009) gave the example of a 10 year old boy from a sample population with SA 0.6 years delay compared to GP reference population. If the boy's SA was 9 years then this boy is 0.4 years behind the expected level of development for this sample.

Table 5.01 Comparison of Results of Relevant Age Estimation Studies

Authors	Population Studied	Sample Size	Age Range (years)	Methodology	Reference Population	Results
Mackay (1952)	East African	1360	0-18	New radiographs with participant detailed participant data	North American	African children have delayed skeletal maturation compared to North American reference sample
E. Andersen (1971)	Danish	1009	7-18	New radiographs.	GP, TW	GP under estimated age by approximately 4 months. Author suggested making 6 month adjustment to GP estimate for it be applicable to Danish population.
Vignolo *et al.* (1992)	Italian	327	1-17	Retrospective study using pre-existing radiographs	GP, FELS, TW	GP underestimated age but within normal variation. GP, FELS and TW are applicable to Italian population.
Loder *et al.* (1993)	American (black and white)	841	0-18	Retrospective study using pre-existing radiographs	GP	GP over estimated age in black females in late childhood and adolescence, in white males and black males during adolescence. GP not applicable to contemporary populations especially where accuracy is needed.
Ontell *et al.* (1996)	American (white, black, Asian and Hispanic)	765	0-19	Retrospective study using pre-existing radiographs	GP	GP over estimated age in late childhood and adolescence in black and Hispanic females, Asian and Hispanic males. Advised to use GP with caution when examining populations of varying ethnicity.
Groell *et al.* (1999)	Central European	47	0-18.8	Retrospective study using pre-existing radiographs	GP	GP underestimated age but not significantly. GP applicable to Central European population.
Phillips & Thompson (2000)	South African (Caucasian, Negroid and Mixed)	189	2-21	Used pre-existing radiographs	GP	GP underestimated age for this population. Advised to apply method to larger sample.
Mora *et al.* (2001)	North American (African American and European American)	534	0-19	New radiographs with detailed participant information.	GP	Both samples differ to GP reference population. Post-pubertal European American males are significantly in advance of African American males. Advised new population specific standards be made.
van Rijn *et al.*(2001)	Above average SES Dutch Caucasian	572	5-19.9	Radiographs + detailed participant data.	GP	GP is applicable.
Lewis *et al.* (2002)	Malawian	139	1-28	Retrospective study using pre=existing radiographs and height weight data	GP	GP under estimated age. Reasons given: poor nutrition and general health status.

Table 5.01 continued

Authors	Population Studied	Sample Size	Age Range (years)	Methodology	Reference Population	Results
Garamendi *et al.* (2005)	Moroccan	114	13-25	New radiographs with physical examination.	GP, Demirjian.	GP underestimated age but due to individuals being older than maximum age for GP method of 19 years. Advise to use GP in conjunction with other methods for better accuracy
Büken *et al.* (2007)	Turkish of low-middle SES	743	11-19	New radiographs + height, weight data.	GP	GP reference population in advance at ages 15-17 years, delayed at 18-19 years in boys. With SD more than 1 year. Advised to use cautiously.
Schmidt *et al.* (2007)	German	649	1-18	Retrospective study using pre=existing radiographs	GP and Thiemann-Nitz	Ethnic origin does not affect ossification rate at all ages, greater effect is by SES and Health status. Thiemann-Nitz reference population accelerated compared to GP population.
Lynnerup *et al.* (2008)	Danish	159	11-19	Retrospective study using pre-existing radiographs	GP, Odontological examination	GP applicable but should adhere to SD deviations stated and state inclusive ages and likely age ranges.
Schmidt *et al.* (2008b)	German population	649	1-18	Used pre-existing radiographs	GP	GP is applicable. SES effect on skeletal maturation > ethnicity.
Zhang *et al.* (2009)	American (African American, Caucasian, Hispanic and Asian)	1390	0-18	New radiographs + height, weight data.	GP	Ethnic and racial differences in growth found between GP reference population and Asian and Hispanic samples. These children matured in advance of African American children. Advised to consider ethnicity when using GP.

GP Greulich & Pyle method; *TW* Tanner & Whitehouse method; *SD* standard deviation

5.3.4 Age and Sex Specific Differences between Skeletal Age and Chronological Age

As instructed in the GP Atlas each radiograph was selected at random and compared to the same sex standard which it most closely matched and the difference between SA and CA was noted. These differences are shown in *Table 4.03* in *Chapter 4: Results*. These tables show the range of differences between SA and CA with the corresponding standard deviations (SD) at each CA. The largest difference was found at CA 19 to 21 years in the male sample which is similar to van Rijn *et al.* (2009). This result was also reported in E. Andersen (1971) and van Rijn *et al.* (2009). This would indicate that although the SA is less than the CA, the significant readings were reached after the assumed age of skeletal maturation according to Greulich and Pyle Atlas (1959). Yet only 23 % of 19 year old individuals in the current sample had undergone complete epiphyseal fusion and attained full skeletal maturity. Büken *et al.* (2007) reported similar results, with skeletal maturation in the male sample occurring after the CA of 19 years. The female sample did not register a significant difference between CA and SA. The small sample size limits the inferences that can be made regarding this result.

The females in the current sample registered advanced skeletal development compared to males. In the CA age groups of 16, 17 and 18 years, proportions of 40%, 50% and 67% respectively exhibited complete epiphyseal fusion. However, GP standards failed to determine the age at which termination of growth and complete epiphyseal fusion takes place, with epiphyseal union still active at age 20 years in some individuals. Compared to GP, a delay of up to 3 years was recorded, and this is well above the acceptable range of error given in GP Atlas. This is less than the 94.1% complete fusion reported in Büken *et al.* (2007) in 18 year old females and 95.7% of 19 year old males. This showed not only the advance in skeletal development in females compared to males, but a delay in the skeletal maturation of the current sample as a whole compared to the sample in the study by Büken *et al.* (2007). Once again this shows that the reference population for GP matured in advance of the current population although the difference in CA and SA is not significant and is still within the standard deviation stated in Greulich and Pyle (1959).

The difference between CA and SA is illustrated graphically in the scatter plots (see *Figures 4.03* and *4.04*). It can be seen that more than 78.1% of the female sample and 74% of the male sample had a SA less than the CA and this difference was fairly consistent with the increase in age for males and increased sharply with increasing age for the females but this may be due to the small sample size. In van Rijn *et al.* (2001) the difference between CA and SA decreased with increasing CA for males and the opposite was observed for the females.

A delay of 1.7 months in females and of 3.3 months in males was reported by van Rijn *et al.* (2001) in the SA relative to CA. They also concluded that these values, supported by the high correlation figures between CA and SA, were within an acceptable range, rendering GP standards applicable to a modern Dutch ‘Caucasian’ population. However these authors did not consider that the high correlation was expected because SA and CA are measuring the same thing, an increase in age over time. A little more information could be gained from the scatter plots (van Rijn *et al.*, 2001) where although the majority of the sample was within the two year difference on either side of the CA-SA=0 line, there were some individuals who fell outside of these boundaries. More of these individuals were found in the male sample than in the female sample (van Rijn *et al.*, 2001). This result is similar to the current study and is indicative of males being more delayed in skeletal development than the females.

5.4 Categorical Data: Schmidt *et al.* (2008b) Method Results

The advantage of using categories to describe the level of epiphyseal fusion is that, it is based on the appearance of the epiphysis and the process of epiphyseal fusion regardless of the age at which it occurs. The age can then be determined after the state of epiphyseal fusion has been identified. It would appear as though the identification of the state of epiphyseal fusion is age independent whereas the process of epiphyseal fusion is age dependent. Meaning that an epiphysis with no sign of union is indicative of a young individual, but this epiphysis will over time eventually become ossified as that individual grows older and attains adulthood.

From *Table 4.11* and *4.12* it can be seen that the standard deviation recorded per stage of union per epiphysis is fairly consistent, indicating that the margin of error is constant between the stages of union. However when the different epiphyses were compared, the results alluded to the sequence of fusion. It was observed that the phalanges, distal followed by proximal then middle, were in advance of the metacarpals and they in turn, were in advance of the radius and ulna. This is the general sequence reported in Greulich and Pyle (1959) and also in Garn *et al.* (1961b, *fig. 2*).

However this sequence also showed variation in the sample studied by Garn *et al.* (1961b), where a small percentage of the sample showed distal phalanges followed by proximal and middle concurrently then metacarpals and radius and ulna while even smaller percentages showed other variations. The proximal and middle phalanges showed greater variation in sequence (Garn *et al.*, 1961b). The sequence of ossification recorded for the current sample by looking at the median age for Schmidt *et al.* (2008b) Ossification Stage 5 was distal phalanx followed by middle phalanx and metacarpal then the epiphyses of the proximal phalanx and the ulna and radius in the male sample, a result similar to the sequence recorded in 256 individuals of the Garn *et al.* (1961b) study. The female sample however differed in that the distal phalanx was preceded by the proximal phalanx. It was then followed by the metacarpal epiphysis then that of the middle phalanx and ulna and radius. This sequence is most similar to the sequence observed in 26 individuals examined by Garn *et al.* (1961b). However another study by Garn *et al.* (1961a) acknowledged that alternative sequences of carpal, metacarpal and phalangeal ossification are rare. They have been observed early in development and are associated with sequences observed in later development.

To gain a better understanding with regards to the age at which the various stages of epiphyseal ossification or fusion were being reached, refer to *Tables 4.11* and *4.12* where it is shown that an increase in CA was associated with increased epiphyseal fusion stage which is consistent with Schmidt *et al.* (2008b). The age of earliest detection of complete epiphyseal fusion and the subsequent disappearance of the epiphyseal scar was detected in the distal phalanx in males and in the proximal phalanx in females while in Schmidt *et al.* (2008b), it was at the metacarpals in the female and distal phalanx in the male samples. But in both this and the current study, the distal radius registered as the last epiphysis to completely fuse, which is consistent with literature (Greulich and Pyle, 1959).

In terms of sex specific difference, significant differences in the age at which the stages of ossification were reached were recorded in the metacarpal and distal phalangeal epiphyses, which were both in advance of the radius. It was also observed that the sex difference in age increased with the increased ossification stages only in the metacarpal and proximal phalangeal epiphyses. In both cases the females were in advance of males. The chronological sequence of reaching ossification Stage 5 or complete epiphyseal fusion as described in Schmidt *et al.* (2008b) was generally observed in the current sample although it was better shown in the female rather than male sample. The sequence given by using the minimum ages was: distal phalanx, metacarpal followed by proximal and middle phalanges then the ulna and radius. In the males, the minimum ages for reaching Stage 5 were similar for the metacarpal, proximal, middle and distal phalangeal epiphyses at 14.3 years. This gave the following fusion sequence: metacarpal, proximal, middle and distal phalanges concurrently followed by radius and ulna concurrently. However the median age gives a better resolution.

There was a 3-year difference between the minimum age for reaching ossification Stage 5 in the radius for females and a 2-year difference in males compared to other epiphyses. Both the ages were less than those reported in Schmidt *et al.* (2008b). This may be due to biological differences where the current sample is in advance of the Schmidt *et al.* (2008b) population. However the mean age for reaching Stage 5 was older than that of the Schmidt *et al.* (2008b) sample where ages of 18.8 years (n = 30) was recorded for male sample and 17.8 years (n = 14) for the female sample. This in comparison to 19.8 years (n = 30) for the male sample and 20.0 years (n = 7) for the female sample in the current study. What this shows is that although the current sample is developmentally delayed compared to the Schmidt *et al.* (2008b) sample, this method is still appropriate for determining when an individual has reached skeletal maturation and is therefore physiologically an adult, as characterised by complete epiphyseal fusion in the hand and wrist. It is also evident that the difference between the male and female mean ages for reaching ossification stages 4 and 5 decreases with increasing age. This again confirms the "catch-up growth" referred to in *Subsection 4.3.2* of *Chapter 4* and in Schmidt *et al.* (2008b).

An equivalent epiphyseal ossification method was developed by Cardoso (2008a) and applied to a skeletal population. Cardoso's method used only 3 ossification stages: no ossification, incomplete ossification and complete ossification. The intervening stages described by Schmidt *et al.* (2007) were not easily detected on dry bone. Nonetheless, these results are still relevant to the present study. Cardoso (2008a) reported that the radial and ulnar epiphyses undergo complete epiphyseal fusion at an age older than 17 years. This result could be verified using cemetery records. For the present study, the age range for reaching a certain stage of ossification could be determined. The smallest range was observed for completing Stage 5. The expansion of the number of stages of ossification therefore allowed for these ranges to be radiographically detected (O'Connor *et al.*, 2008; Schmeling *et al.*, 2004; Schmidt *et al.*, 2008b).

In terms of sex differences, females were in advance of males (Cardoso, 2008a; Schmidt *et al.*, 2008b). The sequence of union was described in Garn *et al.* (1961b) as distal, followed by proximal and middle phalangeal epiphyses, followed by metacarpal epiphyses, and having the first metacarpal act like a proximal phalanx. This sequence corresponds to ages 15.9, 16.2, 16.4, 16.4 years respectively in males and ages 13.6, 14.3, 14.4, 14.6 years respectively in females (Garn *et al.*, 1961b). In the current sample the sequence was not as clear, having the distal phalanx then the metacarpal epiphysis followed by the middle then proximal phalangeal epiphyses with the corresponding ages 18.8, 18.9, 19.0 and 19.1 years respectively in the males and with 17.6, 17.6, 17.7 and 18.2 years in females. Although quite different to results from Garn *et al.* (1961b) it does show that the females are in advance of males developmentally, which is documented in the literature and it agrees with what is presented in Greulich and Pyle (1959).

Table 4.13 and *4.14* show the data pertaining to the whole sample separated into chronological age groups according to sex and the percentages reaching skeletal maturation. It was found that 22.9% of the male sample and 21.9% of the female sample had reached the termination point of skeletal development, as characterised by stage 5 at the distal radial epiphysis, where the epiphysis is completely ossified and the epiphyseal scar had been obliterated. However, it should be noted that this scar may persist well into adulthood. This is a normal phenomenon and is not necessarily population specific (Greulich and Pyle, 1959). The minimum age at which this occurred for this sample is 16.3 years for males and 16.8 years for the females, a result which is contrary to what was found by Schmidt *et al.* (2008b). Due to the small sample size for the female sample, no conclusions can be made about this result, while the possibility of misinterpretation of epiphyseal fusion due to image distortion was acknowledged (personal communication, Phillips, 2010).

For the current study, while GP method was able to track ossification it was not a good method for determining the age of termination of growth and epiphyseal fusion. Thus a complimentary categorical method had to be employed in the form of ossification stages used in the Schmidt *et al.* (2008b). This method defined the complete ossification stage and then this was compared to the chronological age in order to determine the age at which this process began and where termination of growth occurred.

5.5 Limitations and Recommendations

There were some difficulties experienced in the performance of this study. Some delays were encountered while applying for ethical approval. Time for data collection was lost as the methodology had to be revised to suit the conditions of the ethical approval to perform the study. Initially it was proposed that new radiographic images would be generated using a digital X-ray machine. Due to the hazards of exposing healthy individuals to unnecessary radiation, this was changed. Pre-existing radiographs taken of the hand and wrist were then used.

Unfortunately the use of pre-existing radiographs means that there is no control over the quality and quantity of images which can be used. Also there is little chance for additional data from the test subject to be collected regarding life style, biological affiliation, socio-economic status, source and type of health care used. Thus it is recommended that further data be collected.

The results of the current study have shown that indeed the GP method is consistently under estimating age in this population group. But more data need to be gathered in order to assess the applicability of this result to the general population. This is a first step toward generating population specific skeletal age estimation standards. Also it would be beneficial to generate new radiographs with quality control over image position and clarity and the opportunity to gather demographic data will also be sort at the time that the radiographs are taken. In effect, a larger sample with accompanying demographic data will be most beneficial in generating population specific standards.

Overall this study has provided further proof for the need for population specific age estimation standards. It has also brought to the fore, the general limitations associated with determining age in living individuals. Some of these are the need for large enough samples to test separately the effect of biological origin (race) and socio-economic status (Cunha *et al.*, 2009). Samples for such studies will need large numbers with data on genetic and geographic origin and state of health, along with detailed descriptions of the methods and features to be examined (Schmeling *et al.*, 2008). According to Schmeling *et al.* (2008) this will “increase the diagnostic accuracy…and improve the identification of age-relevant developmental disorders...” Other recommendations pertain to the method of imaging. If this type of research is to expand, the use of more efficient high resolution low radiation imaging may be beneficial. One example is the use of alternative imaging methods (Cunha *et al.*, 2009) such as low dosage digital X-ray technology, or Computed Tomography scanning or ultrasonography.

CHAPTER 6: CONCLUSIONS

The Greulich and Pyle Atlas assigns an age to the whole hand in contrast to TW2 method which uses weighted scales for the individual bones of the hand and wrist. It is therefore easier to apply, and is thus one of the most commonly used skeletal age estimation methods.

The results of this study have shown that the current skeletal age estimation standards, proposed by Greulich and Pyle in their 1959 publication of the *Radiographic Atlas of Skeletal Development of the Hand and Wrist,* are not directly applicable to a South African population of African biological origin. The GP method was found useful in its ease of application and the level of precision with practice was high. However, in terms of reliability for the current sample, the GP method for determining skeletal maturity ceased to apply from the chronological age of 16.5 years in males and 15.5 years in females. According to Greulich and Pyle, these ages are close to the start of epiphyseal fusion of the distal radius, the last epiphyses to fuse. Not long after that, at chronological ages 19 years for males and 17 years for females, Greulich and Pyle (1959) predicted that epiphyseal fusion is complete in the hand and wrist. This was not recorded in the current study.

For the current population, epiphyseal fusion was still in progress at the ages of 19 for the males and 17 years for the females. Therefore the duration of the epiphyseal fusion process was recorded as being at least 3 years in the female sample and 2 years in the male sample. The oldest individual in which epiphyseal fusion was incomplete as characterised by Schmidt *et al.* (2008b) Ossification Stage 3, was 21.5 years recorded in the male sample. The average age in this study at which complete epiphyseal fusion was observed was 18.1 years in the female and 19.1 years in the male sample. These values are approximately one year older than Greulich and Pyle (1959) recorded.

Thus the first aim of the project has been met. The timing of epiphyseal fusion for the current South African population of African descent has been determined to extend beyond the 17 year and 19 year marks for females and males given in the GP Atlas as recorded above. This shows a delay in skeletal development in the current sample compared to the reference population on which the GP standards are based. Specifically, the South African sample population currently tested was on average 1 year behind in skeletal development. This is in line with the second aim of the project in which these results were to be compared to the results of Phillips and Thompson (2000). Accordingly the current results show that the GP method under-estimated age by up to one year while Phillips and Thompson (2000) reported an over-estimation of age by that much. Taking specifically the results for the 'Negroid' sample, the difference between the Phillips and Thompson (2000) results and the current results may be due to the particularly small sample size of 14 individuals for the 'Negroid' sample in the Phillips and Thompson research.

With regards to the third aim, it is not possible to identify the exact reason why there is an overall delay in skeletal age of the current sample compared to GP and Phillips and Thompson (2000). Although the sample collected for this study is homogenously African and is made up of both 'better off' (private) and 'less well off' (state) patients, the large majority of individuals were state patients and therefore were drawn from a relatively poorer section of the community. Therefore it is still possible that the delay was caused by poor socioeconomic level, rather than biological difference from the GP reference group.

Although the difference recorded is within the accepted limits of error given by Greulich and Pyle (1959), by virtue of its constancy it would be advisable to formulate new standards in which the one year delay of development has been calculated. This perception is supported and recommended by van Rijn *et al.* (2009) where it is suggested that if a population consists of groups of individuals of different biological origin or 'races', the average deviation from the GP standard should be calculated for each group. This can then be used to adjust the age intervals for the population groups. If this is done for the very diverse South African population groups then it will make the skeletal age estimation standards more applicable to a South African population and more accurate in determining developmental age.

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APPENDIX A Data collection sheet for male sample: Schmidt *et al.* Method results.

Individuals with skeletal anomalies are highlighted in Red

DOB	ASSIGNED CODE	DATE OF RADIOGRAPH	FOLDER #	IMAGE			CHRONOLOGICAL AGE (years)	LANGUAGE	Schmidt *et al.* EPIPHYSEAL CLOSURE						COMMENTS Including carpal morphology indicated by letters A to G adapted from Greulich WW. 1960. Skeletal features visible on roentgenogram of the hand and wrist which can be used for establishing individual identification. Am J Roentgenol 83:756-764.	TRAUMA
				LEFT	RIGHT	VIEW			Radius	Ulna	Metacarpal III	Proximal Phalanx III	Middle Phalanx III	Distal Phalanx III		
15/03/1985	GSM002	28/02/2006	15959075		x	PA	21.0	XH	5	5	5	5	5	5	slight over exposure at wrist	
04/08/1987	GSM003	22/01/2007	89247142	x		PA	19.5	XH	5	5	5	5	5	5		
27/05/1992	GSM006	24/05/2008	24879109	x		PA	16.0	XH	3	3	5	4	5	5	line visible A type carpals	Fracture to proximal ⅓ of metacarpal 5
15/03/1989	GSM007	23/06/2007	82457961	x		PA	18.3	XH	2	2	5	5	5	5	B^ pattern radius, C type carpals with A type scaphoid	thumb dislocation at metacarpal-phalangeal joint, ulna styloid process damage
24/12/1987	GSM008	18/06/2007	28503647	x		PA	19.5	FR	5	5	5	5	5	5		injury to distal phalanx
07/06/1990	GSM009	24/05/2007	26938555	x		PA	17.0	XH	3	3	5	4	3	4	F type carpals with B type capitate	Fracture to proximal end of metacarpal 3
21/11/1992	GSM013	15/07/2008	41166950	x		PA	15.7	FR	3	2	5	4	4	5		
02/09/1987	GSM014	10/08/2007	29663937	x		PA	19.9	XH	3	3	4	4	2	2		Fracture to distal end of middle phalanx
22/02/1994	GSM018	01/11/2007	32272791		x	PA	13.7	XH	2	3	3	3	3	4	proximal phalanx 1&2 fused and 4&5 = 16 yeas SA but phalanx 3 mid phalangeal epiphysis still not fused = 15.5 years SA.	
03/02/1987	GSM019	25/05/2008	39565791		x	PA	21.3	XH	5	5	5	5	5	5		injury to proximal phalanges 2 and 3
06/06/1987	GSM020	30/05/2008	39561725		x	PA	21.0	XH	5	5	5	5	5	5	C type carpals with B type scaphoid.	Fracture proximal end of proximal phalanx 3
23/10/1987	GSM021	10/05/2008	34266817	x		PA	20.5	EN	4	5	5	4	5	5	line visible. Referred from Khayelitsha clinic	
04/06/1994	GSM022	27/11/2007	29636867		x	PA	13.5	XH	1	1	1	1	1	1	including metacarpal epiphyses	
03/12/1986	GSM025	22/10/2006	23323439	x		PA	19.9	EN	5	5	5	5	5	5		injury to proximal end of metacarpal 3.
22/05/1994	GSM026	18/09/2007	31177439		x	PA	13.3	XH	1	1	1	1	1	1		
13/03/1987	GSM027	11/10/2007	31771405	x		PA	20.6	XH	4	5	5	5	5	5	line visible	

DOB	ASSIGNED CODE	DATE OF RADIOGRAPH	FOLDER #	IMAGE			CHRONOLOGICAL AGE (years)	LANGUAGE	Schmidt *et al.* EPIPHYSEAL CLOSURE						COMMENTS Including carpal morphology indicated by letters A to G adapted from Greulich WW. 1960. Skeletal features visible on roentgenogram of the hand and wrist which can be used for establishing individual identification. Am J Roentgenol 83:756-764.	TRAUMA
				LEFT	RIGHT	VIEW			Radius	Ulna	Metacarpal III	Proximal Phalanx III	Middle Phalanx III	Distal Phalanx III		
07/06/1990	GSM028	29/04/2007	26938555	x		PA	16.9	XH	3	3	5	5	3	4		
08/09/1988	GSM029	02/07/2007	28971539	x		PA	18.8	XH	3	3	5	5	5	4		dislocation at metacarpo-phalangeal joint 5.
28/02/1987	GSM031	07/02/2008	34401562	x		PA	20.9	?	5	5	5	5	5	5	of African origin from name	
09/12/1988	GSM032	28/02/2008	36453538	x		PA	19.2	EN	4	5	5	5	5	5	line visible. Referred from Nolunge Clinic	Tip of distal phalanx3 is broken.
07/03/1991	GSM033	18/03/2008	37176559		x	PA	17.0	AF	3	3	5	5	5	5	line visible. Referred from Vredenburg..	Injury to metacarpal 5
01/08/1986	GSM034	18/02/2008	68555531		x	PA	21.5	XH	4	5	4	5	5	5	line visible C type carpals small ulnar styloid process	
06/06/1986	GSM035	10/09/2007	68366053	x		PA	21.3	XH	4	4	5	5	5	5	line visible. C type carpals	Distal ulna is broken and middle and distal phalanges of digit 5 are missing.
13/01/1989	GSM036	20/11/2007	73725087		x	PA	18.9	XH	4	5	5	4	5	5	no line visible. H type carpals. 3rd radiograph used for analysis	Distal Fracture to metacarpal 5
25/12/1989	GSM037	14/04/2008	38186011	x	x	PA	18.3	EN	4	4	5	5	5	5	line visible on both hands. Similar development observed on both hands. A type carpals	
07/04/1988	GSM038	13/11/2007	32691008	x		PA	19.6	XH	5	5	5	5	5	5		injury to proximal phalanx 3,4
06/07/1993	GSM039	16/10/2007	31819014	x		PA	14.3	XH	2	1	2	2	1	1		
15/03/1985	GSM040	14/02/2006	15959075		x	PA	20.9	XH	5	5	5	5	5	5	carpals not clear for morphological analysis	
16/06/1989	GSM041	06/10/2008	32787368		x	PA	19.3	EN	5	5	5	5	5	5		
13/11/1987	GSM043	13/11/2008	44428308		x	PA	21.0	XH	3	2	5	4	4	5	proximal phalanges show recent fusion especially 4,5 which show very recent fusion. All other phalanges fully fused. Referred from Somerset Hospital	
08/05/1990	GSM044	04/02/2009	38078374		x	PA	18.7	XH	3	3	5	5	5	5		injury on proximal phalanx 4
12/02/1990	GSM045	23/07/2008	25839366		x	PA	18.4	EN	4	5	5	5	5	5		

DOB	ASSIGNED CODE	DATE OF RADIOGRAPH	FOLDER #	IMAGE			CHRONOLOGICAL AGE (years)	LANGUAGE	Schmidt *et al.* EPIPHYSEAL CLOSURE						COMMENTS Including carpal morphology indicated by letters A to G adapted from Greulich WW. 1960. Skeletal features visible on roentgenogram of the hand and wrist which can be used for establishing individual identification. Am J Roentgenol 83:756-764.	TRAUMA
				LEFT	RIGHT	VIEW			Radius	Ulna	Metacarpal III	Proximal Phalanx III	Middle Phalanx III	Distal Phalanx III		
04/08/1987	GSM046	22/08/2006	89247142	x		PA	19.1	XH	5	5	5	5	5	5		
25/11/1990	GSM047	05/04/2009	48143119		x	PA	18.4	XH	4	3	5	5	5	5	line visible. A^ pattern ulna.	
19/09/1986	GSM048	22/01/2008	34271197		x	PA	21.3	XH	5	5	5	5	5	5		injury observed on proximal phalanx 4
12/10/1988	GSM049	20/07/2007	29308103	x		PA	18.8	XH	5	5	5	5	5	5	F type scaphoid with G type carpals	
27/05/1992	GSM050	24/05/2008	24879108	x		PA	16.0	XH	3	4	5	5	5	5	H type carpals	injury observed on metacarpal 5 and on proximal end of metacarpal 4
06/05/1992	GSM051	15/04/2009	74952276	x		PA	16.9	EN	5	5	5	4	4	4	epiphyseal line still visible on distal radius. B^ pattern ulna shape. B* pattern carpals.	Fracture on 5th digit.
11/05/1992	GSM052	27/02/2009	77664332		x	PA	16.8	EN	1	1	1	1	1	5	B^ pattern ulna. B* pattern ulna. E* pattern carpals. B* pattern radius.	
03/11/1991	GSM054	31/03/2009	47888524		x	PA	17.4	EN	1	1	1	1	1	3	From Gugulethu Hospital.A* pattern ulna. C* pattern radius. B* pattern carpals	
27/07/1990	GSM055	15/04/2009	74884545	x		PA	18.7	EN	2	2	5	5	5	5	B^ pattern ulna. Fracture on metacarpal 1. F* pattern ulna. H* pattern carpals.	
02/07/1990	GSM057	06/03/2009	46691713		x	PA	18.7	EN	5	5	5	5	5	5	very small ulnar styloid process. G* pattern radius. H* pattern carpals.	
19/04/1991	GSM059	23/03/2009	45043825		x	PA	17.9	XH	3	3	5	5	5	5	B^ pattern ulna. C* pattern radius. E* pattern carpals. A* type ulna	
29/05/1991	GSM060	13/11/2008	29043122		x	PA	17.5	XH	4	4	5	5	5	5	.	Fractured 3 and 4 metacarpals as well as proximal phalanx 4 and ulnar styloid process
01/01/1996	GSM064	12/01/2009	13812185		x	PA	13.0	XH	1	1	1	1	1	1	B^ pattern ulna.	
02/04/1994	GSM065	30/07/2008	41589961		x	PA	14.3	XH	2	3	3	3	1	1	. A* pattern carpals.	Fractured ulnar styloid process and Injured lateral metacarpals and carpals.

DOB	ASSIGNED CODE	DATE OF RADIOGRAPH	FOLDER #	IMAGE			CHRONOLOGICAL AGE (years)	LANGUAGE	Schmidt *et al.* EPIPHYSEAL CLOSURE						COMMENTS Including carpal morphology indicated by letters A to G adapted from Greulich WW. 1960. Skeletal features visible on roentgenogram of the hand and wrist which can be used for establishing individual identification. Am J Roentgenol 83:756-764.	TRAUMA
				LEFT	RIGHT	VIEW			Radius	Ulna	Metacarpal III	Proximal Phalanx III	Middle Phalanx III	Distal Phalanx III		
27/08/1985	GSM066	26/07/2007	31301922		x	PA	21.9	XH	5	5	5	5	5	5	. small ulnar styloid process. B^ pattern ulna. H* pattern carpals. D* pattern ulna. H* pattern radius	Fractured metacarpal 2
15/08/1992	GSM069	26/02/2009	46480810		x	PA	16.5	XH	2	3	3	2	1	1	B^ pattern ulna.	Fracture on metacarpal 1.
21/01/1988	GSM070	17/12/2007	33487760	x		PA	19.9	XH	5	5	5	5	5	5	.A^ pattern ulna. B* pattern ulna. H* pattern carpals. D* pattern radius.	Injury on proximal phalanx 4
10/03/1992	GSM071	20/06/2008	80266729	x	x	PA	16.3	EN	5	5	5	5	5	5	The angle of right metacarpal 1 is not appropriate for morphological comparison *. Small styloid process on ulna of both sides.	Injury on left proximal phalanges 2 and 3. injury on middle phalanx 4.
06/06/1987	GSM072	30/05/2008	39561725		x	AP	21.0	XH	5	5	5	5	5	5	A^ pattern ulna.	
10/12/1989	GSM074	28/12/2006	80342751		x	PA	17.1	XH	4	4	5	5	5	5	C type carpals	distal ulna injury
06/06/1987	GSM075	13/07/2007	70754189	x		PA	20.1	XH	5	5	5	5	5	5	A type carpals	
06/04/1988	GSM076	17/11/2007	32691008	x		PA	19.6	XH	4	5	5	5	5	5	H type carpals	trauma to proximal ⅓ of proximal phalanges 3 and 4
23/01/1995	GSM078	27/03/2008	37328267		x	PA	13.2	XH	2	2	1	1	1	1	B type carpals	
13/01/1989	GSM079	20/11/2007	73725087		x	PA	18.9	XH	4	5	5	5	5	5	D type carpals	
14/02/1986	GSM082	08/04/2003	89024426		x	PA	17.2	XH	5	5	5	5	5	5	A type carpals	injured middle phalanx 2.
03/07/1989	GSM083	01/08/2003	74350885		x	PA	14.1	EN	1	1	3	2	1	2	A type carpals with C type scaphoid	distal injury to proximal phalanx 3
08/03/1988	GSM084	29/03/2005	14019715	x		PA	17.1	XH	4	5	5	4	5	5	A type carpals with C type scaphoid	
13/09/1989	GSM085	14/12/2004	13576392	x	x	PA	15.3	UN	2	2	2	2	1	1	both hands developing similarly. Name reflects African descent. G type carpals. Distal phalanges 3 and 4 are fused to each other on both hands.	fractured ulnar styloid process on left. Fractures on distal phalanges 3 and 4 of both hands.
01/01/1985	GSM086	17/06/2004	12959839	x	x	PA	19.5	XH	3	4	5	5	5	5	right hand used as left ulnar and radius epiphyses were unclear. A type carpals with C type scaphoid.	Mid-shaft fracture on left metarcarpal 1

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				LEFT	RIGHT	VIEW			Radius	Ulna	Metacarpal III	Proximal Phalanx III	Middle Phalanx III	Distal Phalanx III		
06/01/1986	GSM087	15/09/2004	88981097		x	PA	18.7	XH	2	1	2	2	1	5	D type carpals	
12/12/1984	GSM088	25/01/2003	88795596	x		PA	18.1	UN	2	1	2	3	2	5	Name reflects African descent. F type carpals with E type scaphoid	
09/08/1984	GSM089	14/07/2003	68891894	x		PA	18.9	XH	5	5	5	4	5	5	H type carpals	Mid-shaft fracture on metacarpals 4 and 5.
19/10/1983	GSM090	14/10/2000	64624588	x		PA	17.0	EN	2	1	2	1	1	5	A type carpals with H type scaphoid	
12/03/1984	GSM092	02/07/2000	65685810	x		PA	16.3	AF	2	1	3	5	4	5	G type carpals with C type hamate. Small ulndar styloid process.	
14/10/1986	GSM093	05/03/2000	68888379		x	PA	13.4	AF	1	1	1	1	1	1	F type carpals with G type capitate.	fracture on proximal end of metacarpal 4.
07/12/1987	GSM094	29/04/2003	89077440		x	PA	15.4		2	2	2	1	1	3	small ulnar styloid process. Carpals unclear for analysis of morphology	crushing trauma to distal end of metacarpal 5
01/01/1984	GSM096	24/08/2000	86421542	x	x	PA	16.6	EN	2	2	3	4	3	5	A type carpals with G type capitate. Both hands developing similarly	Mid-shaft fracture of proximal phalanx2.
20/02/1989	GSM097	01/08/2005	14428700	x		PA	16.4	XH	2	2	5	4	4	5	H type carpals with G type capitate. Lunatotriquetral fusion	extensive fractures to proximal ends of metacarpls 4 and 5
30/03/1988	GSM098	08/03/2004	71340202	x		PA	15.9	XH	2	2	2	1	1	4	All available radiographs used for analysis. C type carpals with A type scaphoid.	distal ends of metacarpals 4 and 5 fractured.
22/06/1988	GSM099	05/10/2004	12808820		x	PA	16.3	XH	3	3	5	5	5	5	G type carpals.	distal end of metacarpal 1 fractured.
27/09/1982	GSM100	16/02/2003	88861588		x	PA	20.4	XH	5	5	5	4	5	5	G type carpals. Large ulnar styloid process	fractures to distal ends of metacarpals 4 and 5
28/05/1986	GSM101	22/04/2004	11484169		x	PA	17.9	XH	2	3	4	5	5	5	A type carpals. Small ulnar styloid process.	fracture to proximal end of metacarpal 3 and mid-shaft fracture to metacarpal 2
15/08/1985	GSM102	15/03/2003	88947296		x	PA	17.6	XH	2	3	4	4	2	5	H type carpals.	Mid-shaft injury to proximal phalanx 3 and fracture to distal end of distal phalanx 5

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				LEFT	RIGHT	VIEW			Radius	Ulna	Metacarpal III	Proximal Phalanx III	Middle Phalanx III	Distal Phalanx III		
13/04/1985	GSM103	17/05/2004	12848180	x	x	PA	19.1	XH	2	2	5	5	5	5	B type carpals. Both hands developing similarly.	Mid-shaft fracture to left metacarpal 2. Mid-shaft fracture to right metacarpal and middle phalanx 1.
15/07/1984	GSM104	26/07/2003	89333355		x	PA	19.0	XH	4	5	5	4	5	5	F type carpals with C type scaphoid.	
03/09/1986	GSM105	07/01/2004	24806010	x		PA	17.3	ST	4	5	5	4	5	5	very small ulnar styloid process (under developed).	dislocation of carpals at trapezium trapezoid and scaphoid juntions.
19/09/1985	GSM106	07/02/2005	13832043		x	PA	19.4	XH	4	5	5	4	5	5	B type carpals with A type scaphoid.	fracture to proximal end of metacarpal 5
09/02/1987	GSM107	14/04/2003	69778132		x	PA	16.2	XH	1	1	2	1	1	2	D type carpals with H type scaphoid.	soft tissue trauma observed.
14/12/1987	GSM108	23/07/2001	87226114	x	x	PA	13.6	EN	1	1	1	1	1	1	both hands developing similarly. F type carpals	soft tissue trauma observed.
19/03/1985	GSM109	08/10/2001	71551071	x		PA	16.6	EN	1	1	1	1	1	1	A type carpals with B type scaphoid. Referred from Guguletu clinic. Small ulnar styloid process	injury to distal phalanx 4
23/08/1985	GSM110	23/11/2002	88639067		x	PA	17.3	XH	2	2	2	2	1	3	H type carpals with G type scaphoid. Referred from Guguletu clinic.	Fracture to distal end of proximal phalanx 4.
25/11/1985	GSM111	17/05/2001	87059671		x	PA	15.5	EN	1	1	1	1	1	1	H type carpals.	fractures to distal ends of metacarpals 4 and 5
26/03/1990	GSM112	13/06/2005	81307928		x	PA	15.2	XH	2	4	2	1	1	1	G type carpals.	ulnar styloid process fractured
03/05/1985	GSM113	26/08/2002	14513543		x	PA	17.3	XH	4	5	5	4	5	5	G type carpals. Very prominent ulnar styloid process.	Mid-shaft fracture of metacarpal 2 and 3. longitudinal fracture on proximal phalanx 1.
18/03/1986	GSM114	20/05/2004	12848644	x		PA	18.2	XH	5	5	5	5	5	5	D type carpals with G type scaphoid	
24/02/1984	GSM115	28/08/2003	89428775		x	PA	19.5	XH	3	5	5	4	5	5	referred from Guguletu clinic. B type carpals with C type scaphoid. Small ulnar styloid process	
01/01/1985	GSM116	26/07/2003	89333256		x	PA	18.6	XH	1	1	2	1	1	1	carpals appear superimposed so individual morphology is indistinguishable	Mid-shaft fractures on distal ⅓ of metacarpal 4

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				LEFT	RIGHT	VIEW			Radius	Ulna	Metacarpal III	Proximal Phalanx III	Middle Phalanx III	Distal Phalanx III		
01/01/1986	GSM117	16/04/2000	16417917		x	PA	14.3	UN	4	5	5	5	5	5	G type carpals. Referred from Guguletu clinic.	soft tissue trauma observed.
19/05/1987	GSM118	24/09/2004	13333042	x	x	PA	17.3	XH	3	2	5	4	5	5	distinct difference between ulna and radius development and between ulna and metacarpals and phalanges. Observed in both hands. C type carpals.	
27/03/1986	GSM119	05/03/2004	12491635		x	PA	17.9	XH	2	2	5	4	5	5	H type carpals	soft tissue trauma observed.
05/02/1984	GSM120	29/01/2002	87682480		x	PA	18.0	EN	2	3	4	4	5	5	G type carpals	
01/01/1982	GSM121	27/07/2003	89335285		x	PA	21.6	XH	4	5	5	4	5	5	A type carpals. Small ulnar styloid process.	fractures observed on distal end of proximal phalanx 4 and proximal end of middle phalanx 4
10/06/1985	GSM122	12/08/2004	13044862		x	PA	19.2	XH	4	5	5	5	5	5	lunato-triquetral fusion. Small ulnar styloid process. G type carpals with C type scaphoid.	fracture of distal end of proximal phalanx 3
01/12/1983	GSM123	30/05/2005	14278980		x	PA	21.5	XH	3	3	5	5	5	5	carpals are over-exposed so no morphological analysis possible.	fracture at base of ulnar styloid process.
18/07/1983	GSM124	04/12/2003	75062034		x	PA	20.4	XH	4	5	5	4	5	5	G type carpals.	injury to distal end of metacarpal 1 and proximal end of proximal phalanx 2.
19/11/1983	GSM125	04/04/2004	12597571		x	PA	20.4	XH	4	5	5	4	5	5	B type carpals with E type scaphoid. Small ulnar styloid process.	Hunter's Bow of 4 and 5th fingers.
04/01/1984	GSM126	15/10/2004	13414503	x		PA	20.8	XH	5	5	5	4	5	5	B type carpals with H type scaphoid.	crushing trauma to distal ⅓ of proximal phalanx 2.
06/06/1984	GSM127	03/10/2005	14756829	x		PA	21.3	XH	5	5	5	5	5	5	E type carpals with B type scaphoid.	distal phalanx 5 amputation.
10/07/1984	GSM128	08/08/2004	13148085	x		PA	20.1	UN	2	2	5	5	5	5	C type carpals with D type scaphoid.	Mid-shaft fracture to metacarpal 2. fracture to ulna styloid process.
15/09/1988	GSM129	07/08/2003	74407438		x	PA	14.9	XH	1	1	1	1	1	1	carpals still developing	

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				LEFT	RIGHT	VIEW			Radius	Ulna	Metacarpal III	Proximal Phalanx III	Middle Phalanx III	Distal Phalanx III		
18/09/1984	GSM130	21/11/2004	13558242	x	x	PA	20.2	XH	5	5	5	4	5	5	both hands developing similarly. A type carpals	injury to lateral aspect of right proximal phalanx 2
23/03/1985	GSM131	28/12/2005	15763170	x		PA	20.8	XH	4	5	5	5	5	5	E type carpals with B type scaphoid. Referred from Guguletu clinic	Mid-shaft fractures of 3rd and 4th metacarpals.
04/10/1984	GSM132	04/10/2005	15451917	x		PA	21.0	XH	1	1	2	3	2	4	G type carpals. Lunato-triquetral fusion.	crushing trauma to distal phalanx 5.
08/03/1988	GSM133	14/11/2005	15556194		x	PA	17.7	XH	3	3	5	4	5	5	G type carpals	
09/07/1984	GSM134	03/01/2001	87621017		x	PA	16.5	XH	2	2	5	4	5	4	C type carpals	dislocation at proximal interphalangeal joint 2
28/03/1984	GSM135	31/10/2003	89518062	x		PA	19.6	XH	5	5	5	5	5	5	B type carpals	crushin g trauma to mid-shaft region of middle phalanx 2
04/12/1983	GSM136	25/01/2001	86779014	x		PA	17.1	EN	3	4	5	5	5	5	B type carpals with H type scaphoid.	midshaft injury to proximal phalanx 5 with additional soft tissue trauma
28/01/1984	GSM137	14/04/2003	64570096		x	PA	19.2	XH	5	5	5	5	5	5	E type carpals with C type scaphoid.	tip of distal phalanx 2 injured.
06/12/1982	GSM138	17/05/2003	89135867	x		PA	20.4	EN	5	4	5	4	5	5	carpal shapes undiscernable	ulnar styloid process fractured
24/12/1984	GSM139	12/12/2000	66090010		x	PA	16.0	EN	3	3	5	4	5	5	C type carpals with B type scaphoid.	Mid-shaft fracture to proximal phalanx 5
26/05/1991	GSM140	25/11/2005	76124726		x	PA	14.5	XH	1	1	1	1	1	1	A type carpals. Referred from Guguletu clinic.	ulnar styloid process fractured
09/06/1988	GSM141	02/04/2004	12593901		x	PA	15.8	UN	2	1	1	1	1	1	carpal shapes indiscernible	crushing trauma to distal phalanx 4
26/12/1984	GSM142	26/12/2003	89754402	x	x	PA	19.0	XH	1	1	1	1	1	1	both hands developing similarly. B type carpals	left metacarpo-phalangeal joint 5 dislocation.
08/02/1987	GSM143	11/12/2001	87774394		x	PA	14.8	UN	1	1	1	1	1	1	G type carpals	
12/08/1991	GSM144	30/03/2006	16235848	x		PA	14.6	XH	1	1	1	1	1	1	G type carpals.	crushing trauma to distal end of distal phalanx 4
30/05/1986	GSM147	19/03/2005	13995576	x		PA	18.8	EN	4	5	5	4	5	5	G type carpals.	fracture to head of metacarpal 5.
17/05/1992	GSM148	12/06/2006	17145475	x		PA	14.1	XH	1		1	1	1	1	B type carpals with C type scaphoid	trauma to distal end of ulna diaphysis.

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				LEFT	RIGHT	VIEW			Radius	Ulna	Metacarpal III	Proximal Phalanx III	Middle Phalanx III	Distal Phalanx III		
15/10/1987	GSM149	07/11/2006	23644479		x	PA	19.1	XH	2	2	5	4	5	5	B type carpals with C type scaphoid	Mid-shaft fractures to proximal phalanges 3,4
18/08/1987	GSM150	11/07/2006	70466941		x	PA	18.9	XH	2	2	5	5	5	5	carpal shapes indiscernible	distal end of distal phalanx 5 fractured
30/03/1990	GSM151	01/06/2006	17053901	x		PA	16.2	XH	1	1	2	3	1	5	G type carpals with C type scaphoid.	fracture at diaphysis-epiphyseal junction in proximal phalanges 3 and 5. thus analysis performed on 4th finger
12/04/1991	GSM152	14/11/2006	23768336	x		PA	15.6	XH	1	1	4	4	4	5	carpal shapes indiscernible	trauma to lateral aspect of the hand. Triquetral fractured/crushed
21/09/1989	GSM153	09/11/2006	23678311	x		PA	17.1	XH	4	5	4	4	5	4	G type carpals	
08/10/1990	GSM154	17/07/2006	84503218		x	PA	15.8	XH	1	1	1	1	1	1	H type carpals	
17/08/1986	GSM155	08/04/2006	16327579		x	PA	19.6	UN	4	5	5	5	5	5	C type carpals with E type scaphoid.	Mid-shaft fractures to metacarpal 3 and 4
12/07/1990	GSM156	07/10/2005	14776371	x		PA	15.2	XH	1	1	1	1	1	1	A type carpals.	dislocation at proximal interphalangeal joint 3.
01/02/1989	GSM157	23/05/2006	15505795		x	PA	17.3	XH	2	3	5	5	5	5	C type carpals.	Mid-shaft fracture to proximal phalanx 4
18/03/1992	GSM158	19/02/2006	77231272	x	x	PA	13.9	XH	1	1	1	1	1	1	G type carpals. Small ulnar styloid process. Both hands developing similarly.	crushing trauma to left proximal and distal phalanges 3. thus analysis performed on right hand
14/09/1986	GSM160	22/05/2006	16917718		x	PA	19.7	XH	3	5	5	4	4	4	H type carpals.	fracture to distal end of metacarpal 5
16/04/1985	GSM161	03/10/2006	20740684		x	PA	21.5	XH	4	5	5	4	5	5	D type carpals.	longitudinal fracture to proximal aspect of metacarpal 3, mid-shaft transverse fracture to distal end of metacarpal 4

APPENDIX B Data collection sheet for female sample: Schmidt *et al.* Method results.

Individuals with skeletal anomalies are highlighted in Red.

DOB	ASSIGNED CODE	DATE OF RADIOGRAPH	FOLDER #	IMAGE			CHRONOLOGICAL AGE (years)	LANGUAGE	Schmidt *et al.* EPIPHYSEAL CLOSURE						COMMENTS Including carpal morphology indicated by letters A to G adapted from Greulich WW. 1960. Skeletal features visible on roentgenogram of the hand and wrist which can be used for establishing individual identification. Am J Roentgenol 83:756-764.	TRAUMA
				LEFT	RIGHT	VIEW			Radius	Ulna	Metacarpal III	Proximal Phalanx III	Middle Phalanx III	Distal Phalanx III		
09/11/1992	GSF001	21/12/2006	78670676	x		PA	14.1	XH	3	3	4	4	3	2	Khayetsha referral. C type carpals	
23/04/1986	GSF002	06/12/2005	14388797	x		PA	19.6	XH	5	5	5	5	5	5		
02/07/1988	GSF004	17/03/2008	26070946	x	x	PA	19.7	EN	5	5	5	5	5	5	extra numery digit on both hands (under developed 6th digit). Both hands similar in development	
07/07/1992	GSF005	25/01/2008	34130906		x	PA	15.6	XH	4	3	5	5	5	5	lunate-triquetral fusion. G type carpals	trauma to lateral side of capitate and medial side of hamate
28/02/1995	GSF007	08/10/2008	44315892		x	PA	13.6	XH	3	3	5	5	3	5	carpals angled so no morphological analysis	
11/08/1985	GSF008	22/06/2006	17384470	x		PA	20.9	XH	5	5	5	5	5	5	no line	
28/12/1989	GSF009	16/11/2008	44432078		x	PA	18.9	XH	4	5	5	4	5	5	line visible. G type carpals	
08/12/1992	GSF010	08/05/2009	33811274	x		PA	16.4	XH	3	3	5	5	5	4	Injury on proximal phalanx 3. F* pattern carpals. H* pattern radius and ulna.	
04/01/1992	GSF011	06/02/2009	45766839		x	PA	17.1	XH	4	4	5	5	5	5	Line visible B^ pattern ulna. A* pattern carpals. A* pattern radius and ulna. From Khayelitsha Hospital.	
07/12/1985	GSF012	22/07/2007	19341999	x	x	PA	21.6	XH	5	5	5	5	5	5	A^ pattern ulna. Both hands similar in development and morphologogy. D* pattern radius. A* pattern ulna. F* pattern carpals.	

DOB	ASSIGNED CODE	DATE OF RADIOGRAPH	FOLDER #	IMAGE			CHRONOLOGICAL AGE	LANGUAGE	Schmidt *et al.* EPIPHYSEAL CLOSURE						COMMENTS Including carpal morphology indicated by letters A to G adapted from Greulich WW. 1960. Skeletal features visible on roentgenogram of the hand and wrist which can be used for establishing individual identification. Am J Roentgenol 83:756-764.	TRAUMA
				LEFT	RIGHT	VIEW			Radius	Ulna	Metacarpal III	Proximal Phalanx III	Middle Phalanx III	Distal Phalanx III		
04/06/1987	GSF013	16/07/2008	41234956		x	PA	21.1	XH	5	5	5	5	5	5	A^ pattern ulna. Both hands similar in development and morphologogy. D* pattern radius. A* pattern ulna. F* pattern carpals.	
28/02/1995	GSF014	10/11/2008	43241892		x	PA	13.8	XH	3	3	5	5	4	5	dislocated thumb. B* pattern carpals. A* pattern ulna. A* pattern radius.	
14/06/1992	GSF017	05/12/2005	15700933	x		PA	13.5	XH	2	2	3	4	2	5	carpals not very clear for analysis of morphology	
25/02/1987	GSF018	01/08/2003	89325930		x	PA	16.4	XH	3	5	5	5	5	5	A type carpals.	Thumb dislocation
04/07/1987	GSF019	16/08/2000	86413531	x		PA	13.1	EN	1	1	2	1	1	1	too young for analysis of carpal morphology	
20/05/1985	GSF020	21/12/2002	88714282		x	PA	17.6	XH	4	5	5	4	5	4	H Type carpals	
16/04/1985	GSF021	30/11/2001	87552287	x		PA	16.6	EN	3	3	5	4	4	5	A type carpals with G type scaphoid.	
09/09/1983	GSF022	05/02/2001	86806692		x	PA	17.4	EN	2	2	3	4	2	5	F type carpals with H type scaphoid.	
06/02/1990	GSF023	25/08/2004	80722986	x		PA	14.6	XH	1	1	1	1	1	1	F type carpals with D type scaphoid.	
16/04/1982	GSF024	15/06/2002	88158175	x		PA	20.2	XH	4	5	5	4	5	5	The epiphyseal lines on the proximal phalanges are still visible. G type carpals.	

DOB	ASSIGNED CODE	DATE OF RADIOGRAPH	FOLDER #	IMAGE			CHRONOLOGICAL AGE (years)	LANGUAGE	Schmidt *et al.* EPIPHYSEAL CLOSURE						COMMENTS Including carpal morphology indicated by letters A to G adapted from Greulich WW. 1960. Skeletal features visible on roentgenogram of the hand and wrist which can be used for establishing individual identification. Am J Roentgenol 83:756-764.	TRAUMA
				LEFT	RIGHT	VIEW			Radius	Ulna	Metacarpal III	Proximal Phalanx III	Middle Phalanx III	Distal Phalanx III		
20/04/1986	GSF027	20/04/2005	68902014	x	x	PA	19.0	XH	4	5	5	4	5	5	C type carpals. Both hands developing similarly	
20/01/1987	GSF028	03/09/2002	88394101		x	PA	15.6	XH	2	3	2	3	1	1	G type carpals with C type scaphoid.	
23/10/1986	GSF029	01/04/2003	89004089	x	x	PA	16.4	XH	2	2	5	5	5	5	Both hands developing similarly. G type carpals with C type scaphoid.	
21/10/1984	GSF030	15/08/2001	65731887		x	PA	16.8	EN	5	5	5	5	5	5	C type carpals with A type scaphoid.	
09/10/1985	GSF031	17/08/2001	69658128		x	PA	15.9	EN	2	2	5	4	5	5	C type carpals. Both hands developing similarly	amputated distal phalanx 5.
01/01/1986	GSF032	09/04/2001	86968443		x	PA	15.3	EN	2	1	2	2	1	1	carpals not very clear for analysis of morphology	distal fracture of middle phalanges 2 and with crushing fracture to proximal end of middle phalanx 2.
29/03/1987	GSF033	03/04/2001	86952595	x		PA	14.0	EN	1	1	1	1	1	1	G type carpals.	
01/05/1983	GSF034	08/10/2001	87409926		x	PA	18.4	EN	4	5	5	4	5	5	G type carpals with C type scaphoid.	
26/06/1989	GSF035	30/10/2006	74683210		x	PA	17.3	XH	4	5	5	5	5	5	F type carpals with C type scaphoid.	thumb dislocation at the interphalangeal joint.
19/08/1992	GSF036	23/05/2006	82544198	x		PA	13.8	XH	3	2	5	5	5	5	B type carpals with C type scaphoid.	dislocation at the proximal interphalangeal joint 1.
24/06/1989	GSF037	25/05/2009	29237104	x		PA	19.9	EN	5	5	5	5	5	5	Apparent agenesis of styloid process on ulna. F* pattern radius. B* pattern carpals.	
28/12/1989	GSF038	16/11/2008	44432078		x	PA	18.9	XH	4	4	5	5	5	5	B* pattern radius. C* pattern ulna. F* pattern carpals.	

APPENDIX C Data analysis sheets for Greulich & Pyle Estimations

a) Male Sample

ASSIGNED CODE	FOLDER #	LEFT	RIGHT	VIEW	CHRONOLOGICAL AGE (years)	LANGUAGE	Greulich & Pyle EPIPHYSEAL CLOSURE ESTIMATES FOR SKELETAL AGE					Final (SA)	CA-SA difference (in years)	CA-SA difference (in months)
							Radius	Ulna	EST 1	EST 2	EST 3			
GSM064	13812185		x	PA	13.0	XH	11.5	11	12	11.5		11.8	1.3	15.4
GSM078	37328267		x	PA	13.2	XH	14	13.5	13.5	14		13.8	-0.6	-6.9
GSM026	31177439		x	PA	13.3	XH	10	10	10.5	10	10.5	10.3	3.1	36.9
GSM093	68888379		x	PA	13.4	AF	13.5	13.5	13.5	13.5		13.5	-0.1	-1.3
GSM022	29636867		x	PA	13.5	XH	11	11	11	11	10.5	11.0	2.5	29.8
GSM108	87226114	x	x	PA	13.6	EN	12.5	12.5	12.5	12.5		12.5	1.1	13.3
GSM018	32272791		x	PA	13.7	XH	15.5	15.5	15.75	15.5	16	15.6	-1.9	-23.2
GSM158	77231272	x	x	PA	13.9	XH	14	14	14	14		14.0	-0.1	-1.0
GSM148	17145475	x		PA	14.1	XH	13.5	13.5	13.5			13.5	0.6	6.8
GSM083	74350885		x	PA	14.1	EN	13.5	14	13.75	13.5		13.6	0.5	5.4
GSM039	31819014	x		PA	14.3	XH	15	14	14	14.5	14.5	14.3	0.0	0.3
GSM117	16417917		x	PA	14.3	UN	19	19	19	19		19.0	-4.7	-56.5
GSM065	41589961		x	PA	14.3	XH	15	15.5	15	15		15.0	-0.7	-8.1
GSM140	76124726		x	PA	14.5	XH	14	14	14	14	14	14.0	0.5	6.0
GSM144	16235848	x		PA	14.6	XH	14	13.5	13.5	13.75	12.75	13.6	1.0	12.1
GSM143	87774394		x	PA	14.8	UN	14	14	14	14	14	14.0	0.8	10.1
GSM129	74407438		x	PA	14.9	XH	12.5	12.5	12.5	12.5		12.5	2.4	28.7
GSM112	81307928		x	PA	15.2	XH	15	15.5	15.5	15.25		15.4	-0.2	-1.9
GSM156	14776371	x		PA	15.2	XH	14	14	14	14		14.0	1.2	14.8
GSM085	13576392	x	x	PA	15.3	UN	15	14	15	14.5		14.8	0.5	6.0
GSM094	89077440		x	PA	15.4	UN	14	14	14	14		14.0	1.4	16.7

ASSIGNED CODE	FOLDER #	LEFT	RIGHT	VIEW	CHRONOLOGICAL AGE (years)	LANGUAGE	Greulich & Pyle EPIPHYSEAL CLOSURE ESTIMATES FOR SKELETAL AGE					Final (SA)	CA-SA difference (in years)	CA-SA difference (in months)
							Radius	Ulna	EST 1	EST 2	EST 3			
GSM111	87059671		x	PA	15.5	EN	14	14	14	14		14.0	1.5	17.7
GSM152	23768336	x		PA	15.6	XH	16	16.5	16.25	16.5		16.4	-0.8	-9.4
GSM013	41166950	x		PA	15.7	FR	17	16	16	16.5	16.5	16.3	-0.6	-7.2
GSM154	84503218		x	PA	15.8	XH	14	14	14	14		14.0	1.8	21.3
GSM141	12593901		x	PA	15.8	UN	15	14	14.5	14.5	14.5	14.5	1.3	15.8
GSM098	71340202	x		PA	15.9	XH	15	15	15	15.5		15.3	0.7	8.3
GSM139	66090010		x	PA	16.0	EN	17	18	17.5	17.5		17.5	-1.5	-18.4
GSM006	24879109	x		PA	16.0	XH	17	17	17	17	17.5	17.0	-1.0	-12.1
GSM050	24879108	x		PA	16.0	XH	17	17	17	17	17	17.0	-1.0	-12.1
GSM151	17053901	x		PA	16.2	XH	16	15.5	15.5	15.75		15.6	0.5	6.5
GSM107	69778132		x	PA	16.2	XH	15	15	15	15		15.0	1.2	14.2
GSM071	80266729	x	x	PA	16.3	EN	19	19	19	19		19.0	-2.7	-32.7
GSM099	12808820		x	PA	16.3	XH	17	17	17	17	17	17.0	-0.7	-8.6
GSM092	65685810	x		PA	16.3	AF	16.5	16	16.25	17		16.6	-0.3	-3.8
GSM097	14428700	x		PA	16.4	XH	18	17	17	17.5		17.3	-0.8	-9.6
GSM134	87621017		x	PA	16.5	XH	16	17	16.5	16.5	16.5	16.5	0.0	-0.2
GSM069	46480810		x	PA	16.5	XH	15	15	14.5	15		14.8	1.8	21.4
GSM109	71551071	x		PA	16.6	EN	14	14	14	14.5		14.3	2.3	27.6
GSM096	86421542	x	x	PA	16.6	EN	16	16	16	16		16.0	0.6	7.8
GSM052	77664332		x	PA	16.8	EN	15	15	15	15		15.0	1.8	21.5
GSM028	26938555	x		PA	16.9	XH	16	16	16.5	16	16	16.3	0.6	7.7
GSM051	74952276	x		PA	16.9	EN	19	19	19	19		19.0	-2.1	-24.7
GSM009	26938555	x		PA	17.0	XH	17	17	16.5	16.5	16	16.5	0.5	5.6
GSM090	64624588	x		PA	17.0	EN	15.5	15.5	15.5	15.5		15.5	1.5	17.8

ASSIGNED CODE	FOLDER #	LEFT	RIGHT	VIEW	CHRONOLOGICAL AGE (years)	LANGUAGE	Greulich & Pyle EPIPHYSEAL CLOSURE ESTIMATES FOR SKELETAL AGE					Final (SA)	CA-SA difference (in years)	CA-SA difference (in months)
							Radius	Ulna	EST 1	EST 2	EST 3			
GSM033	37176559		x	PA	17.0	AF	17.5	17	17.5	17.25	17	17.4	-0.3	-4.1
GSM074	80342751		x	PA	17.1	XH	18	18	18	18		18.0	-0.9	-11.4
GSM084	14019715	x		PA	17.1	XH	18.5	18	18.25	18.25		18.3	-1.2	-14.3
GSM153	23678311	x		PA	17.1	XH	19	19	19	18.5	18.5	18.8	-1.6	-19.4
GSM136	86779014	x		PA	17.1	EN	18	17	17	17.5	17.5	17.3	-0.1	-1.3
GSM082	89024426		x	PA	17.2	XH	19	19	19	19		19.0	-1.9	-22.2
GSM110	88639067		x	PA	17.3	XH	15	15.5	15.25	15.25		15.3	2.0	24.0
GSM157	15505795		x	PA	17.3	XH	17	17	17	17		17.0	0.3	3.7
GSM113	14513543		x	PA	17.3	XH	18.5	18	18.25	18.25		18.3	-0.9	-11.2
GSM105	24806010	x		PA	17.3	ST	18.5	18.5	18.5	18.5	18.5	18.5	-1.2	-13.9
GSM118	13333042	x	x	PA	17.3	XH	18	15	16.5	16.5		16.5	0.8	10.2
GSM054	47888524		x	PA	17.4	EN	15.5	15.5	15.5	15.5		15.5	1.9	22.9
GSM060	29043122		x	PA	17.5	XH	18	17	18.5	18.5		18.5	-1.0	-12.5
GSM102	88947296		x	PA	17.6	XH	16	16	16	16	16	16.0	1.6	19.0
GSM133	15556194		x	PA	17.7	XH	17.5	17	17	17.5	17.5	17.3	0.4	5.2
GSM101	11484169		x	PA	17.9	XH	17	16	16.5	16.5	16.5	16.5	1.4	16.8
GSM059	45043825		x	PA	17.9	XH	18	17	18.5	18.5		18.5	-0.6	-6.9
GSM119	12491635		x	PA	17.9	XH	17	17	17	17		17.0	0.9	11.3
GSM120	87682480		x	PA	18.0	EN	17	17	17	17		17.0	1.0	11.8
GSM088	88795596	x		PA	18.1	UN	15	16	16.5	16.5		16.5	1.6	19.4
GSM114	12848644	x		PA	18.2	XH	19	19	19	19		19.0	-0.8	-9.9
GSM007	82457961	x		PA	18.3	XH	17	17	17.5	17	17	17.3	1.0	12.3
GSM037	38186011	x	x	PA	18.3	EN	18	18	18	18	18	18.0	0.3	3.6
GSM047	48143119		x	PA	18.4	XH	18	17	18	17.5	17.5	17.8	0.6	7.3

ASSIGNED CODE	FOLDER #	LEFT	RIGHT	VIEW	CHRONOLOGICAL AGE (years)	LANGUAGE	Greulich & Pyle EPIPHYSEAL CLOSURE ESTIMATES FOR SKELETAL AGE					Final (SA)	CA-SA difference (in years)	CA-SA difference (in months)
							Radius	Ulna	EST 1	EST 2	EST 3			
GSM045	25839366		x	PA	18.4	EN	18	18	18	18	18	18.0	0.4	5.4
GSM116	89333256		x	PA	18.6	XH	15.5	15.5	15.5	14.5		15.0	3.6	42.8
GSM057	46691713		x	PA	18.7	EN	19	19	19	19		19.0	-0.3	-3.9
GSM087	88981097		x	PA	18.7	XH	16	15.5	15.5	15.5		15.5	3.2	38.3
GSM055	74884545	x		PA	18.7	EN	16.5	17	17	17		17.0	1.7	20.6
GSM044	38078374		x	PA	18.7	XH	17	17	17	17	16.5	17.0	1.7	20.9
GSM049	29308103	x		PA	18.8	XH	18	18	18	18	18	18.0	0.8	9.3
GSM147	13995576	x		PA	18.8	EN	19	19	19	19		19.0	-0.2	-2.4
GSM029	28971539	x		PA	18.8	XH	17	17	17	17	17	17.0	1.8	21.8
GSM036	73725087		x	PA	18.9	XH	19	19	19	19	19	19.0	-0.1	-1.8
GSM079	73725087		x	PA	18.9	XH	19	19	19	19		19.0	-0.1	-1.8
GSM150	70466941		x	PA	18.9	XH	17	17	17	17		17.0	1.9	22.8
GSM089	68891894	x		PA	18.9	XH	19	19	19	19		19.0	-0.1	-0.8
GSM142	89754402	x	x	PA	19.0	XH	15	15	15	15	15	15.0	4.0	48.0
GSM104	89333355		x	PA	19.0	XH	18	18	18	18.5		18.3	0.8	9.4
GSM046	89247142	x		PA	19.1	XH	18	18	18	18	18	18.0	1.1	12.6
GSM149	23644479		x	PA	19.1	XH	17	16	16.5	16.5		16.5	2.6	30.7
GSM103	12848180	x	x	PA	19.1	XH	18	17	17.5	17.5		17.5	1.6	19.1
GSM122	13044862		x	PA	19.2	XH	18.5	19	18.75	19		18.9	0.3	3.6
GSM137	64570096		x	PA	19.2	XH	19	19	19	19		19.0	0.2	2.5
GSM032	36453538	x		PA	19.2	EN	18	18	18	18	18	18.0	1.2	14.6
GSM041	32787368		x	PA	19.3	EN	18	18	18	18	18	18.0	1.3	15.7
GSM106	13832043		x	PA	19.4	XH	19	19	19	19		19.0	0.4	4.6
GSM086	12959839	x	x	PA	19.5	XH	18	17.5	17.75	18		17.9	1.6	19.0

ASSIGNED CODE	FOLDER #	LEFT	RIGHT	VIEW	CHRONOLOGICAL AGE (years)	LANGUAGE	Greulich & Pyle EPIPHYSEAL CLOSURE ESTIMATES FOR SKELETAL AGE					Final (SA)	CA-SA difference (in years)	CA-SA difference (in months)
							Radius	Ulna	EST 1	EST 2	EST 3			
GSM003	89247142	x		PA	19.5	XH	18	18	18	18	18	18.0	1.5	17.6
GSM008	28503647	x		PA	19.5	FR	18	18	18	18	18	18.0	1.5	17.8
GSM115	89428775		x	PA	19.5	XH	18	18	18	18		18.0	1.5	18.1
GSM135	89518062	x		PA	19.6	XH	19	19	19	19		19.0	0.6	7.1
GSM038	32691008	x		PA	19.6	XH	18	18	18	18	18	18.0	1.6	19.2
GSM076	32691008	x		PA	19.6	XH	18	19	18.5	18.5		18.5	1.1	13.4
GSM155	16327579		x	PA	19.6	UN	19	19	19	19		19.0	0.6	7.7
GSM160	16917718		x	PA	19.7	XH	18.5	18	18.5	18.5		18.5	1.2	14.3
GSM025	23323439	x		PA	19.9	EN	18	18	18	18	18	18.0	1.9	22.6
GSM070	33487760	x		PA	19.9	XH	19	19	19	19		19.0	0.9	10.9
GSM014	29663937	x		PA	19.9	XH	16	15.5	16	16.75	16	16.4	3.6	42.8
GSM128	13148085	x		PA	20.1	UN	16	17	16.5	17	17	16.8	3.3	39.9
GSM075	70754189	x		PA	20.1	XH	19	19	19	19		19.0	1.1	13.2
GSM130	13558242	x	x	PA	20.2	XH	19	19	19	19		19.0	1.2	14.1
GSM125	12597571		x	PA	20.4	XH	19	19	19	19	18.5	19.0	1.4	16.5
GSM124	75062034		x	PA	20.4	XH	19	19	19	19	19	19.0	1.4	16.5
GSM100	88861588		x	PA	20.4	XH	19	19	19	19		19.0	1.4	16.6
GSM138	89135867	x		PA	20.4	EN	19	19	19	19		19.0	1.4	17.4
GSM021	34266817	x		PA	20.5	EN	18	18	18	18	18	18.0	2.5	30.6
GSM027	31771405	x		PA	20.6	XH	18	18	18	18	18	18.0	2.6	30.9
GSM131	15763170	x		PA	20.8	XH	19	19	19	19		19.0	1.8	21.2
GSM126	13414503	x		PA	20.8	XH	19	19	19	19		19.0	1.8	21.4
GSM040	15959075		x	PA	20.9	XH	19	19	19	19	18	19.0	1.9	23.0
GSM031	34401562	x		PA	20.9	?	18	18	18	18	18	18.0	2.9	35.2

ASSIGNED CODE	FOLDER #	LEFT	RIGHT	VIEW	CHRONOLOGICAL AGE (years)	LANGUAGE	Greulich & Pyle EPIPHYSEAL CLOSURE ESTIMATES FOR SKELETAL AGE					Final (SA)	CA-SA difference (in years)	CA-SA difference (in months)
							Radius	Ulna	EST 1	EST 2	EST 3			
GSM002	15959075		x	PA	21.0	XH	18	18	18	18	18	18.0	3.0	35.4
GSM020	39561725		x	PA	21.0	XH	19	19	19	19	18	19.0	2.0	23.8
GSM072	39561725		x	AP	21.0	XH	19	19	19	19		19.0	2.0	23.8
GSM043	44428308		x	PA	21.0	XH	16.5	16.5	16.5	16.5	16.5	16.5	4.5	54.0
GSM132	15451917	x		PA	21.0	XH	16	16	16	16		16.0	5.0	60.0
GSM035	68366053	x		PA	21.3	XH	18	18	18	18	18	18.0	3.3	39.1
GSM019	39565791		x	PA	21.3	XH	18	18	18	18	18	18.0	3.3	39.7
GSM127	14756829	x		PA	21.3	XH	19	19	19	19	19	19.0	2.3	27.9
GSM048	34271197		x	PA	21.3	XH	18	18	18	18	18	18.0	3.3	40.1
GSM161	20740684		x	PA	21.5	XH	19	19	19	19	19	19.0	2.5	29.6
GSM123	14278980		x	PA	21.5	XH	18	17	17.5	17.5	17.5	17.5	4.0	48.0
GSM034	68555531		x	PA	21.5	XH	19	19	19	19	18	19.0	2.5	30.6
GSM121	89335285		x	PA	21.6	XH	18	18.5	18.5	18.5	18.5	18.5	3.1	36.9
GSM066	31301922		x	PA	21.9	XH	19	19	19	19		19.0	2.9	35.0

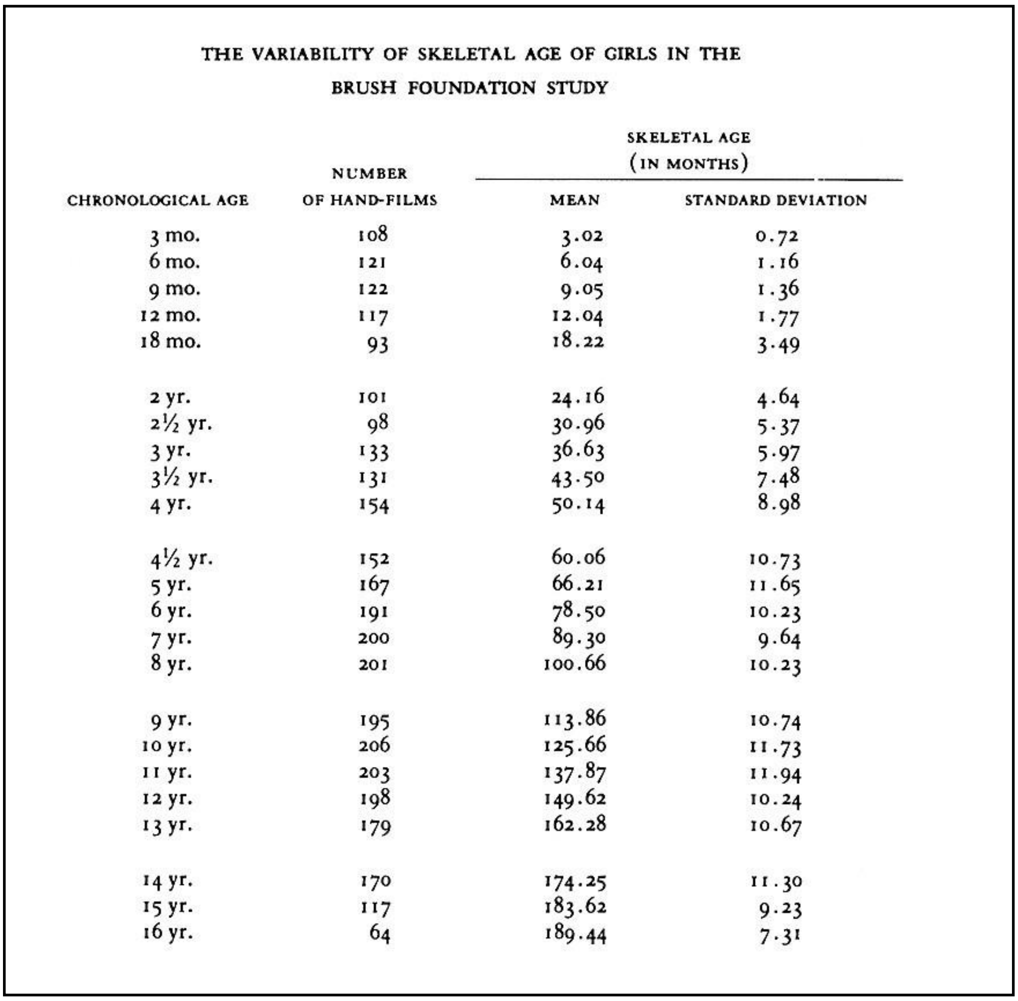
b) Female Sample

ASSIGNED CODE	FOLDER #	LEFT	RIGHT	VIEW	CHRONOLOGICAL AGE (years)	LANGUAGE	Greulich & Pyle EPIPHYSEAL CLOSURE ESTIMATES FOR SKELETAL AGE					Final (SA)	CA-SA Difference (in years	CA-SA Difference (in months)
							Radius	Ulna	EST 1	EST 2	EST 3			
GSF019	86413531	x		PA	13.1	EN	12	12	12	12	12	12.0	1.1	13.4
GSF017	15700933	x		PA	13.5	XH	14	13.6	14	14	14	14.0	-0.5	-6.3
GSF007	43241891		x	PA	13.6	XH	15	16	16	15.5	14.5	15.8	-2.1	-25.7
GSF014	43241892		x	PA	13.7	XH	15	15	15	15		15.0	-1.3	-16.1
GSF036	82544198	x		PA	13.8	XH	16	15	15.5	15	15.5	15.3	-1.5	-17.9
GSF033	86952595	x		PA	14.0	EN	12	12	12	12	11	12.0	2.0	24.1
GSF001	78670676	x		PA	14.1	XH	14	14	13.5	13.25	13.25	13.4	0.7	8.9
GSF023	80722986	x		PA	14.6	XH	12	12	12	12	12	12.0	2.6	30.6
GSF032	86968443		x	PA	15.3	EN	13	13	13	13	13	13.0	2.3	27.3
GSF005	34130906		x	PA	15.6	XH	16.5	16.5	16.5	16.5	16	16.5	-0.9	-11.4
GSF028	88394101		x	PA	15.6	XH	15	15	14	14	14.5	14.0	1.6	19.4
GSF031	69658128		x	PA	15.9	EN	16	15	15.5	15.5	15	15.5	0.4	4.3
GSF010	33811274	x		PA	16.4	XH	15	15	15	16	17	15.5	0.9	11.0
GSF018	89325930		x	PA	16.4	XH	17	17	17	17	17.5	17.0	-0.6	-6.8
GSF029	89004089	x	x	PA	16.4	XH	15	14	14.5	14.5	15	14.5	1.9	23.3
GSF021	87552287	x		PA	16.6	EN	15	14	14.5	14.5	14.5	14.5	2.1	25.5
GSF030	65731887		x	PA	16.8	EN	17	17	17	17	17	17.0	-0.2	-2.2
GSF011	45766839		x	PA	17.1	XH	16.5	16.5	16.5	16.5		16.5	0.6	7.1
GSF035	74683210		x	PA	17.3	XH	17	17	17	17	17.5	17.0	0.3	4.1
GSF022	86806692		x	PA	17.4	EN	14	14	14	13.75	13.75	13.9	3.5	42.4
GSF020	88714282		x	PA	17.6	XH	17	17	17	17	17	17.0	0.6	7.0
GSF034	87409926		x	PA	18.4	EN	17	16	17	16.5	16.5	16.8	1.7	20.2
GSF009	44432078		x	PA	18.9	XH	17	17	17	17	17.5	17.0	1.9	22.6
GSF038	44432078		x	PA	18.9	XH	17	17	17	17		17.0	1.9	22.8

ASSIGNED CODE	FOLDER #	LEFT	RIGHT	VIEW	CHRONOLOGICA L AGE (years)	LANGUAGE	Greulich & Pyle EPIPHYSEAL CLOSURE ESTIMATES FOR SKELETAL AGE					Final (SA)	CA-SA Difference (in years	CA-SA Difference (in months)
							Radius	Ulna	EST 1	EST 2	EST 3			
GSF027	68902014	x	x	PA	19.0	XH	17	17	17	17	17	17.0	2.0	24.0
GSF002	14388797	x		PA	19.6	XH	18	19	18	18.5	17.5	18.3	1.4	16.4
GSF004	26070946	x	x	PA	19.7	EN	18	18	18	18	17.5	18.0	1.7	20.5
GSF037	29237104	x		PA	19.9	EN	17	17	17	17		17.0	2.9	34.8
GSF024	88158175	x		PA	20.2	XH	17	17	17	17	17	17.0	3.2	38.0
GSF008	17384470	x		PA	20.9	XH	16.5	17	17	16.75	17.5	16.9	4.0	47.9
GSF013	41234956		x	PA	21.1	XH	18	18	18	18		18.0	3.1	37.4
GSF012	19341999	x	x	PA	21.6	XH	18	18	18	18		18.0	3.6	43.5

APPENDIX D Greulich & Pyle Standard Deviation Tables

Standard Deviation Tables from Radiographic Atlas of Skeletal Development of the Hand and Wrist (Greulich and Pyle, 1959) pages 51 showing margins of error for the male sample.



THE VARIABILITY OF SKELETAL AGE OF GIRLS IN THE BRUSH FOUNDATION STUDY

CHRONOLOGICAL AGE	NUMBER OF HAND-FILMS	SKELETAL AGE (IN MONTHS) MEAN	STANDARD DEVIATION
3 mo.	108	3.02	0.72
6 mo.	121	6.04	1.16
9 mo.	122	9.05	1.36
12 mo.	117	12.04	1.77
18 mo.	93	18.22	3.49
2 yr.	101	24.16	4.64
2½ yr.	98	30.96	5.37
3 yr.	133	36.63	5.97
3½ yr.	131	43.50	7.48
4 yr.	154	50.14	8.98
4½ yr.	152	60.06	10.73
5 yr.	167	66.21	11.65
6 yr.	191	78.50	10.23
7 yr.	200	89.30	9.64
8 yr.	201	100.66	10.23
9 yr.	195	113.86	10.74
10 yr.	206	125.66	11.73
11 yr.	203	137.87	11.94
12 yr.	198	149.62	10.24
13 yr.	179	162.28	10.67
14 yr.	170	174.25	11.30
15 yr.	117	183.62	9.23
16 yr.	64	189.44	7.31

Standard Deviation Tables from Radiographic Atlas of Skeletal Development of the Hand and Wrist (Greulich and Pyle, 1959) pages 51 showing margins of error for the female sample.

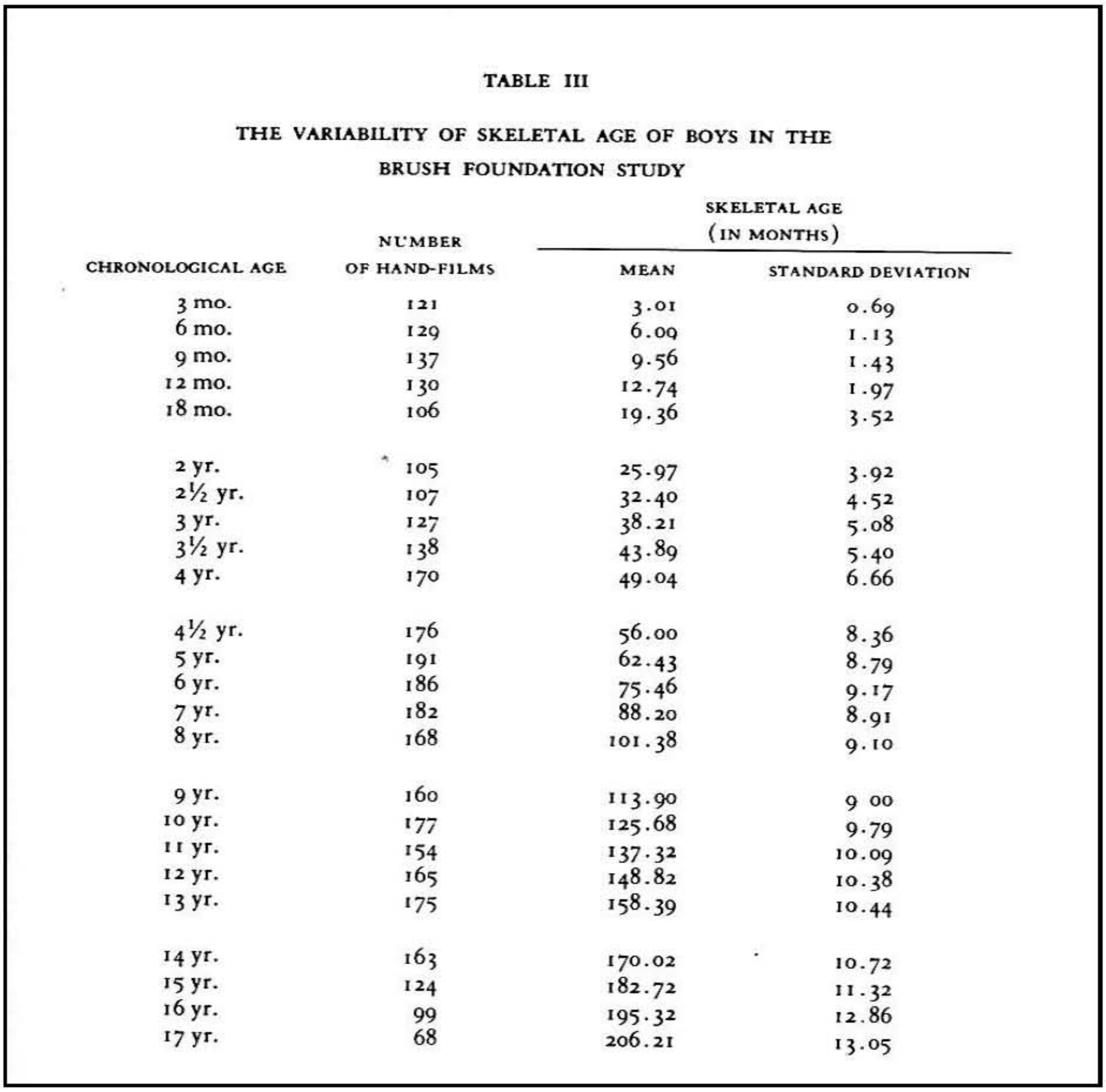


TABLE III

THE VARIABILITY OF SKELETAL AGE OF BOYS IN THE BRUSH FOUNDATION STUDY

CHRONOLOGICAL AGE	NUMBER OF HAND-FILMS	SKELETAL AGE (IN MONTHS)	
		MEAN	STANDARD DEVIATION
3 mo.	121	3.01	0.69
6 mo.	129	6.09	1.13
9 mo.	137	9.56	1.43
12 mo.	130	12.74	1.97
18 mo.	106	19.36	3.52
2 yr.	105	25.97	3.92
2½ yr.	107	32.40	4.52
3 yr.	127	38.21	5.08
3½ yr.	138	43.89	5.40
4 yr.	170	49.04	6.66
4½ yr.	176	56.00	8.36
5 yr.	191	62.43	8.79
6 yr.	186	75.46	9.17
7 yr.	182	88.20	8.91
8 yr.	168	101.38	9.10
9 yr.	160	113.90	9 00
10 yr.	177	125.68	9.79
11 yr.	154	137.32	10.09
12 yr.	165	148.82	10.38
13 yr.	175	158.39	10.44
14 yr.	163	170.02	10.72
15 yr.	124	182.72	11.32
16 yr.	99	195.32	12.86
17 yr.	68	206.21	13.05

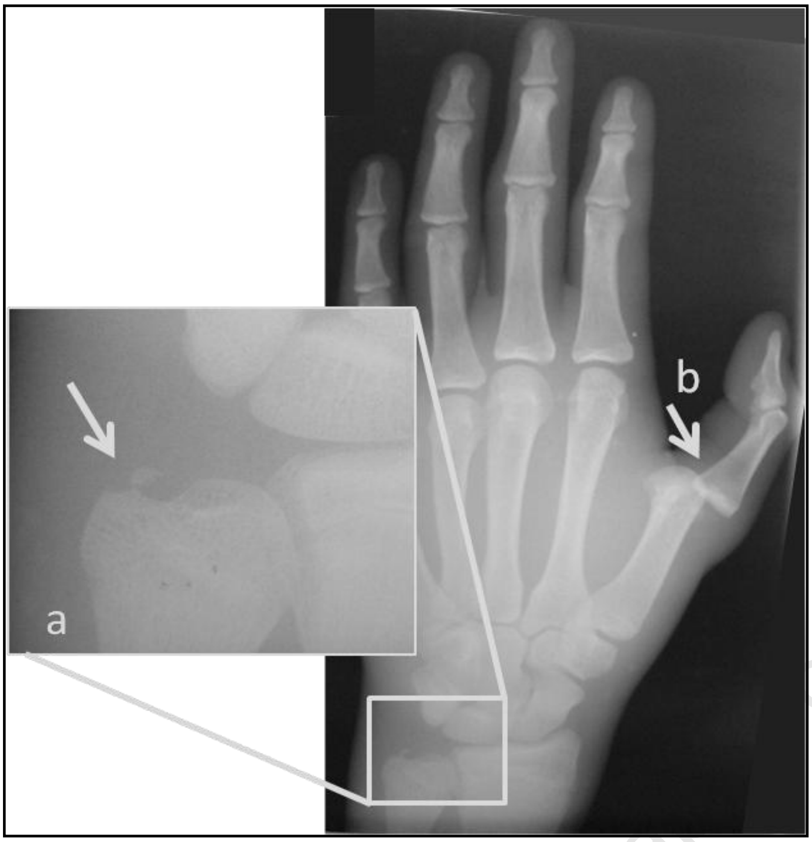
APPENDIX E Types of Trauma

b) Illustrations of types of trauma observed

[redacted]

[redacted]

GSM 151 Showing a displaced fracture to proximal epiphysis of proximal phalanx 3, indicated by arrow. This injury occurred at the metacarpal phalangeal joint.



GSM007 Showing a complete fracture to the base of the styloid process on the ulnar indicated by the arrow in inset (a). More trauma is shown by the arrow at (b) indicating dislocation at the metacarpal-phalangeal joint of the thumb.

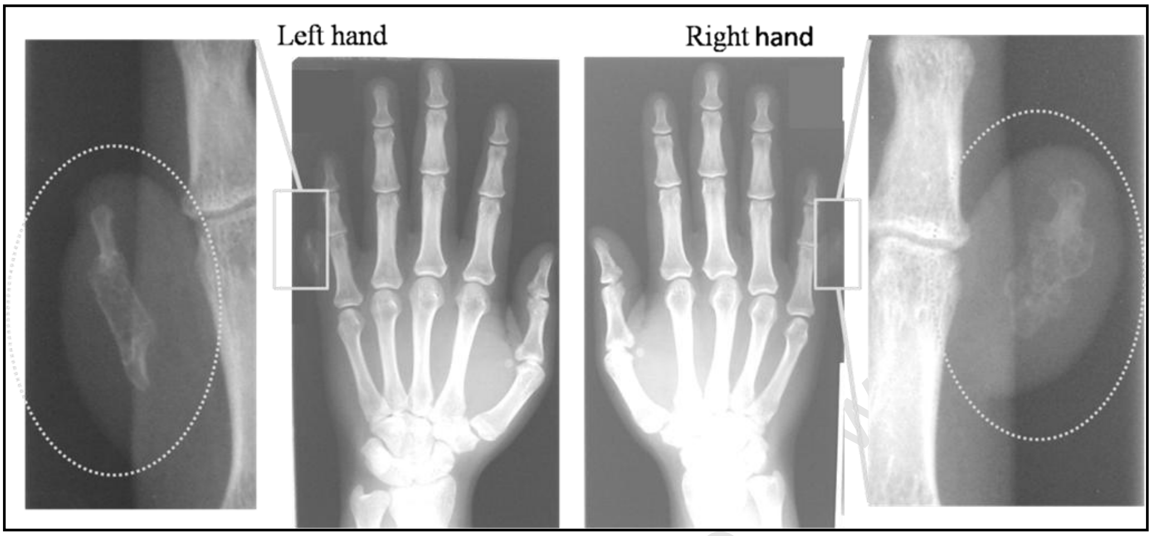
b) Record of Type and Frequency of Trauma

Description of Trauma/Injury	Area	Number of Observations	
		Male	Female
Fracture (mid-shaft, proximal, distal)	metacarpals	30	1
	phalanges	30	2
Crushing (includes multiple fractures)	carpals	1	
	metacarpals	2	
	phalanges	6	1
Fracture (distal ulna)	ulnar styloid	12	
Soft tissue trauma	metacarpals, phalanges	5	
	carpal area	1	
Dislocation	metacarpo-phalangeal joint	3	3
	proximal interphalangeal joint	3	1
Fracture (whole digit)	metacarpal, all phalanges	2	
Hunter's Bow		1	
Amputation	at midshaft middle phalanx	2	1

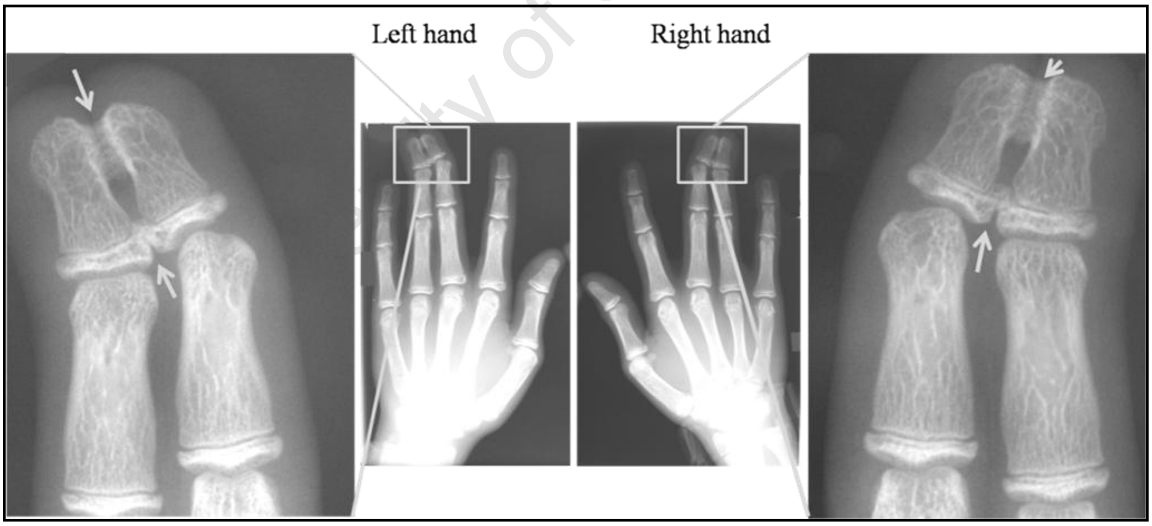
APPENDIX F Record of Anomalies

a) Illustrations of types of skeletal anomalies observed.

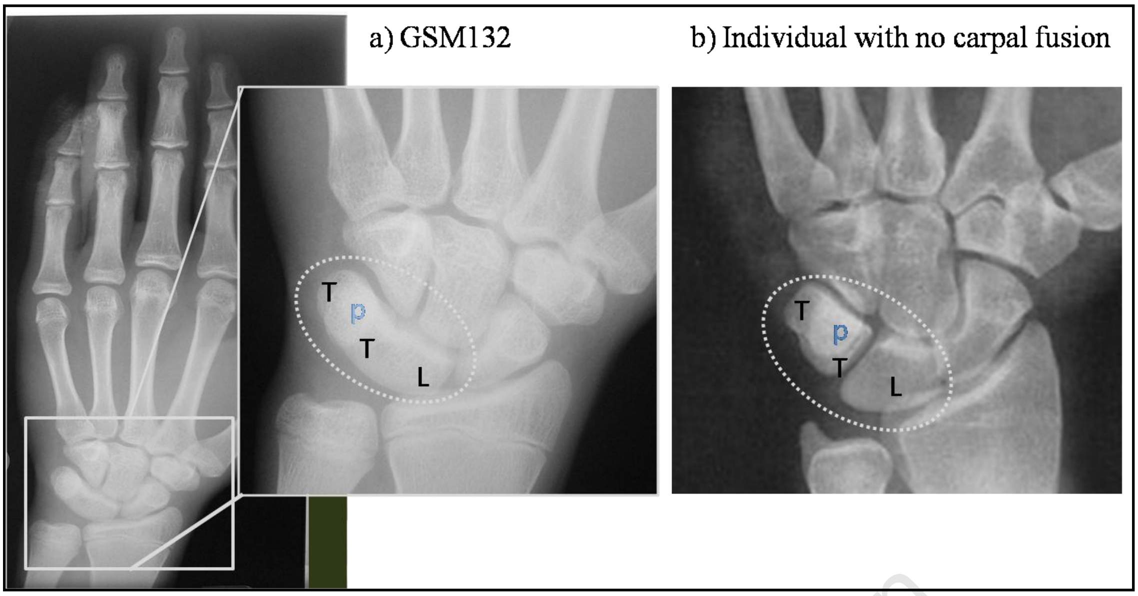
The anomalies shown below were the only incidences recorded for this sample



GSF004 Supernumery digits on both hand**s**. These "extra fingers" shown in the insets were growing from the soft tissue (opaque areas indicated by the circles) at the level of the proximal phalanx of the fifth digit of both the left and right hands.



GSM085 Showing fusion of the distal and proximal parts of the distal phalanges observed on the third and fourth digits of both hands. The downward pointing arrows are showing areas where the bones of the two phalanges have fused distally and the upward pointing arrows are showing the fusion proximally. The area of bone fusion proximally is involving the epiphyses of the distal phalanges. Also evident is the soft tissue involvement of the fusion visible in the opaque areas surrounding the bone.


a) GSM132

b) Individual with no carpal fusion

GSM132 Showing an individual showing carpal fusion. **a)** Non-pathological fusion has occurred between the triquetral bone indicated by the 'T' and the lunate bone indicated by the 'L'. These bones are normally separate as shown in the picture shown in **b)**. 'P' is indicating the position of the pisiform bone which is lies deep to the lunate and triquetral bones on their palmar surfaces.

b) Incidence of Carpal Fusion in African children

Incidences of carpal fusion have been recorded in children of African biological descent. Beresowski and Lundie (1952) recorded two incidences of fusion between the hamate and capitate in their study. This type of carpal fusion was not observed in this sample. Levine (1972) recorded an incidence of 4.57% for lunate-triquetral fusion, in a sample of South African 'negroes'. This type of fusion was observed in the current sample. Both studies Beresowski and Lundie (1952) and Levine (1972) were performed on South African samples. However measurement of the incidence of carpal fusion and its implications were not the main focus of this study and the small sample size prevent further discussion of this phenomenon.

c) Table showing type of skeletal anomalies and their instances

Type of Anomaly	Specific Area	Number of observations	
		Male	Female
Supernumery digits	At level of proximal phalanx 5 left and right		1
Fusion of distal phalanges	Phalanges 3 and 4 left and right	1	
Carpal Fusion	Lunate to triquetral	3	1