A LONGITUDINAL ANALYSIS OF CRANIOFACIAL GROWTH AND SKELETAL MATURATION

Joseph A. Dugoni, DDS

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In culmination of years of effort; dedicated to my wife Laurie, daughter Meredith, and companion Annie. . .

'All the wide world is beautiful, and it matters but little where we go. . .
The spot where we chance to be always seems the best' (John Muir, 1890)

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INTRODUCTION

The study of human growth is believed to have been initiated in 1759 when Guenuea de Montebeilland began an 18-year study of his son to determine annual stature growth.(1) Since that time, many investigative efforts have been conducted to determine the timing and extent of adolescent growth and its influence on the craniofacial complex. Presumably, two growth spurts follow birth and typically occur at approximately 6-7 years of age and again at puberty.(2) During the pubertal adolescent growth spurt, the velocity of growth is greater than at any other time after age 2, however, the onset, intensity, and duration of growth is quite variable. This variability in timing of growth reflects differences in physical maturity of children of the same chronolgical age.

Since postnatal skeletal growth occurs largely during the adolescent growth phase, it becomes extremely important to the orthodontist to accurately anticipate or predict timing and intensity of skeletal growth. Although the facial growth spurt and stature growth are thought to occur at approximately the same time, the variability in timing of the adolescent spurt makes it difficult for the clinician to take advantage of the effects of growth to its fullest extent.

Given the uncertainties of growth prediction, orthodontic diagnosis and treatment is frequently based on chronologic age and dental development. Unfortunately, neither chronologic age or dental development are considered to be reliable indicators of skeletal development or, more importantly, of craniofacial growth. Other clinicians have chosen to rely on routine cephalometric evaluations to better correlate biomechanical therapy with the biological aspects of facial growth and development. It becomes apparent, however, that orthodontic diagnosis based on an evaluation of a patients growth according to cephalometric standards is equally questionable, as these standards are customarily based on chronolgical age. Because it has become more widely accepted that dental, chronological and maturational ages are not necessarily the same for an individual at any given time, researchers have sought ways to measure and utilize skeletal maturational age as a more valid means of assessing physiological development.

Principles of skeletal maturation, based on the underlying premise that osseous change is indicative of general change, were first described by Crampton in 1928 (3) and later developed by Todd (1937) (4) and others. More recently, skeletal aging derived from hand and wrist radiographs have been hypothesized as a means to estimate an individuals physical maturity, thereby allowing prediction of timing of the adolescent growth spurt. Greulich and Pyle (1959) developed radiographic standards for specific ages by sex, whereby each bone in the hand and wrist is assigned to a skeletal age depending on its stage of development .(5) This technique requires the radiograph of the patient in question to be compared to a representative standard. Subsequently, Fishman (1982) has developed a skeletal maturation index based on the progressive maturation of hard tissue in the hand and wrist. (6)

It is not the intent of this research to necessarily refute findings of previous studies but rather to elucidate on the clinical application and accuracy of skeletal aging based on hand and wrist films. The specific purpose of the investigation is to compare skeletal aging based on hand and wrist films to craniofacial measurements from a longitudinal sample of non-treated subjects with Class I molar relationship. All subjects were part of the child growth study at The Oregon Health Sciences University.

MATERIALS AND METHODS

This study is based on craniofacial measurements and hand and wrist skeletal aging from longitudinal records in the Oregon child growth study at OHSU. Fifteen males and 15 females, all with Class I molar relationship and complete longitudinal records at annual intervals from age 8 through 17 were selected. None of the individuals selected received orthodontic treatment prior to age 17. Data were collected from a total of 300 lateral head cephalograms and 300 hand and wrist radiographs.

Craniofacial Measurements

All lateral cephalograms were taken with a standardized Broadbent-Bolton cephalometer at the Department of Orthodontics, OHSU. Measurements were taken off annual radiographs ±6 months of the individuals birthday anniversary. More than 92% of the films were taken within one month of the anniversary date.

Six points were identified on the lateral film and designated as nasion (N), menton (Mn), articulare (Ar), pogoion (Po), anterior nasal spine (ANS), and posterior nasal spine (PNS) as defined by Salzmann.(7) Points were traced on acetate at each age interval and 3 craniofacial measurements (Fig. 1) were made to monitor vertical facial growth (N-Mn), maxillary anteroposterior growth (ANS-PNS), and mandibular anteroposterior growth (Ar-Po).

Craniofacial measurements were made from the points transferred to acetate using a Bull caliper. All measurements were recorded to the nearest 1/20 of a

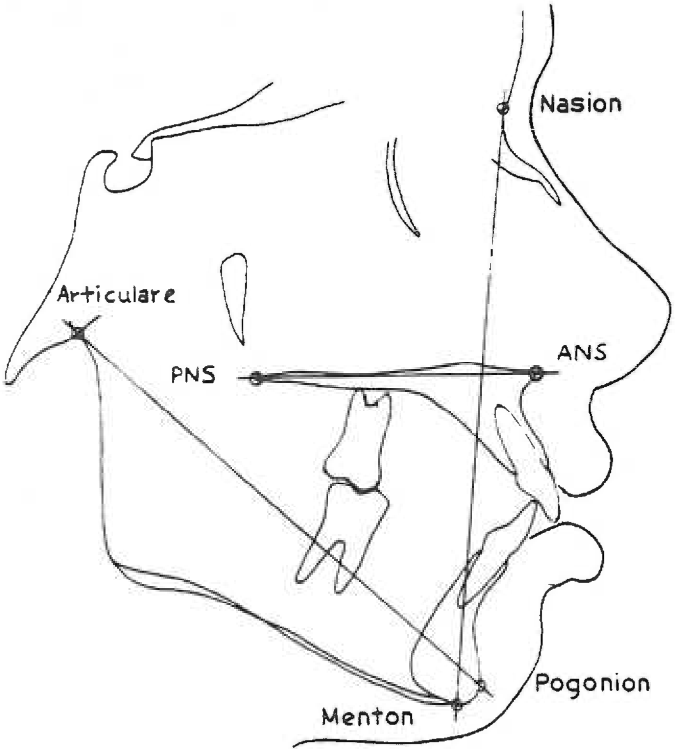


Figure 1. Cephalometric landmark identification of points nasion (N), menton (Mn), articulare (Ar), pogonion (Po), anterior nasal spine (ANS), and posterior nasal spine (PNS) utilized to determine vertical facial growth (N-Mn), maxillary anteroposterior growth (ANS-PNS), and mandibular anteroposterior growth (Ar-Po).

millimeter. All landmark identification and measurements were completed by one individual to maintain consistency. The subject of reproducibility and accuracy of landmark identification has been investigated elsewhere and is not discussed herein. Radiographic enlargement was estimated to be 6.0%, however, enlargement corrections were not warranted due to the consistency of the error.(8)

To calculate the craniofacial measurement error, 20 measurements were repeated 3 weeks following the initial measurements using the formula:

$$\text{SE measure} = \sqrt{\frac{\Sigma\, d^2}{2N}}$$

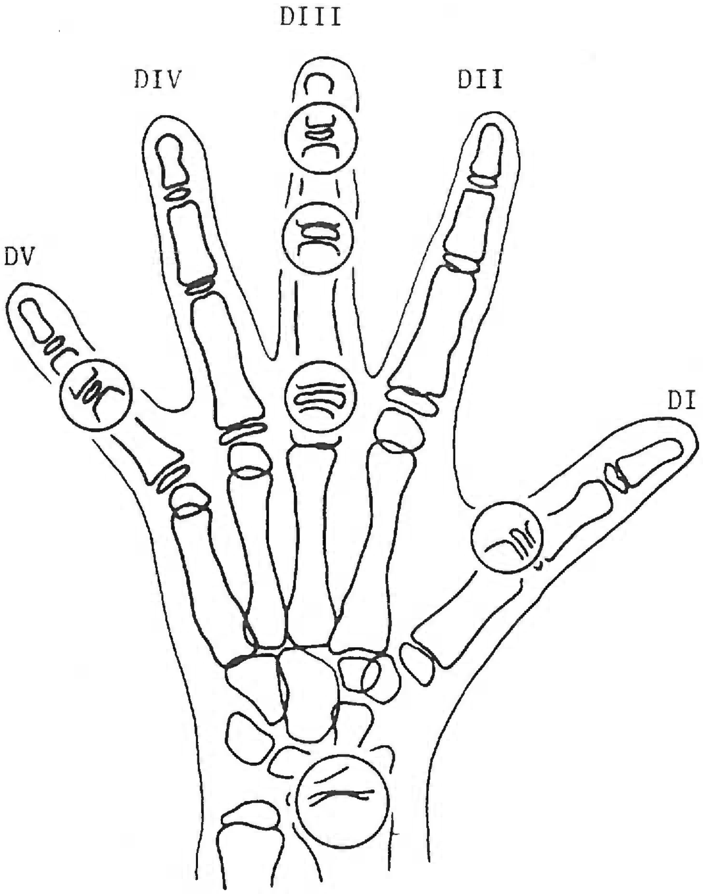
where d is the difference between duplicates and N is the number of scores: the measurement error was determined to be 0.57 millimeters.

Skeletal Maturation

All radiographs to be utilized for skeletal aging were taken of the individuals left hand and wrist and done so annually as described in the aforementioned craniofacial measurement section.

The skeletal maturation assessment (SMA) described by Fishman (1982) was utilized to skeletally age individuals according to maturation of their left hand and wrist. At each age interval, a skeletal maturation index (SMI) from 0-11 was assigned and recorded relative to chronological age. The SMA was selected for its useful approach to maturational assessment using SMI's to identify progressive maturational levels (Fig. 2).

To determine any error involved in the assessment of the SMI, all 15 females



Width of epiphysis as wide as diaphysis
1. DIII - proximal phalanx
2. DIII - middle phalanx
3. DV - middle phalanx

Ossification
4. Adductor sasamoid of thumb

Capping of epiphysis
5. DIII - distal phalanx
6. DIII - middle phalanx
7. DV - middle phalanx

Fusion of epiphysis and diaphysis
8. DIII - distal phalanx
9. DIII - proximal phalanx
10. DIII - middle phalanx
11. Radius

Figure 2. Location of hand and wrist skeletal maturation indicators as utilized by the skeletal maturation assessment (taken from Fishman 1982).

hand and wrist radiographs were re-evaluated 4 weeks following their initial reading. According to the formula previously described, the standard error of the measure was determined to be 0.46.

Statistical Analyses

Means and standard deviations were compiled for craniofacial measurements and skeletal maturation indicators. Data were summarized according to annual growth increments, percent of annual growth change, and percent of the total acquired growth for all parameters. Total growth was defined as size achieved at chronological age 17. A students t-test was used to analyze chronological age differences between craniofacial and skeletal parameters at the 95% confidence level. Variable associations were calculated by Pearson's correlation coefficients.

REVIEW OF LITERATURE

Orthodontic success, especially in those cases where a skeletal discrepancy exists, is frequently dependent upon the rate, intensity, and duration of adolescent skeletal growth.(9) For this reason, the influence of postnatal growth on the facial structure has long been a topic of interest. From 1759-1777 de Mountebeilland conducted the first longitudinal study of growth and found two phases of peak growth acceleration.(1) Since that time, many studies have been conducted regarding the importance of facial growth and prediction.

Adolescent growth is often thought to occur primarily at two times. The first growth spurt is generally small and inconsistent and usually occurs at 6-7 years of age, followed by more substantial growth at the time of puberty.(2) Postnatal growth rates in primates are dominated by the adolescent or pubertal growth spurt,(10) and it is at this time of growth that orthodontic treatment frequently is undertaken. In order to achieve the best treatment result in a reasonable period of time, it becomes apparent that the orthodontist must frequently predict the amount of facial growth yet to occur.

Once it became recognized that adolescent growth can dramatically impact orthodontic success, much emphasis was devoted to further research and facial growth prediction. During adolescence, the growth spurt is consistently present, however, individuals of the same chronological age differ markedly in their physiologic development. For this reason, physiologic markers are commonly prefered to chronological age when evaluating an individuals development.

Hunter (1966), studied 25 males and 34 females from the Denver Child Research Council Study and found that as a child matures, there exists considerable deviation in the onset and duration of adolescent growth spurts as they relate to chronological age.(11) He found males had a mean adolescent spurt onset at age 12.8 versus 10.4 years in females. Males had a 4-year range of onset compared to 5 in females. Females entered the adolescent spurt 2.4 years prior to the males. However, individual growth development is further complicated by the fact that maturational rates and phenomena are conceivably influenced by many factors including genetics, race, climate, season, nutrition, socioeconomic and secular changes.(10,12,13,14,15,16,17)

Bergersen (1972), evaluated 23 serial radiographs from the Denver Child Study and found that the skeletal age estimate of the adolescent spurt onset has 36% the variation of the chronological age estimate and is a more accurate indication of the timing of the spurt.(18) Fishman (1979), conducted a longitudinal study of 60 males and 68 females from the

Denver Child Research Council Study and found only a small percentage of concurrence between chronological and skeletal age utilizing hand and wrist films.(19) In general it is accepted that chronological age does not necessarily correlate with the skeletal age.

DEVELOPMENTAL AGING

In 1908, Crampton was the first to recognize and report physiologic age as a fundamental principle.(3) After years of development, both Liebgott (1978) and Demirjian et al. (1985), independently reported 4 types of physiologic or developmental aging; dental, sexual, morphological and somatic or skeletal.(20,21) Demirjian et al. (1985), hypothesized that the inconsistency of results when comparing the interrelationships of these 4 indices was due to differing methods of collection and that skeletal maturation is perhaps the more commonly applicable prediction tool in routine clinical orthodontics.(21)

Dental

Spier (1918) was believed the first to associate tooth eruption with statural growth,(22) while many other investigators developed the relationship of tooth eruption with skeletal maturation and growth.(23,24,25,26,27,28) In 1958, Lamons and Gray studied 61 Atlanta children and found that only in 60% of the cases, did teeth and hands develop concommitantly.(29) Lewis and Garn (1960) demonstrated variable associations with tooth formation and maturation,(22) while additional research was directed at the possible association of root formation or crown calcification with skeletal maturation.(22,30,31) Similarly, Liebgott (1978) demonstrated only a poor relationship between dental age and pubertal growth spurt (r=.4).(20)

As interest regarding physiologic and skeletal development evolved, researchers studied a myriad of interrelationships including: tooth eruption, root formation, genetics, nutrition, sex characteristics, type of malocclusion including crowding and spacing, and skeletal maturation and growth.(27,32,33,34,35,36) Most of these studies demonstrated varying degrees of non-association to good correlation with skeletal maturation. Studies reporting low correlations between dental and skeletal development all conclude that development of various systems appears independent of one another and that estimates of skeletal maturation are more accurate when done physiologically with hand and wrist films than when done according to dental maturation.(37,38,39,40,41)

Sexual Characteristics

Although frequently difficult or impossible to ascertain in the orthodontic setting, secondary sexual characteristics such as breast budding in females and axillary and pubic hair growth in both sexes are reliable indicators of puberty. The appearance of these characteristics are generally related to earlier parts of the growth curve.(42) Demirjian et al. (1985), longitudinally studied 50 females from 6-15 years of age in the Montreal Human Growth Research Centre and found that sexual maturity, skeletal development, and peak velocity in height are closely related, presumably due to a common controlling mechanism.(43)

The age of menarche is more closely related to skeletal maturation than chronological age and its onset is frequently used to time orthodontic treatment.(43) Derming (1957), reports a high correlation (r=0.9) between menarche and age of peak velocity in height based on the growth of 48 adolescents.(44) Tanner et al. (1976), reports that menarche in females occurs after the peak velocity in height.(42) Tanner (1962) and Anderson et al. (1975), suggest that peak velocity in height precedes menarch by approximately 1 year.(37,45) Hagg et al. (1980), also found that menarche occurred after the peak velocity in growth, therefore, it may not be a reliable indicator.(46) He also found that when males begin to undergo voice change they are in the accelerating phase of their adolescent growth spurt. Similarly, once the adult voice characteristics are fully obtained, growth is presumed decelerating.

Morphological

Numerous investigators have sought to correlate facial growth with general body growth parameters as stature, standing height, shoulder width, and bodily dimensions. Although morphological age can be a useful tool in assesing adolescent growth, it too like sexual characteristics, is difficult to monitor in an orthodontic practice.

Recently, multiple studies have demonstrated a high degree of association of facial growth with general body growth.(11,47,48,49,50) Fishman (1979), reported that studies showing little positive correlation between facial growth and general body growth usually are those that have significant differences in research design and preclude more commonly used linear measurements that are anatomically limited.(19)

Other researchers have been able to demonstrate high degrees of association between facial growth peak and peak in standing height.(3,11) Nanda (1955), Bambha (1961), Bergersen (1972), Bjork (1972), and Grave and Brown (1976) all concluded that the facial growth spurt seems to occur at approximately the same time or just slightly later than peak statural growth.(18,47,48,51,52) Fishman (1979), concluded that studies involving facial growth and general body height all demonstrate strong individual variation.(19)

Bayley and Pinneau (1952), studied 192 Berkeley children from ages 8-18 and concluded that skeletal age correlates with percent mature height (r=.86) after 9 years of age when chronological age is held constant.(53) Bambha (1961) longitudinally measured the face and cranium of 25 boys and girls from age 1 month to 30 years from the Denver Child Research Council Study and determined that the cranium tends to follow neural type of growth while the skull base tends to follow a pattern between neural and skeletal growth.(48) He reported that females had smaller absolute measurements with slower rates of growth and matured 2-3 years earlier than males.

Hunter (1966) longitudinally studied 59 individuals from the Denver Child Research Council Study and determined contrary to other previous efforts, that maximum facial growth was coincident with maximum height growth in 57% of the subjects.(11) Of the others, 14% achieved maximum facial growth before maximum body height and 29% after. He reported that the linear measurement of articulare to pogonion demonstrated the most consistent relationship to stature throughout adolescent growth.

Many investigators have sought to predict facial growth based on body dimensions and have done so only with mild success.(50,54,55,56,57,58,59,60,61) Conversely, Ricketts (1957), concluded that facial growth predictions based on means from facial dimensions and their growth have a high degree of predictive success.(62)

Skeletal

Skeletal growth and skeletal maturation, although interrelated, are not synonymous.(63) The concept of skeletal age or maturation was developed by Todd at Case Western Reserve University where he evaluated the stages of epiphyseal and carpal bone development.(4) Greulich and Pyle (1959) utilizing records of 100 children from the Brush-Bolton Study, expanded on Todds work in a quest to identify a dependable indicator of maturity.(5) They developed radiographic standards for specific ages and sex whereby each bone in the hand and wrist is assigned a skeletal age depending on the stage of development. Generally, the accuracy of prediction from the new tables compared favorably to those of Todd's skeletal ages, although the children in the latter study appeared further developed at a comparable age.(53,64)

Greulich and Pyle (1959) cited that benefits of the hand and wrist technique included: 1) an objective measure of a child's developmental status; 2) the measurement of nutritional status; 3) the revealing of skeletal imbalances; 4) the disclosure of growth interruption; and 5) determination of skeletal growth rate if radiographs were repeated.(5) They further reported that, although skeletal aging had some shortcomings, no feasible substitute existed. Lilliequist and Lundberg (1971), following a comparative investigation, reported that skeletal aging utilizing hand and wrist x-rays was thereotically correct, however, it was entirely dependent on subjective assessments.(64)

In terms of the clinical application of skeletal aging, the x-ray of the individual in question is compared to the standardized film, selected to be representative of normal children at the appropriate chronological age. The skeletal age is determined to be that of the standard film it most closely resembles. Houston (1980) suggests there exists the practical difficulty of matching the individual to a standard due to variable maturational rates of different bones.(2) Other researchers contested that skeletal standards of normality should be adjusted to account for regional variances of skeletal maturation.(65,66)

Hunter (1966) conducted serial skeletal maturation assessments of 25 males and 39 females from the Denver Child Research Council Study by examining carpal bones and adjacent skeletal structures.(11) If skeletal age varied ±1 year or more from chronologic age in 50% or more of the assessments he categorized the growth of individuals as either retarded, average, or accelerated. Subsequently, he found that most individuals remained in their respective growth categories throughout adolescense, however, for those that pass from one group to another it would be difficult to rate their growth with any reliability on a single x-ray assessment. He concluded that in females, final facial growth size was frequently essentially attained before skeletal maturation was complete. Of the males, 88% had some small amount of facial growth after 18 years of age. Residual facial growth of females continued into late twenties and into the third decade of many male individuals.

Independent efforts by Bambha and Van Natta (1963) and Hunter (1966) demonstrated correlations between skeletal age from hand and wrist x-rays and peak of adolescent facial growth.(11,67) This finding was particularly true for males, indicating a predictive quality of skeletal age in determining the time of greatest growth. Others demonstrated that mandibular measurements of facial growth were best suited for skeletal age correlations.(11,50,68,69,70)

Bjork and Helm (1967) studied the initial radiographic appearance of the ulnar sesamoid and found it occurred prior to the attainment of peak stature velocity.(28) They did, however, find that the relationship exhibited some sexual dimorphism. Bowden (1971), confirmed there was sexual dimorphism in the appearance of the ulnar sesamoid relative to both start and peak of the adolescent spurt and that polymorphism existed in initial size and rates of sesamoid growth.(71)

Bergersen (1972) gathered 7 craniofacial measurements on 23 males from the Denver Child Research Council Study and found that articulare to gonion, nasion to menton, and sella to gnathion were useful predictors of pubertal growth.(18) He further concluded that hand and wrist tables predicting adolescent growth eliminate up to 75% of the variation when compared to chronological age.

Grave and Brown (1976), evaluated longitudinal records of 88 aboriginal children in order to study 14 ossification events of the hand and wrist.(51) They concluded that the epiphyseal union of the radius was the radiographic event designating the end of the pubertal growth spurt and that ossification events can be used to assess a childs growth activity.

Bowden (1976) examined serial hand and wrist radiographs of 52 males and 60 females in the University of Melbourne Child Growth Study.(72) He found that epiphyseal and diaphyseal growth stages in hand and wrist occurs in relatively fixed sequential patterns in contrast to primary and secondary ossification centers.

Fishman (1979), conducted a longitudinal study of 60 male and 68 female subjects from 7-1/2 to 15 years of age.(19) He performed 7 linear facial measurements and determined skeletal ages based on hand and wrist films according to Greulich and Pyle (1959). Fishman concluded that cephalometrically there is often not much difference in absolute measurements between chronological and skeletal ages. He reported the significant difference is one of timing and that hand and wrist films allowed him to more accurately determine the time of the pubertal growth spurt when compared to chronological age.

Houston (1980), like Fishman (1979), rated the development stages of the left hand and wrist, however, he utilized different standards.(2) The subjects consisted of 68 males and 58 females of European origin from the Harpenden Growth Study. He reported that, although skeletal aging is established as a method of estimating physical maturity, and might help estimate the timing of adolescent growth, it has not been proven to be of a clinical useful amount. He reported that hand and wrist aging based on the TW2 standards is only of limited value in predicting the time of peak height velocity and growth spurt. According to his investigation, he concluded that the skeletal maturation prediction based on hand and wrist x-rays improves as the average age of the growth spurt is approached.

Fishman (1982), collected anthropometric data from 164 males and 170 females from the longitudinal Denver Child Research Council Study.(6) He also utilized 1000 additional cross-sectional hand and wrist films. From these data, he designed the Skeletal Maturation Assessment (SMA) which relies on four stages of bone maturation found at six anatomical sites located on the thumb, third finger (DIII), fifth finger (DV), and radius. At these sites, eleven discrete adolescent Skeletal Maturation Indicators (SMI's) covering the period of adolescent development can be found. The sequence of four ossification stages includes; 1) the progressive process of epiphyseal widening on selected phalanges; 2) the first observation of the adductor sesamoid of the thumb; 3) the capping of the epiphyses, or the formation of an acute bony angle, over the diaphyses; and 4) the fusion, or time of completion, of selected epiphyses and diaphyses. He found the sequence of the eleven indicators to be exceptionally stable and only detected 3 deviations in over 2000 observations. Further, he concluded that these deviations had no clinical effect on hand and wrist film interpretation. He reported that sexual SMA differences are greatest during and shortly after the time of maximum growth velocity and that facial growth measurements demonstrated a close direct association between variations in the rate of growth in skeletal maturation. Finally, he concluded that maturational age is a more valid means of judging physiologic development than is chronological age.

Snyder (1990), conducted a longitudinal radiographic investigation of 18 males and 20 females from the Denver Child Research Council Study.(73) All subjects had Class I molar relationship as determined cephalometrically and each had a hand and wrist film to confirm the lateral film was obtained during the pubertal growth spurt. Each subject was followed through their pubertal growth spurt and then combined into male and female groups representing accelerating, peak, and decelerating phases of the growth spurt. He concluded that the SMA as described by Fishman is a clinically useful and accurate method of describing the pubertal growth spurt, irrespective of gender.

RESULTS

Means and standard deviations of craniofacial measurements nasion-menton, articulare-pogonion, and anterior nasal spine-posterior nasal spine are reported in Table 1. These linear measurements, taken from longitudinal lateral cephalograms for males (n-15) and females (n=15) from ages 8 to 17, represent vertical face height growth (N-Mn), mandibular anteroposterior growth (Ar-Po), and maxillary anteroposterior growth (ANS-PNS). Annual linear measurements of total growth for each parameter is given ±1 standard deviation. Growth rate data is summarized in Table 2 according to annual growth increments, % annual growth change, and % of acquired total growth. Growth rate data is graphically presented according to sex and chronological age in Figures 3.1-3.4, 4.1-4.4, and 5.1-5.4.

Males and females were tested at ages 8, 12, and 17 to detect differences between any of the three described linear dimensions. In addition to age 17, age 12 was tested since this is a common age during which to undergo orthodontic treatment. Males demonstrated significantly larger nasion-menton, articulare-pogonion, and anterior nasal spine-posterior nasal spine growth than females at age 17 (Table 3).

Mean skeletal maturation data, based on longitudinal hand and wrist radiographs are summarized by sex and chronological age according to Fishman's (1982) skeletal maturation assessment (Table 1). Data regarding the rate of mean incremental and % annual index change are presented in Table 2 and pictorially demonstrated in Figures 6.1-6.3. Mean change of all three craniofacial dimensions, ±1 standard deviation, is graphically depicted relative to the skeletal maturation index for males and females from ages 8 to 17 (Figs. 7.1-7.2, 8.1-8.2, and 9.1-9.2).

The skeletal maturation index, when tested by sex at ages 8, 12, and 17, revealed males and females to have significantly differing levels of maturation at all three ages (Table 2). When craniofacial annual growth rates were tested against the skeletal maturation index, only the female antero-posterior maxillary growth rate (Fig. 12.2) demonstrated a high correlation coefficient (r = - 0.789). All other relationships regarding craniofacial growth rates and SMI were too low to be of predictive value (Figs. 10.2-10.2, 11.1-11.2, and 12.1).

DISCUSSION

The purpose of this study was to evaluate the growth of three craniofacial dimensions from ages 8 to 17 and compare these findings to skeletal maturation aging. Lateral cephalograms were utilized to evaluate the growth of nasion-menton, articulare-pogonion, and anterior nasal spine-posterior nasal spine in fifteen male and female non-treated Class I molar individuals. The three craniofacial dimensions were chosen to represent vertical face height growth (N-Mn), maxillary anteroposterior growth (ANS-PNS), and mandibular anteroposterior growth (Ar-Po). Fishmans (1982) skeletal maturation assessment was applied to longitudinal hand and wrist radiographs in order to skeletally age all subjects.

Total nasion-menton growth was found to be greater in females than males from ages 8 to 14, while both sexes had approximately equal acquired growth at ages 14 and 15 (Fig. 3.1). Male nasion-menton growth exceeded female growth from age 15 to 17 and was still accelerating at age 17. Female nasion-menton growth appeared to peak at age 15 or at SMI 10 (Fig. 7.2). Nasion-menton annual growth rates for males and females were greatest at ages 12 and 14 (Figs. 3.2-3.3). Cumulative growth of males ages 8 and 12 was 83% and 89% respectively (Table 2,

Fig. 3.4). Females realized 87% and 94% of total nasion-menton growth at the ages of 8 and 12. Measurement error probably attributed to the negative nasion-menton growth rate for females between ages 15 and 16 (Table 2).

Acquired articulare-pogonion growth of males exceeded females at all ages (Fig. 4.1). Female growth appeared to plateau at age 16 or SMI 11 (Fig. 8.2), while males were still growing at age 17. Male annual growth rates were greatest at ages 11 and 14 and females demonstrated accelerated annual growth rates at ages 10, 12, and 15 (Fig. 4.2-4.3). Total articulare-pogonion growth of males ages 8 and 12 was about 82% and 90%, while females exhibited 87% and 94% of total growth at the same ages (Table 2, Fig. 4.4). Hunter (1966) found that mandibular length (Ar-Po) was found to be most consistent with growth in statural height throughout adolescense.(11)

Maxillary anteroposterior growth (ANS-PNS) was found to be greater in females from age 9 to 13 (Fig. 5.1). Female growth appeared to increase only slightly after age 13, peaking at age 15 or SMI 10 (Fig. 9.2). Males exceeded females in total growth after age 13 and were still demonstrating continual growth at age 17, although at a decelerating rate. Female horizontal maxillary growth rates were greatest at ages 9, 12 and 14 (Figs. 5.2-5.3). Males exhibited highest annual growth rates at ages 9, 11, and 14. Total growth for males at ages 8 and 12 was 87% and 92% respectively (Table 2, Fig. 5.4). At similar ages, females demonstrated 91% and 97% of their total maxillary growth. Anterior nasal spine-posterior nasal spine radiographic landmarks were frequently difficult to accurately locate, therefore, conclusions drawn from these data are guarded.

Many attempts have been made to define the initiation of the adolescent growth spurt.(2,18,44,72) Boaz (1932) reported that the growth spurt occurs 2 years earlier in females than males.(74) Bergeson (1972) stated that if the velocity of the growth spurt did not exceed the previous year by more than a 0.75mm, then the spurt was questionable.(18) Based on a longitudinal study of 60 males and 68 females, Fishman (1979) concluded that the males maximum growth spurt normally starts at ages 12-13 while the females was usually between 11 and 13.(19) Taranger et al. (1980) reported that the Scandinavian pubertal growth spurt terminated at 17.5 years in females and 19.2 years in males.(75) Hunter (1966) stated the mean pubertal growth period had the same duration in males and females.(11)

According to the SMI, males showed no appreciable skeletal maturation until 10 years of age. The SMI demonstrated males to have continued maturation to age 17 with the greatest index increment occurring between ages 14 and 15 (Figs. 6.1-6.2). Based on the slope of the annual SMI increment change, the greatest acceleration of pubertal growth for males occurred between ages 12 and 17 (Fig. 6.2).

Females appeared to begin their adolescent skeletal maturation by age 8, with accelerated growth occurring until age 15 (Figs. 6.1, 6.3). According to the SMI, females experienced the greatest maturational change between ages 11 and 12. Analysis of the SMI revealed that females experienced accelerating pubertal growth between 11 and 15 years of age (Fig. 6.3).

Overall, the male adolescent growth appeared to start approximately 2 years later than females. Maximum female adolescent growth occurred over a 4-year period while for males it ocurred over a 5-year period. Males were still growing at an accelerating rate at age 17 while females appeared to peak at 15. According to the parameters investigated, the greatest amount of male growth occurred between ages 14 and 15 and between 11 and 12 for females.

Hixon (1968) reported that the correlation coefficient (r) expresses the strength between two variables, but nothing about cause and effect.(54) Since the meaningfulness of r is estimated by squaring r, female maxillary growth as reported herein accounted for approximately 64% of the variation with the SMI (Fig. 12.2). All other correlation coefficients were too low to suggest interrelationships between annual growth increments and the SMI.

SUMMARY

Longitudinal records of fifteen males and fifteen females were utilized to assess dimensional changes of nasion-menton, articulare-pogonion, and anterior nasal spine-posterior nasal spine from ages 8 to 17. At each chronological age, hand and wrist radiographs were analyzed to determine skeletal maturation. The significant clinical findings are:

1) Male nasion-menton growth was still increasing at age 17. Female nasion-menton growth peaked at age 15.
2) Male articulare-pogonion growth was still increasing at age 17. Female articulare-pogonion growth reached a plateau at age 16.
3) Male anterior nasal spine-posterior nasal spine growth was still increasing at age 17. Female anterior nasal spine-posterior nasal spine growth peaked at age 15.
4) When compared at ages 8, 12, and 17, males at age 17 had significantly larger craniofacial dimensions than did females at age 17.
5) According to the SMI, males demonstrated accelerating pubertal growth between ages 12 and 17. Females experienced the same between ages 11 and 15.

6) According to the SMI, the greatest amount of skeletal growth occurred between age 14 and 15 for males and between age 11 and 12 for females.

7) Only female maxillary growth (ANS-PNS) accounted for a meaningful interrelationship with the SMI (r^2 = 64%).

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APPENDIX

Table 1. Means and standard deviations of craniofacial measurements and skeletal maturation based on hand and wrist radiographs.

CHRONOLOGICAL AGE (YEARS)	N-Mn (MEAN/S.D.)	Ar-Po (MEAN/S.D.)	ANS-PNS (MEAN/S.D.)	SMI (MEAN/S.D.)
		MALE (N=15)		
8	102.30/5.04	93.39/3.69	49.86/3.04	0.00/0.00
9	104.41/5.36	95.66/3.49	50.11/3.04	0.00/0.00
10	106.94/5.45	97.96/2.90	51.49/3.27	0.33/0.62
11	108.42/5.69	99.14/3.78	52.02/2.56	1.07/1.16
12	110.25/5.82	101.93/4.34	52.94/2.90	2.13/1.46
13	113.26/5.67	104.31/4.70	54.38/8.32	3.60/1.68
14	115.84/6.45	106.65/3.83	55.00/3.72	4.87/1.30
15	119.54/6.68	109.81/3.83	56.36/3.68	6.87/1.19
16	121.98/6.90	112.07/4.46	57.35/3.73	8.27/1.39
17	123.85/6.73	113.52/5.98	57.58/3.22	9.53/1.30
		FEMALE (N=15)		
8	103.15/5.06	92.98/3.83	50.03/1.73	1.20/1.32
9	105.10/5.07	95.02/3.83	50.88/2.14	1.87/1.55
10	107.63/6.04	96.66/4.47	51.91/2.10	3.07/1.98
11	109.15/5.60	98.83/4.43	52.80/2.47	4.13/2.39
12	111.23/5.81	101.15/4.64	53.52/2.56	6.40/1.84
13	114.47/5.58	103.91/4.97	54.66/2.31	7.80/1.42
14	116.12/4.96	105.37/4.71	54.77/2.45	9.07/1.28
15	119.21/6.31	106.25/4.72	54.88/2.12	10.00/0.65
16	118.51/4.96	107.45/5.79	54.92/2.93	10.47/0.52
17	118.85/4.69	107.13/5.22	54.95/2.39	10.80/0.41

Table 2. Annual growth increment, % annual growth change (mm), and % of acquired growth of craniofacial measurements and skeletal maturation of males and females at chronological age 8 to17.

	N-Mn			Ar-Po			ANS-PNS			SMI		
CA	Annual Growth Increment	% Annual Change	% Of Total	Annual Growth Increment	% Annual Change	% Of Total	Annual Growth Increment	% Annual Change	% Of Total	Annual Index Increment	% Annual Change	% Of Total
						MALE (N=15)						
	mm	%	%	mm	%	%	mm	%	%	#	%	%
8			82.60			82.27			86.59			0.00
9	2.11	9.79	84.30	2.27	11.27	84.27	.25	3.24	87.03	0.00	0.00	0.00
10	2.53	11.74	86.35	2.31	11.47	86.29	1.38	17.88	89.42	0.33	3.46	3.45
11	1.48	6.87	87.54	1.18	5.86	87.33	.53	6.87	90.34	0.74	7.77	11.23
12	1.83	8.49	89.02	2.79	13.85	89.79	.92	11.92	92.04	1.06	11.12	22.35
13	3.01	13.97	91.45	2.38	11.82	91.89	1.44	18.65	94.44	1.47	15.43	37.78
14	2.58	11.97	93.53	2.34	11.62	93.95	.62	8.03	95.52	1.27	13.33	51.10
15	3.70	17.17	96.52	3.16	15.69	96.73	1.36	17.62	97.88	2.00	20.99	72.09
16	2.44	11.32	98.49	2.26	11.22	98.72	.99	12.82	99.60	1.40	14.69	86.78
17	1.87	8.68	100.00	1.45	7.20	100.00	.23	2.59	100.00	1.26	12.59	100.00
						FEMALE (N=15)						
	mm	%	%	mm	%	%	mm	%	%	#	%	%
8			86.79			86.79			91.05			11.11
9	1.95	11.94	88.43	2.04	13.84	88.70	0.83	16.47	92.59	0.67	6.98	17.31
10	2.53	15.49	90.56	1.64	11.13	90.23	1.05	20.83	94.47	1.20	12.50	28.43
11	1.52	9.31	91.84	2.17	14.72	92.25	0.89	17.66	96.09	1.06	11.04	38.24
12	2.08	12.74	93.59	2.32	15.74	94.47	0.72	14.29	97.40	2.27	23.65	59.26
13	3.54	21.68	96.57	2.76	18.72	96.99	1.14	22.62	99.47	1.40	14.58	72.22
14	1.35	8.27	97.70	1.46	9.91	98.36	0.11	2.18	99.67	1.27	13.23	83.98
15	3.09	18.92	100.00	0.88	5.98	99.18	0.21	4.17	100.00	0.93	9.69	92.59
16	-0.07	-4.29	99.71	1.20	8.14	100.00	0.06	1.19	99.95	0.47	4.90	96.94
17	0.34	2.08	100.08	0.27	0.83	100.00	0.03	0.60	100.00	0.33	3.44	100.00

Table 3. Students t-test of craniofacial measurements and skeletal maturation of males and females at chronological ages 8, 12, & 17.

	Chronological Age		
Variable	8	12	17
N-Mn	0.463	0.460	2.360*
Ar-Po	0.304	0.476	3.119*
ANS-PNS	0.192	0.575	2.546*
SMI	3.520*	7.031*	3.591*

$p < 0.05$, df = 28, t = 2.048

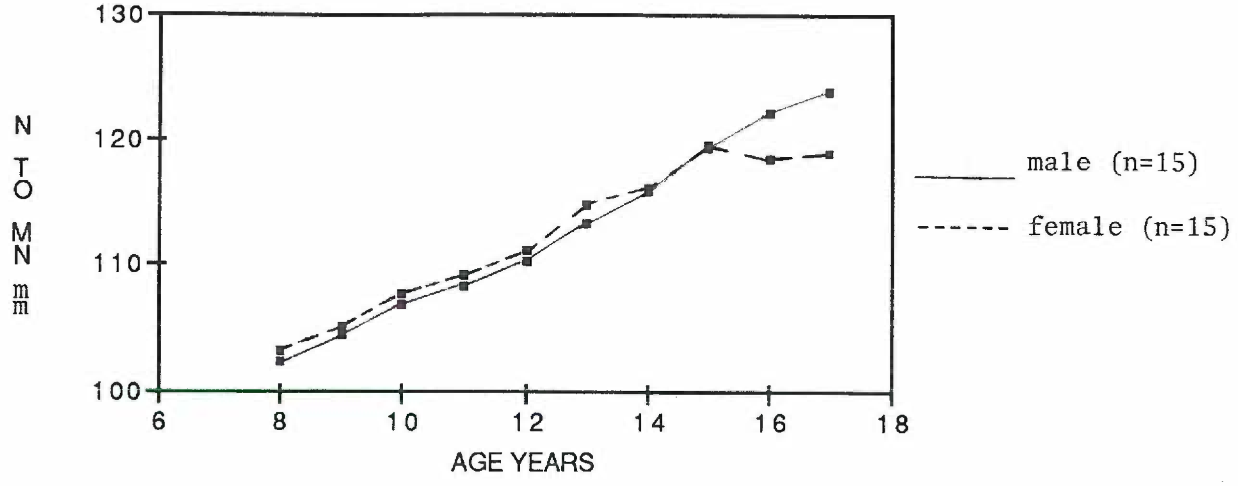

Figure 3.1 Mean total growth of nasion to menton (mm) for males and females from chronological age 8 to 17.

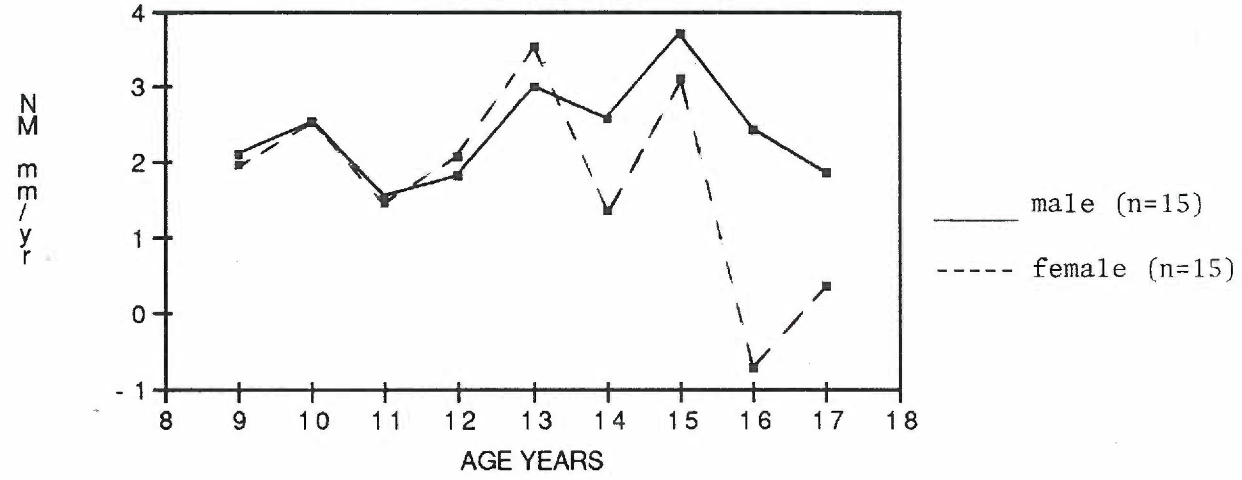

Figure 3.2 Mean annual growth of nasion to menton (mm) for males and females from chronological age 8 to 17.

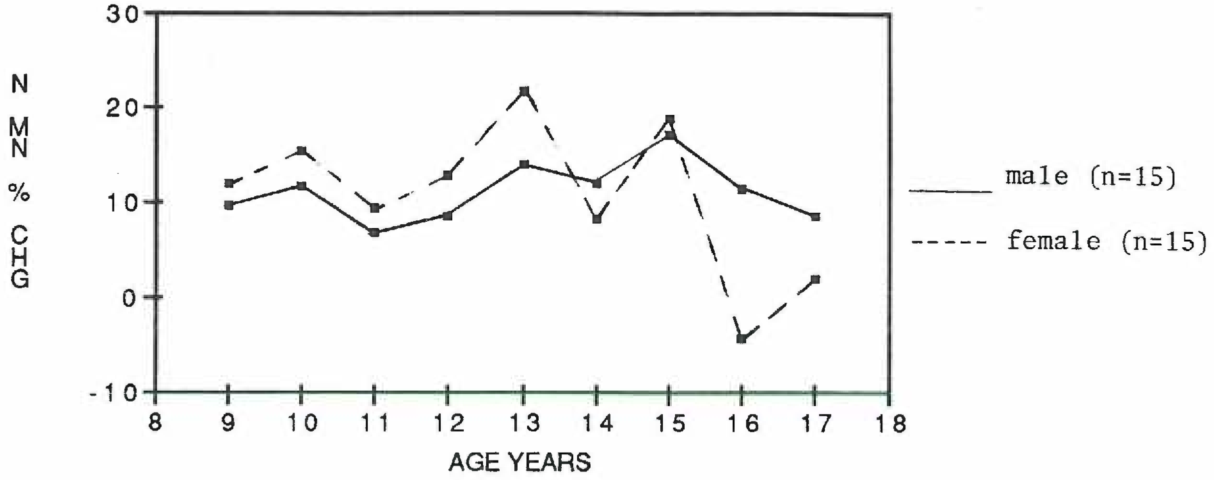

Figure 3.3 Mean annual percent change of nasion to menton for males and females from chronological age 8 to 17.

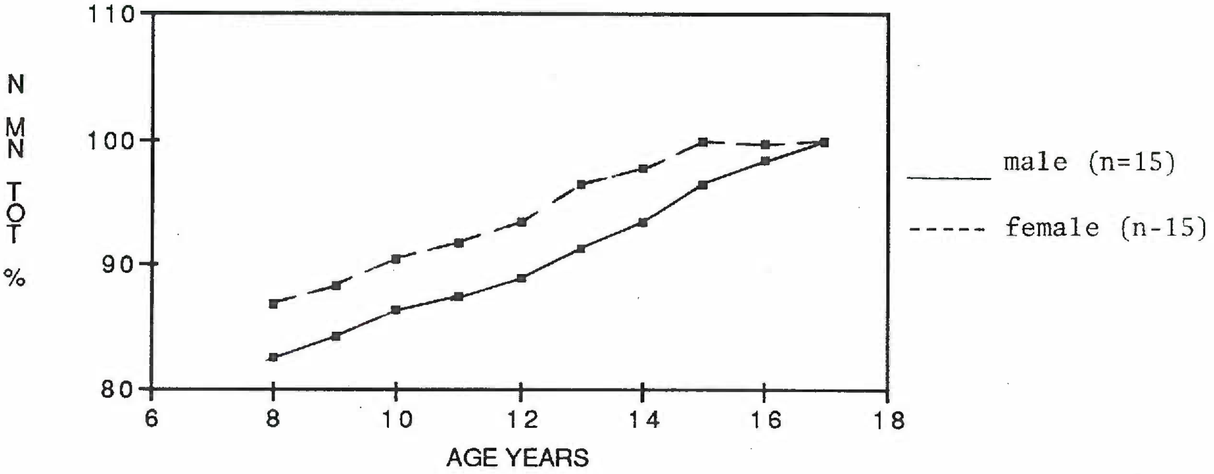

Figure 3.4 Mean total percent annual growth of nasion to menton for males and females from chronological age 8 to 17.

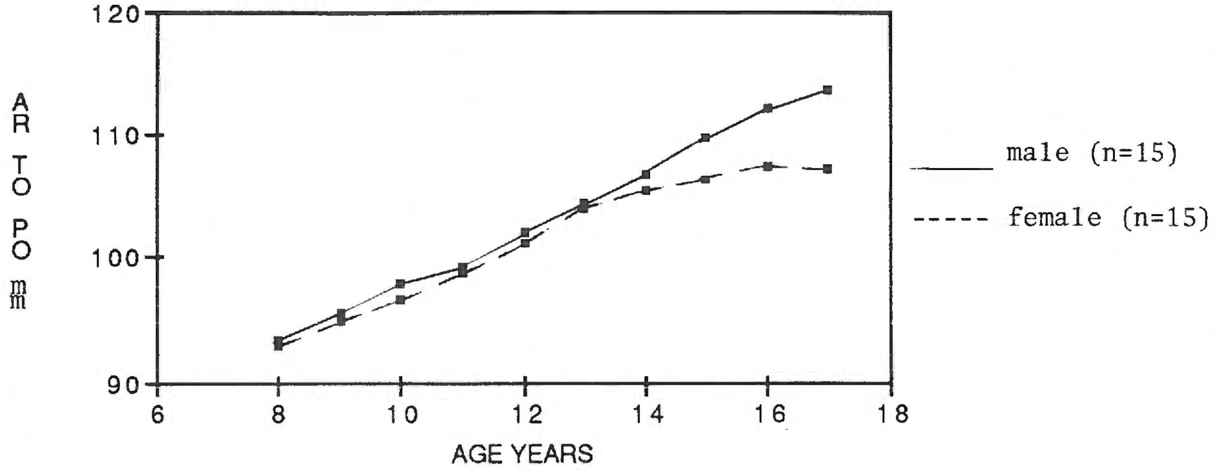

Figure 4.1 Mean total growth of articulare to pogonion (mm) for males and females from chronological age 8 to 17.

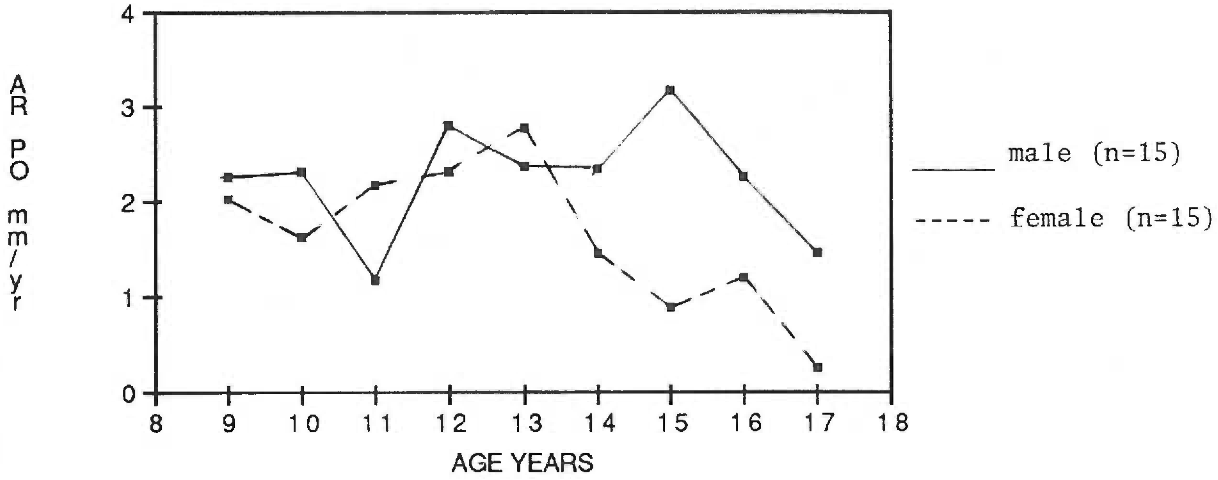

Figure 4.2 Mean annual growth of articulare to pogonion (mm) for males and females from chronological age 8 to 17.

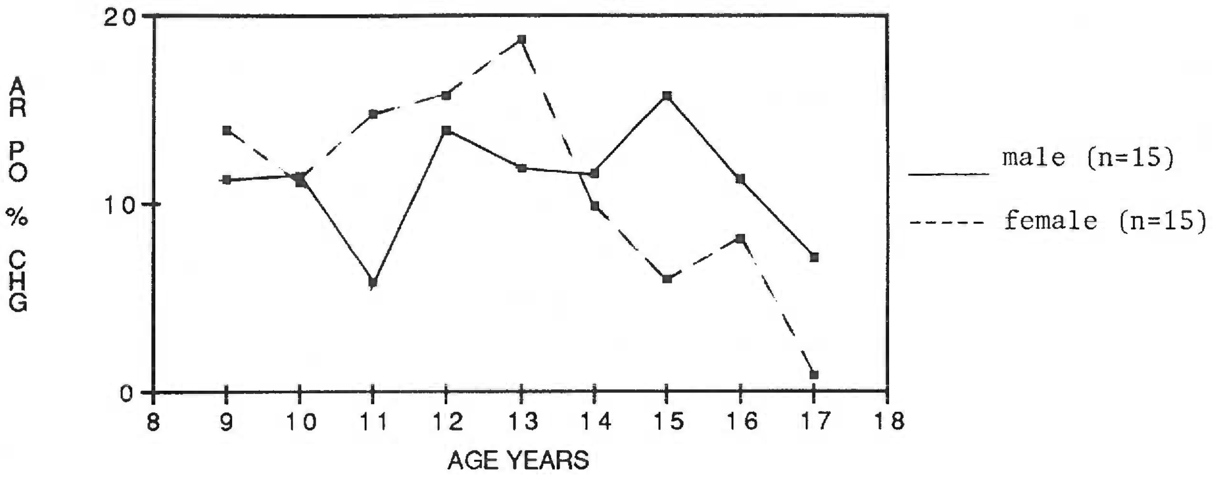

Figure 4.3 Mean annual percent change of articulare to pogonion for males and females from chronological age 8 to 17.

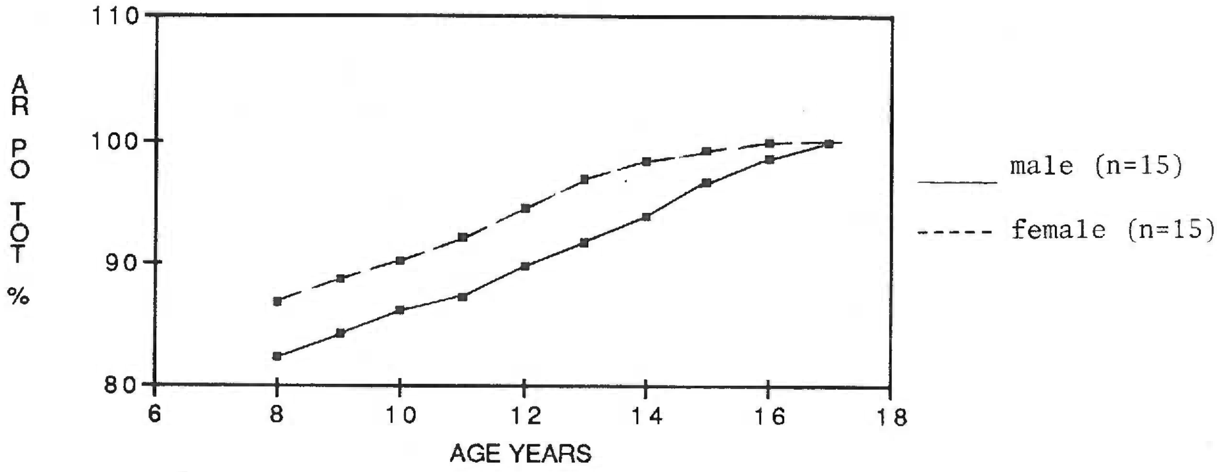

Figure 4.4 Mean total percent annual growth of articulare to pogonion for males and females from chronological age 8 to 17.

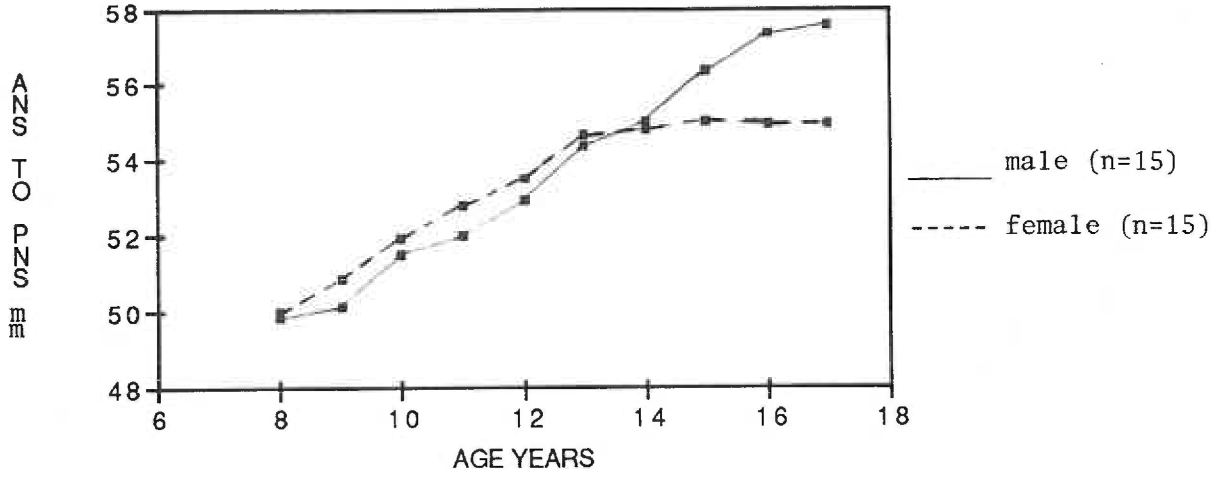

Figure 5.1 Mean total growth of anterior nasal spine to posterior nasal spine for males and females from chronological age 8 to 17.

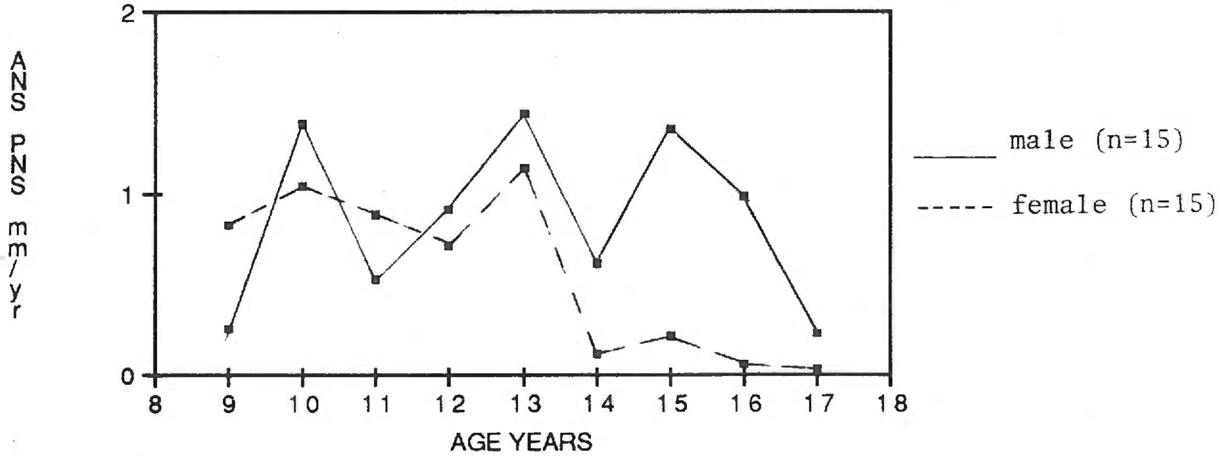

Figure 5.2 Mean annual growth of anterior nasal spine to posterior nasal spine for males and females from chronological age 8 to 17.

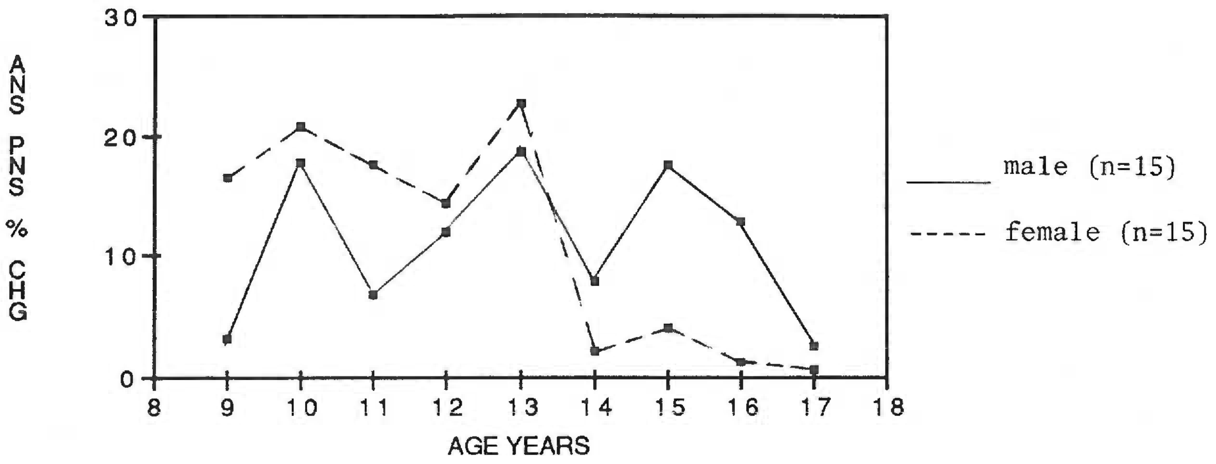

Figure 5.3 Mean annual percent change of anterior nasal spine to posterior nasal spine for males and females from chronological age 8 to 17.

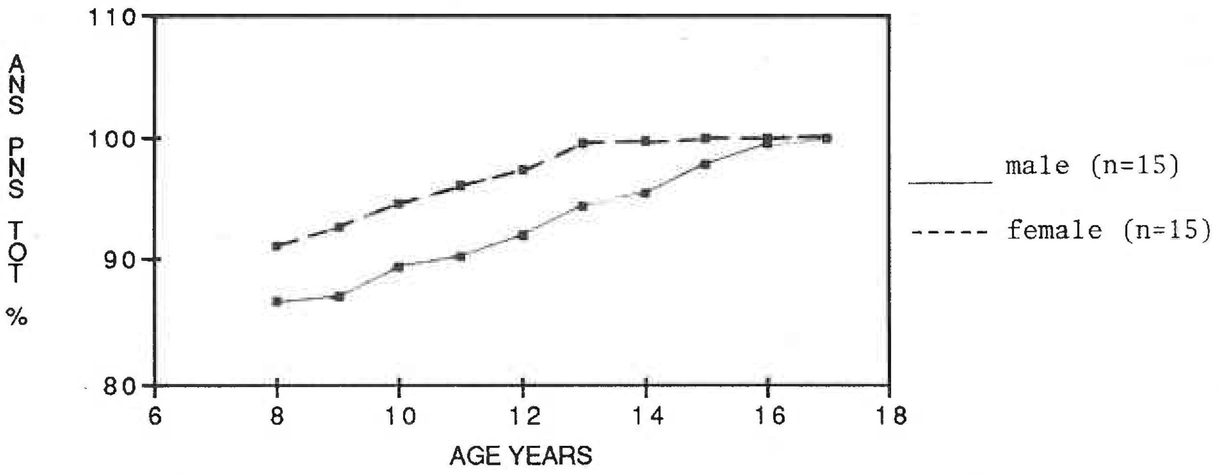

Figure 5.4 Mean total percent annual growth of anterior nasal spine to posterior nasal spine for males and females from chronological age 8 to 17.

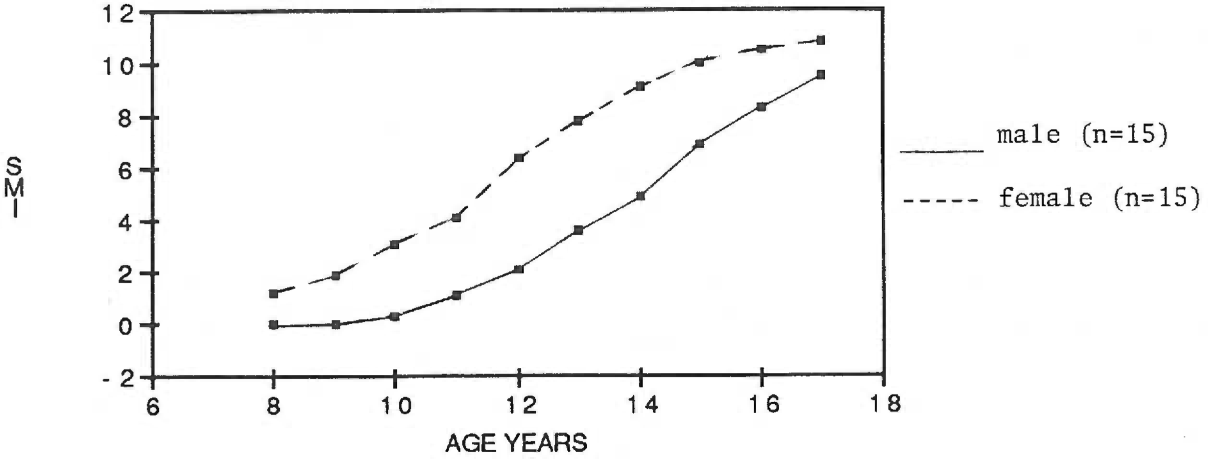

Figure 6.1 Mean changes in skeletal maturation index based on hand and wrist radiographs for males and females from chronological age 8 to 17.

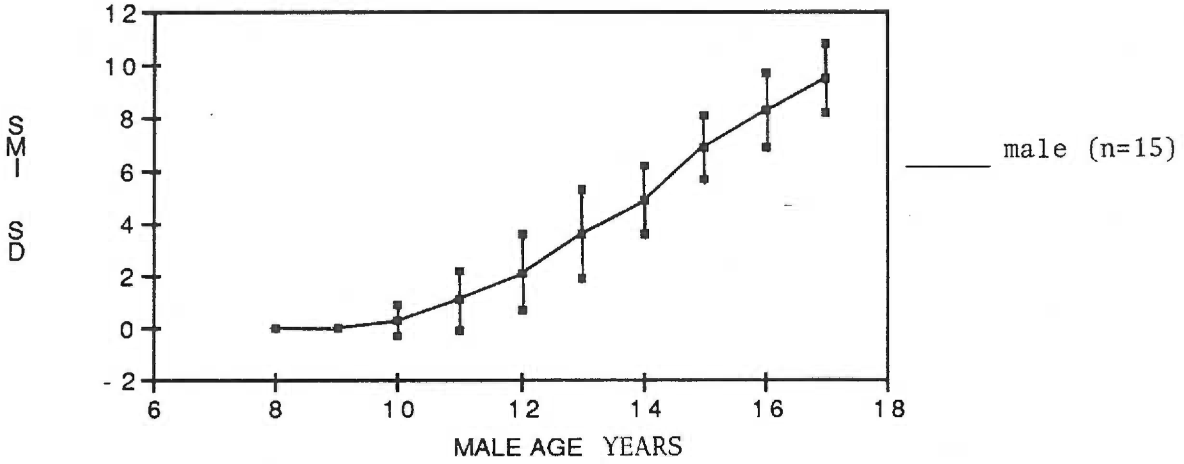

Figure 6.2 Mean change in skeletal maturation index (1 S.D.) based on hand and wrist radiographs for males from chronological age 8 to 17.

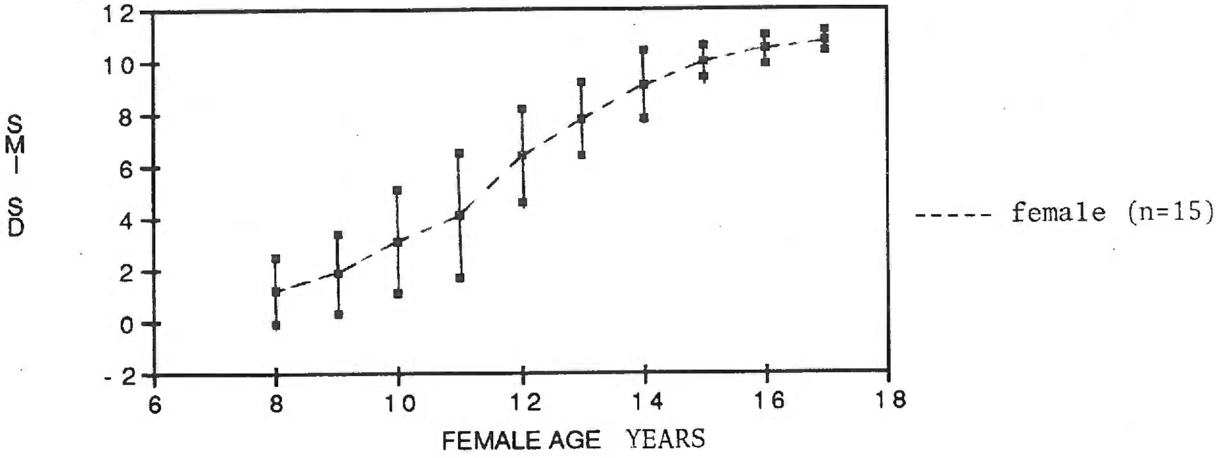

Figure 6.3 Mean change in skeletal maturation index (1 S.D.) based on hand and wrist radiographs for females from chronological age 8 to 17.

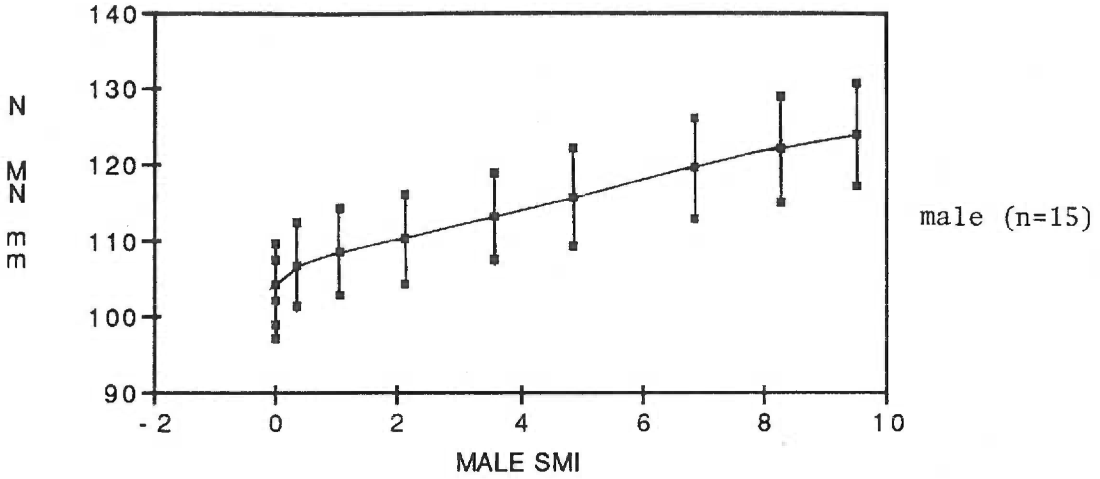

Figure 7.1 Mean change in nasion to menton (mm) growth (1 S.D.) relative to the skeletal maturation index for males from chronological age 8 to 17.

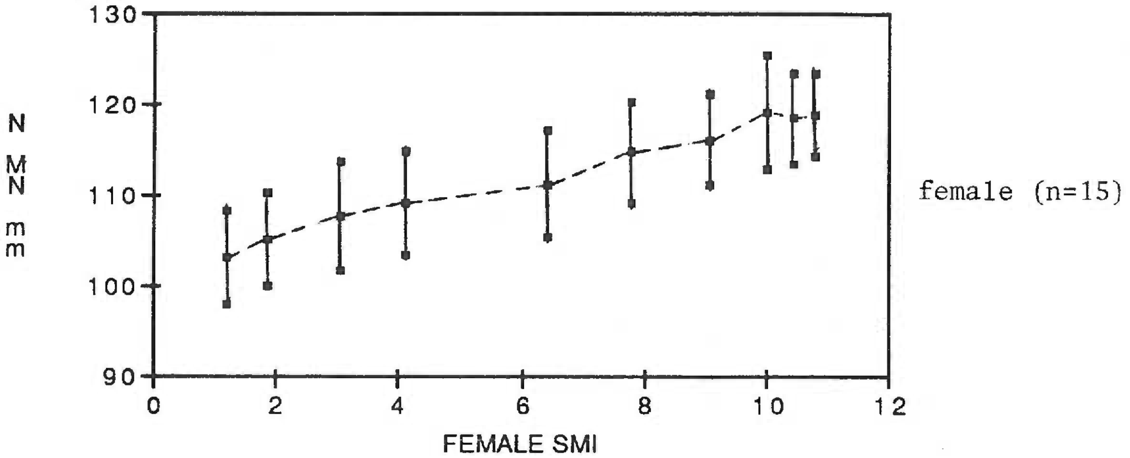

Figure 7.2 Mean change in nasion to menton (mm) growth (1 S.D.) relative to the skeletal maturation index for females from chronological age 8 to 17.

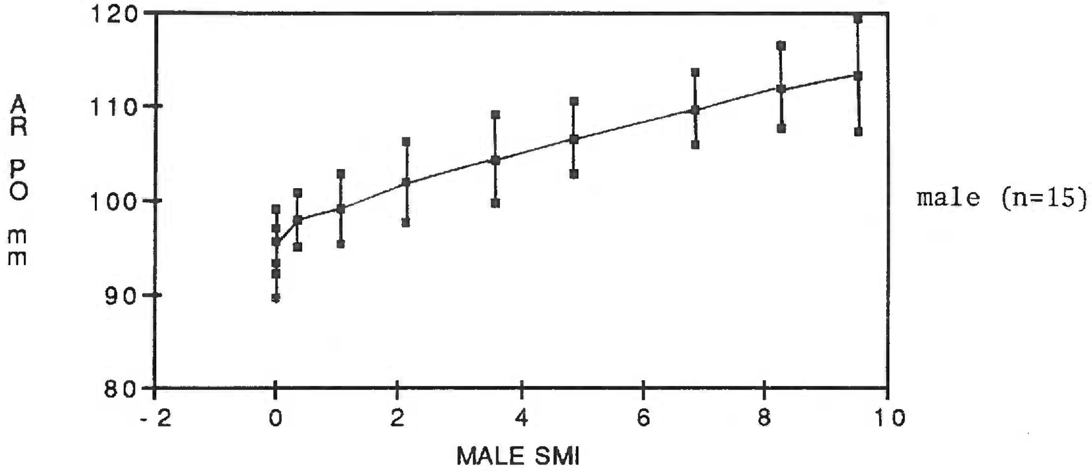

Figure 8.1 Mean change in articulare to pogonion (mm) growth (1 S.D.) relative to the skeletal maturation index for males from chronological age 8 to 17.

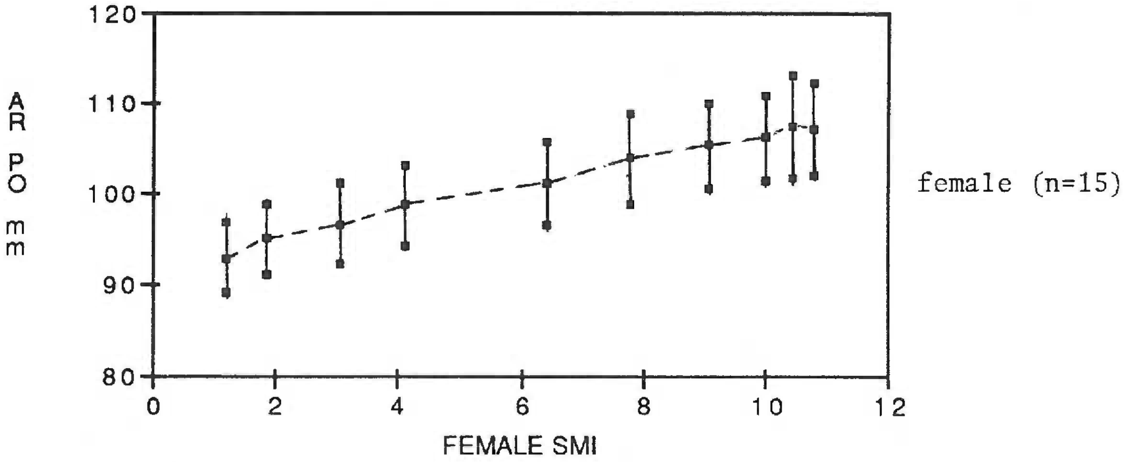

Figure 8.2 Mean change in articulare to pogonion (mm) growth (1 S.D.) relative to the skeletal maturation index for females from chronological age 8 to 17.

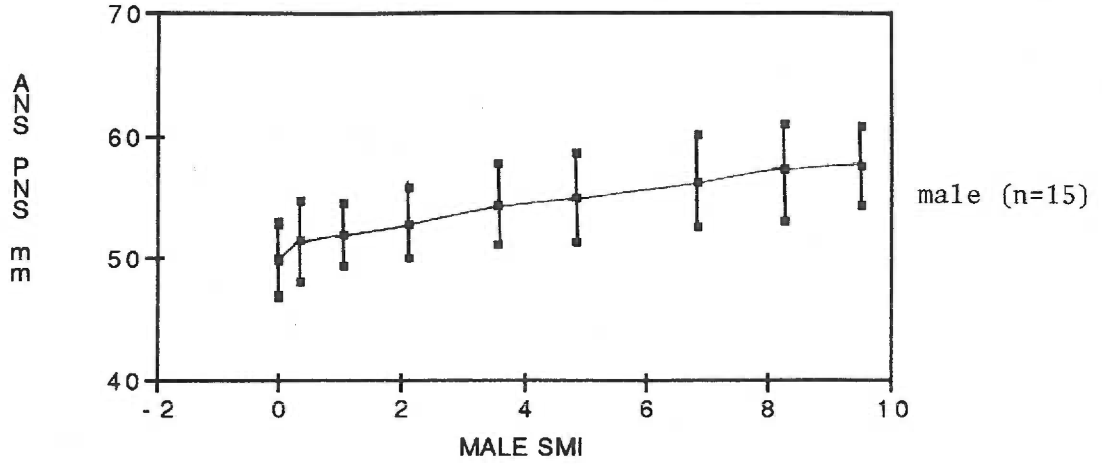

Figure 9.1 Mean change in anterior nasal spine (mm) growth (1 S.D.) relative to the skeletal maturation index for males from chronological age 8 to 17.

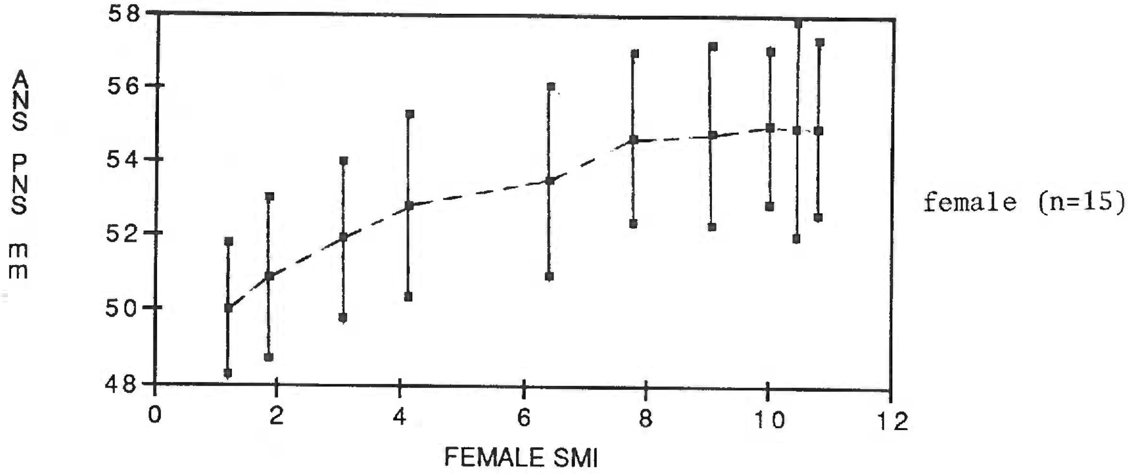

Figure 9.2 Mean change in anterior nasal spine (mm) growth (1 S.D.) relative to the skeletal maturation index for females from chronological age 8 to 17.

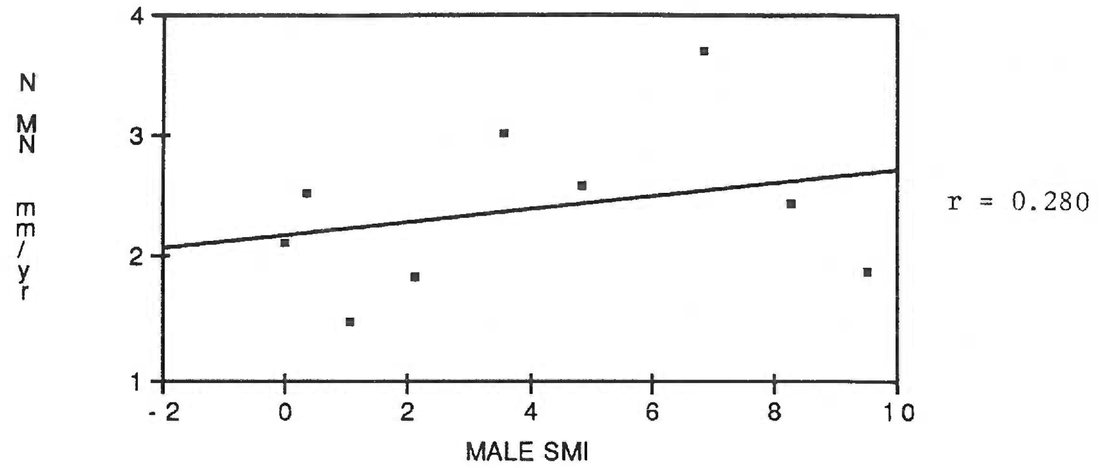

Figure 10.1 Correlation coefficient of nasion to menton (mm) growth and skeletal maturation index for males from chronological age 8 to 17.

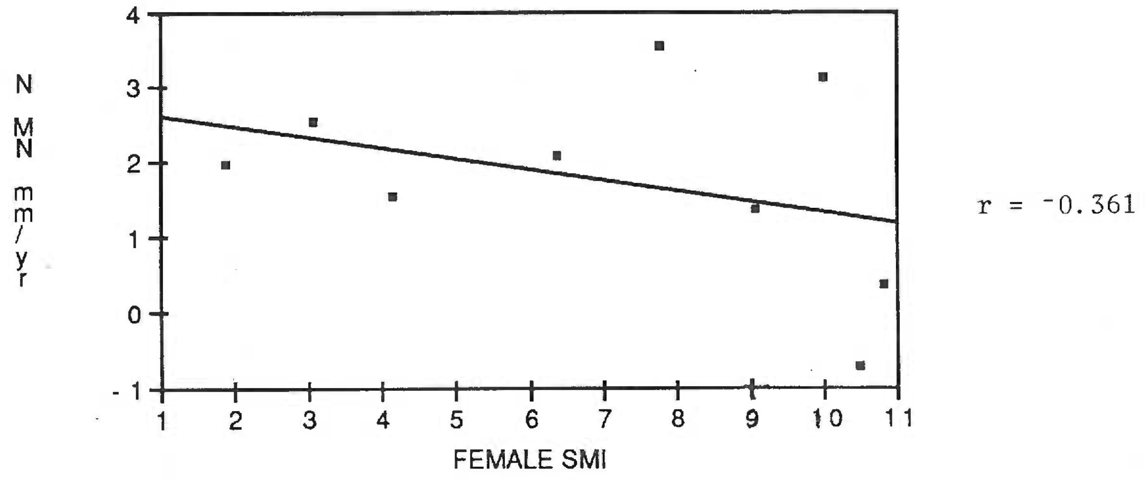

Figure 10.2 Correlation coefficient of nasion to menton (mm) growth and skeletal maturation index for females from chronological age 8 to 17.

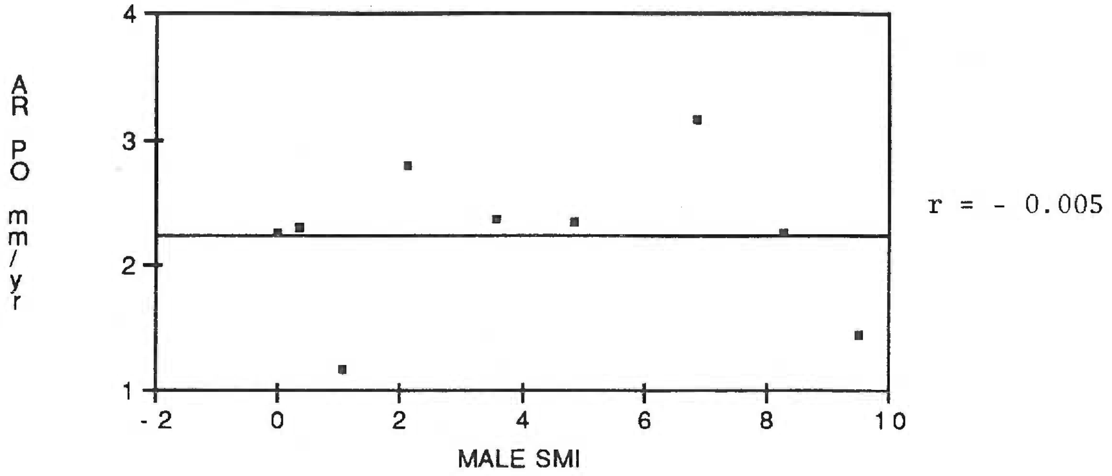

Figure 11.1 Correlation coefficient of articulare to pogonion (mm) growth and skeletal maturation index for males from chronological age 8 to 17.

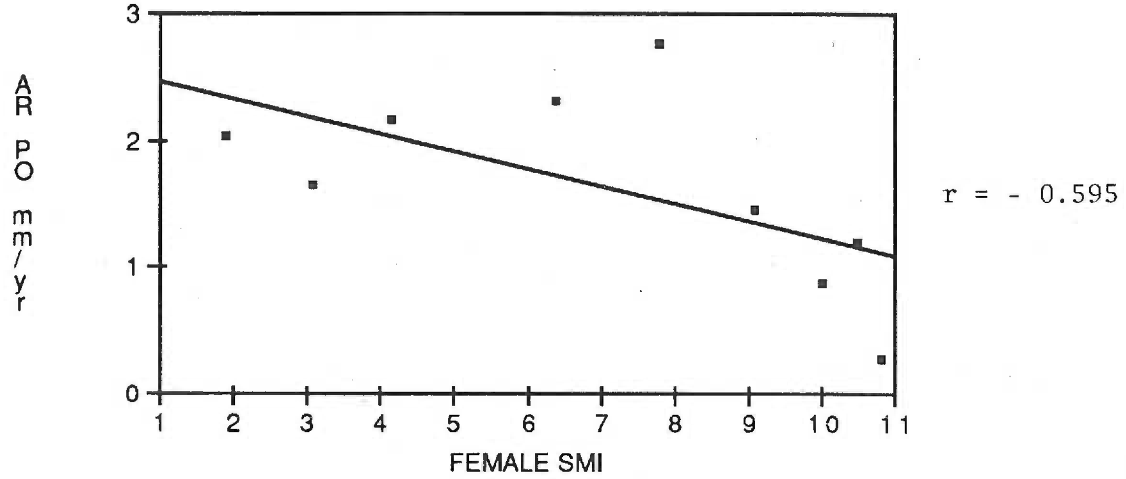

Figure 11.2 Correlation coefficient of articulare to pogonion (mm) growth and skeletal maturation index for females from chronological age 8 to 17.

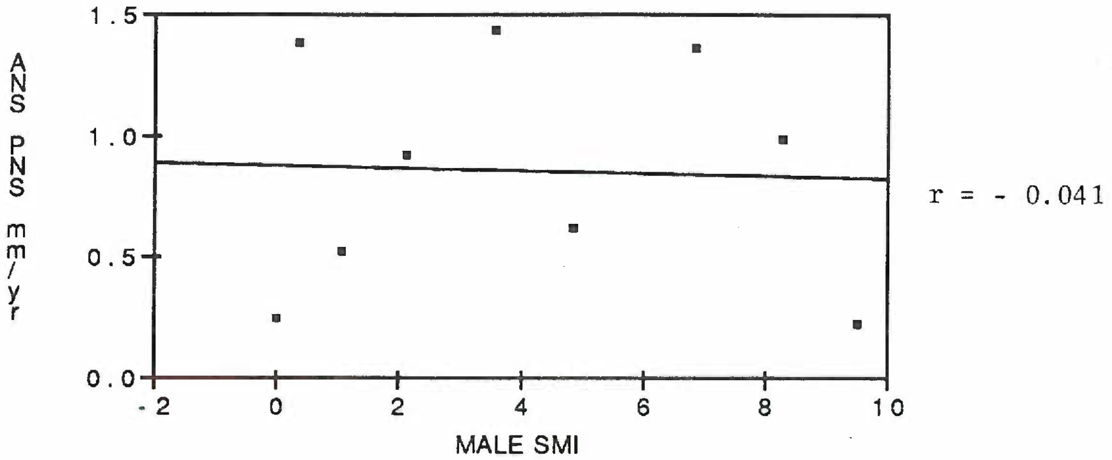

Figure 12.1 Correlation coefficient of anterior nasal spine to posterior nasal spine (mm) growth and skeletal maturation index for males from chronological age 8 to 17.

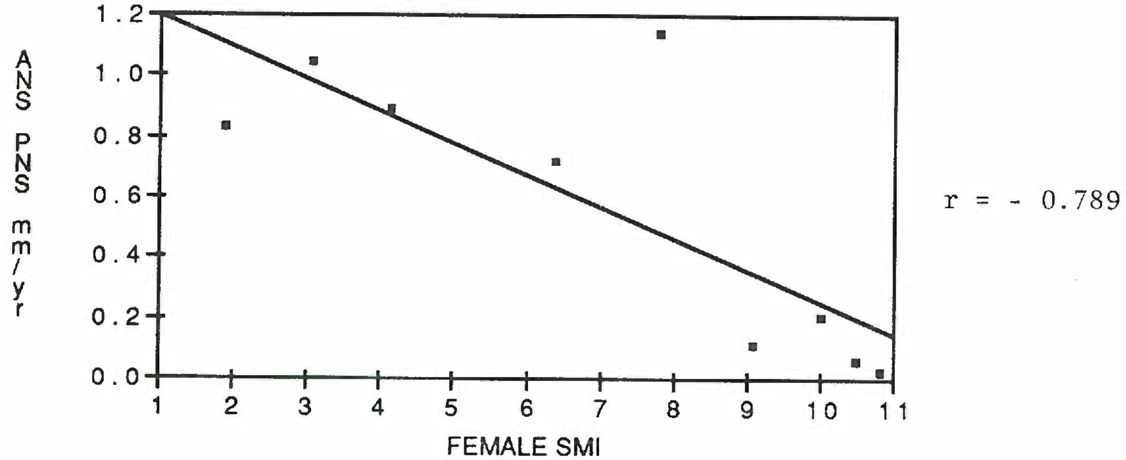

Figure 12.2 Correlation coefficient of anterior nasal spine to posterior nasal spine (mm) growth and skeletal maturation index for females from chronological age 8 to 17.