MORPHOMETRIC MODELS FOR THE ASSESSMENT OF DEVELOPMENTAL STATUS OF BOYS AGE 7 TO 16

by

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Abstract

The purpose of this study was to construct a morphometric system for the assessment of maturational status based on longitudinal data of 125 boys aged 7 to 16 years from the Saskatchewan Growth and Development Study. The available data were augmented in the present study with 5 limb segmental lengths obtained through duplicate measurement of 1200 sets of somatotype photographs. Anthropometric equivalents to the photogrammetric data were derived from the application of both procedures to an independent sample of 45 boys aged 6 to 16 (R^2=.86 to .98).

Both age at PHV and an index of skeletal maturity were regressed on the data using multiple regression analysis based on least squares estimates. While the data appeared to be multivariate normal and highly linear, no equations were found which appreciably reduced the standard error of the residuals to less than that produced by chronological age as the sole independent variable.

From a range of non-parametric models, the best based on minimal differences from a maturity-standardized prototype was modestly associated with the index of skeletal maturity (r=0.60 to 0.75), but not age at PHV (r=0.15 to r=0.53). While the former correlations support the application of this model in group assessment of maturity, they do not warrant its use for individual appraisal or substitution for radiographical procedures.

A high degree of individual variability in morphology present at every developmental level was confirmed by the inability of discriminant function analyses to bring order to maturity groupings. It was evident that mathematical systems based on assumptions of

developmentally-characteristic morphology will likely misrepresent the uniqueness of both individual physique, and patterns of maturation.

In order to produce a systematic display of individual developmental differences, reference norms based on mid-range maturers were used to construct a series of anthropometric maturity charts for the 10 chronological age levels. These included provisions for stanine ratings, sigma scores, and comparison with early and late maturing means for 25 variables at each age. These charts have the advantage of enabling one to generalize about maturity status but not obscure the differing patterns of size and shape at every chronological age.

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Chapter 1 INTRODUCTION

Elapsed time or chronological age is commonly used as the index by which the distance a child has travelled along the path from neonate to adulthood is measured. This path encompasses increases in size (growth), as well as differentiations of physiological function toward mature status (development or maturation). However, the rate at which each child travels this path varies, such that identifiable landmarks of both growth and development are reached at different chronological ages among children. Such individual differences were recognized in the earliest studies of human growth (Lehmann, 1844, cited by Tanner, 1981), while Boas (1932) illuminated the phenomenon by describing it in musical notation as the 'tempo of growth'. He suggested that the melody, or sequence of developmental events is similar in all children, whereas the tempo, or speed at which the melody is played-out is quite variable, both within a child's own development, and in comparison to that of other children.

The artificiality of the conventional chronological age time scale is more than a rhetorical issue. Chronological rather than developmental categorization of a child who is at either end of the normal span of maturation can lead to misinterpretation of clinical, behavioural, and performance appraisal and research. A more biologically-rational and equitable manner of marking progress toward maturity would be on the basis of 'physiologic' or 'developmental' age. While conceptually somewhat imprecise, these terms denote the average age at which children reach specific identifiable stages of growth or development.

1.2 The Need for Information Regarding Developmental Age:

Information regarding a child's developmental progress, either in absolute terms, or relative to chronological age, is critical in the broad areas of clinical, educational, and human performance research and application.

1.2.1 Clinical

1.2.1.1 Growth norms

Anthropometric data are commonly used in clinical practice for investigation of primary and secondary conditions affecting growth. The most frequently used techniques for assessing the normality of height, weight, and growth of children are growth reference curves such as those produced by Tanner, et al. (1966) and the U.S. National Center for Health Statistics (1979). These typically depict percentile norms or Z scores (Waterlow, et al., 1977), from healthy populations, for weight and/or height by chronological age. In some cases weight and height velocity norms are also charted by chronological age.

Such tables have been criticized for the fact that they are developed by averaging growth data of large numbers of individual children, collected either cross-sectionally or longitudinally. Through averaging, the growth curves will not be taking into account the phase differences among individual growth patterns (Tanner, 1978). An additional shortcoming of these charts is that unless a child is followed for a long period of time, no distinction can be made between a growth pattern which is not average but within the range of normality, abnormal growth, and constitution or phenotype. With an estimation of the developmental status of such a child, one could immediately rule out at very least one of these possibilities.

1.2.1.2 Weight norms

Assessing a child's weight can yield information regarding over- or undernutrition when the height and/or age are also taken into consideration. Weight percentile standards similar to those for height are often used for this purpose in clinical practice. Here again, failure to consider the developmental status of a child can lead to misinterpretation of weight standards. Both weight expectancy for height and expected weight gain with growth will depend on the extent of maturation, particularly during adolescence (Billewicz, et al., 1983). Other techniques commonly used to assess obesity and body composition such as the Body Mass Index and densitometry can produce seriously misleading conclusions if developmental status is not taken into consideration (Cole, 1986; Garn et al., 1986; Leitch, 1976; Lohman, 1986; Slaughter et al., 1983).

1.2.1.3 Assessing the influence of malnutrition

Aside from alaying some confusion in the diagnosis of undernutrition and obesity, assessment of developmental age could shed some light on the specific effects of these conditions on growth and development. A number of researchers have described various developmental abnormalities within these extremes of malnutrition (Deutsch, et al., 1985; Eveleth, 1985; Eveleth and Tanner, 1976; Frisancho, 1978; Garn, et al., 1986b; Malina, 1978; Mascie-Taylor and Boldsen, 1987; Schwarz, 1966).

Similarly, an index of developmental age could be employed in evaluating the qualitative nature of 'catch-up growth' subsequent to undernutrition (Tanner, 1981).

1.2.1.4 Other clinical uses

The timing of clinical interventions such as orthodontic procedures requires precise information regarding the developmental status of the patient (Demirjian, 1985; Graber, 1966). Biological maturity or developmental age has been suggested as a factor to be considered in evaluating the risk of low birth weight pregnancies (Stevens-Simon, et al., 1986). Finally, prediction of adult stature has some clinical value as well as functional utility in choosing to develop individuals for elite dance or sport. This cannot be done with any accuracy without knowledge of developmental status (Tanner, et al., 1975).

1.2.2 Behavioural

The concept of developmental age and 'readiness' is a familiar one to those studying psycho-social aspects of human growth. From as early as 1903 (Crampton, reprinted 1944) there have been suggestions that psychological and intellectual development are synchronized to that of overall physiology (Archer, 1981; Bayley,1966; Govatos, 1959; Simon, 1959; Tanner,1962; Tanner,1977; Wolff, 1981). It is hypothesized that the processes of physiological development prepare the individual to respond appropriately to external, experiential stimuli, which, in turn, promote psychological development (Archer, 1981; Wolff, 1981). The limited empirical evidence suggests this hypothesis may hold to some degree at all ages (Bayley, 1966; Simon, 1959; Tanner, 1962; Wolff, 1981; Zeller, 1936). As with appraisal of stature and weight, without some information regarding the status of physiological development of a child, 'standardized' tests of intellect, cognition, or skill acquisition cannot sort out those children who are 'gifted' from those who are merely developmentally advanced (Simon, 1959).

1.2.3 Physical performance

"In the absence of basic facts about human growth patterns, much that is said about children and sport is illusory."
J.Borms, 1986

The developmental status of a child is a primary factor in his absolute and relative physical performance capacities. Observed advantages of strength (Birrer and Levine, 1987; Carron and Bailey, 1974; Haywood, 1986), oxygen uptake (Bell, et al., 1986; Houlsby, 1986; Hughson, 1986; Koboyashi, et al., 1978; Mirwald, et al., 1981; Rutenfranz, et al., 1982; Sprynarova, 1987), movement mechanics (Jensen, 1981), and certain skills (Haywood, 1986) are observed among boys who are developmentally more advanced than their chronological age peers. These advantages, along with concerns about permanent tissue damage occurring as a result of sports injuries sustained during critical growth periods have led to conclusions that the knowledge and understanding of maturational differences in physical capacity of children could set the foundation of a more equitable and safer system of sport participation among children and adolescents (Birrer and Levine, 1987; Caine and Broekhoff, 1987).

1.3. Existing Systems for Assessment of Developmental Age:

The growth and developmental parameters of a number of physiological systems can be standardized to derive an index of the degree and velocity of the progression of that system towards maturity. There is distinct variation in the relative timing and individual rates of development of many of these systems as to imply that the developmental processes are not absolutely coordinated. Perhaps no individual system can reflect the maturation of all other systems or of the organism as a whole. Yet, while there exists some specific control of each, there is undoubtedly a general 'maturity factor' which assures the ultimate growth and maturation of all systems on a similar temporal scale (Bielicki, et al., 1984; Tanner, 1978).

A number of physiological systems are accessible for the monitoring of growth and maturation and are used as indices of overall 'developmental' or 'physiological' age. The most ideal are those which carry the same developmental sequence in all children; which can be applied throughout all ages of childhood and adolescence; and which are irreversible, ultimately reaching the same state in each individual (Acheson, 1966; Marshall, 1966a).

1.3.1 Somatic systems:

1.3.1.1 Stature

Size is one rather obvious marker of physiological development. As Medawar (1945) suggested, "other things being equal, the size of an organism can be treated as a function of its age". Yet assessment of stature and weight can yield a poor estimate of physiological development because the distinction between phenotype and maturity cannot be made (Marshall, 1966; Tanner, 1962). Use of cross-tabulated norms for height, weight and age; height-weight ratios; and sytems such as Tanner's (1962)

'Height Developmental Age', (that age where a child's height equals the average of a group of children of a given chronological age), do not overcome this problem.

1.3.1.2 Percent of adult stature

Once adult phenotype is established, however, a strong correlation exists between degree of progress toward maturity (assessed by skeletal maturation; discussed below) and proportion of adult stature achieved at a given chronological age (Bayley and Pinneau, 1952). This relationship is strongest in adolescence where age at 90% of adult stature has been identified to be the single best index of physiological maturity over others such as secondary sex characteristics, bone maturation, and peak height velocity (Bielicki, 1984; Marshall, 1974; Nicolson and Hanley, 1953). The latter authors provide the caveat that while on average there exists a strong association, useful predictions of maturational status of an individual cannot be made solely from percent of mature height. A more obvious restriction is the retrospective nature of such measures.

1.3.1.3 Stature velocity

The failure of absolute stature to mark an individual's developmental status does not rule out a relationship between growth in stature and developmental progress. Bayley (1956) observed that growth in height is closely related to rates of physical maturity. Pre-pubertal advancement or retardation of skeletal maturation has been shown to parallel similar (but not equivalent) degrees of relative tallness or shortness for chronological age (Hewitt and Acheson, 1961; Tanner, 1962).

1.3.1.4 Peak height velocity

Retrospective identification of the age at which maximal growth in height or peak height velocity (PHV) occurred has proven to be one of the more stable means of identifying relative maturational status (Marshall, 1966). It is an identifiable parameter for most individuals, reflecting neither chronological age, size, nor does it occur at a fixed percentage of adult size (Zacharias and Rand, 1983). PHV occurs on average, early in female adolescence, and about 2 years following the onset of puberty in males (Marshall, 1966).

PHV is commonly used as a parameter upon which to re-align the growth curves of children from whom longitudinal data have been obtained. This adjustment reduces the variance in timing of developmental events of adolescence ordinarily demonstrated by the chronological age scale (Malina, 1978). Growth in stature and appearance of other biological markers of puberty are thus frequently keyed to PHV (Malina, 1978; Tanner, 1978).

Obviously, one needs not only longitudinal growth data, but those covering the adolescent growth phase in order to derive PHV. There are additional limitations to the overall usefulness of this parameter. First, for unknown reasons, not all children exhibit definable growth spurts at puberty (Bielicki, et al.,1984; Buckler, 1984). A second uncertainty is the association of age at PHV holds with the nature of growth and development during the pre-pubescent period (Bielicki, et al., 1984; Marshall, 1974).

Other parameters of the mean stature growth curve can be obtained by fitting various functions to growth data. Age at mid-growth spurt, age at take-off of adolescent growth spurt, ages at maximal acceleration and deceleration in the spurt are commonly identifiable. To date, only age at PHV has been generally adopted as a parameter upon which longitudinal growth data can be adjusted for standardization of developmental status.

1.3.2 'Dental Age' system:

1.3.2.1 Principles

Eruption of both deciduous and permanent dentition has a discrete order which arguably correlates with other measures of physical maturation (Bielicki,et al.,1984; Demirjian, 1979; Demirjian, 1985; Marshall, 1966; Tanner, 1978). While tooth emergence and those systems characterizing somatic, skeletal, and sexual development are loosely associated (therefore reflecting the underlying presence of some general factor controlling physiological maturation), it has been suggested that they likely gauge two different sorts of development (Demirjian, 1985; Filipson and Hall, 1976; Tanner, 1978; Van der Werf ten Bosch, 1966).

1.3.2.2 Limitations

The appearance of dentition is an unreliable index of developmental status as it is readily affected by premature extraction or loss of preceding deciduous teeth, tooth crowding, and oral infection (Demirjian, 1985). A further drawback is the temporal limits of the system. From the ages of 2 to 6, and from the time full permanent dentition is established (circa age 13), little information on developmental status can be gleaned from counting erupted teeth (Tanner, 1978).

1.3.3 Secondary sex characteristics:

1.3.3.1 Principles

The initial appearance and development to adult form of pubic and axillary hair are milestones of sexual maturation in humans, as are testicular and penis growth in males, and breast formation and menarche in females. For most of these secondary sex characteristics Tanner (1962, 1978) and others (Greulich, 1938; Nicolson and Hanley, 1953) have established criteria for identification of discrete developmental stages within each continuum to maturity. While these arbitrarily defined stages are always passed through sequentially within any one characteristic, there is considerable variation in the speed at which individuals pass through a given sequence to maturity (Tanner, 1978). Similarly, the order in which these sequences move toward maturity is not identical among all boys or all girls (Tanner, 1978).

1.3.3.2 Limitations

With the possible exception of menarchal age, evaluations of secondary sexual development are invasive. They involve inspection of the nude body, and are thus almost always carried out clinically or from examination of clinical photographs. Further, Billewicz (1983) has commented that while assessment of pubertal status by such systems is simple on paper, it requires considerable experience to ensure consistent results. Finally, the development of these secondary sex characteristics as demonstrations of an individual's progression through adolescence are useful in appraising post-pubescent maturation only. Pre-pubescent children, and adolescents who have achieved full sexual maturity can only be described as such.

1.3.4 'Skeletal Age' systems:

1.3.4.1 Principles

The fundamental element of appraising bone or skeletal age (SA) is the fact that postnatal bone development follows a standard sequence of events, beginning with the replacement of cartilage at what are known as a primary centers of ossification, passing through gradual stages of enlargement and shape transformation, and with the fusion of the epiphyses, ultimately reaching a state of maturity which is the same in all individuals (Malina, 1971; Marshall, 1966a).

Any or all parts of the skeleton can be used for assessment of skeltal maturation (Tanner, 1978) however, the hand-wrist is the area most commonly examined. This area represents 28 to 30 separate centers for bone growth and maturation (Malina, 1971); both round and long bones are exposed (Marshall, 1966a); it is sufficiently far from the gonads to minimize radiation exposure, and it is the area offering the most convenience, economy, expedience, and cooperation of subjects (Cobb, 1971). Although there is some variation in the rates of skeletal progression towards maturity among the different regions, it is felt that the hand-wrist is fairly representative of the remainder of the skeleton (Malina, 1971). Two methods of classifying skeletal maturity of the hand-wrist and so identifying 'skeletal age' are in common use, the Greulich-Pyle and the Tanner-Whitehouse.

1.3.4.2 Greulich-Pyle Method

The Greulich-Pyle (Pyle et al., 1959) or Atlas method is a refinement of a system developed by Todd (1937). This is an inspectional technique, where individual bones, or more frequently, the entire hand-wrist radiograph are compared to an atlas of standards for chronological age. The skeletal age of the child being rated is that age standard which his or her radiograph most closely approximates. Critics of this system state that there is frequently maturity imbalance, not only among the bones of the skeleton, but among different bones within the same area, and even between centers of one bone, such that it becomes very difficult to match entire radiographs to standards (Lee, 1971). Further criticism of the Greulich-Pyle method suggests the standards used came from such priviliged American children, that even though they were established in the 1930's, they continue to be more advanced than children of contemporary middle socio-economic class (Buckler, 1984; Roche, 1980; Tanner, 1978).

1.3.4.3 Tanner-Whitehouse Method

The Tanner-Whitehouse (1962) and TW2 (1975) methods require individual evaluation of each of 20 characteristics of the hand-wrist radiograph, each characteristic divided into 8 distinct maturational stages, each stage having a numerical score. These scores have been derived mathematically so that the sum of scores for all characteristics "represents the best overall estimate of skeletal maturity" (Tanner, 1978). The skeletal maturity score, or the total of these 20 ratings, can then be translated into Skeletal Age (SA), which is the mean chronological age represented by that skeletal score in a large sex-matched random sample of urban and rural Scottish children measured in the 1950's.

1.3.4.4 Limitations and relationships with other systems

The co-existence of two schemes which technically measure the same aspect of maturation is an important illustration of two features of all systems for the assessment of developmental age. The first point is that different techniques can be successfully applied to the same aspect of development. The second is that developmental markers can only be related to sample-specific norms. In using any system, age ascription will always be relative to the reference sample used by that system.

Whichever system is employed, skeletal age is a well established index of physiological maturity (Maresh, 1964; Marshall, 1966; Tanner, 1962). It is not as restricted in the developmental periods in which it can be applied as those systems discussed to this point. Skeletal age techniques can be used from the age of about 18 months (Tanner, 1978) to the point where skeletal maturity is attained, on average 18 years in males and 16 years in females (Tanner, et al., 1975).

However, radiography is an invasive procedure, having strict limits regarding annual exposures to gamma radiation set by national and international health protection agencies (Gofman, 1983; Health and Welfare Canada, 1980). The size and expense of radiographic equipment and the skill necessary to accurately rate bone developmental stages further preclude the extensive use of either skeletal age system outside the clinical context.

The nature and degree to which skeletal maturation relates to other systems of physiological development are not well understood (Marshall, 1974). While state of skeletal maturity and stature are sufficiently associated that prediction of adult stature is improved by the introduction of skeletal age to such formulae (Tanner et al., 1975), there is variation in bone age at PHV (Houston, 1980; Marshall, 1974). Similar broad distributions are seen in skeletal ages at which different phases of sexual development appear (Marshall, 1974; Stevens-Simmons et al., 1986). Yet Tanner (1978) notes, that while the events of puberty and skeletal maturation are only loosely associated, the relationship strengthens at the extremes of early and late maturation, both within and outside the limits of normality.

1.3.5 Summary

In the developing human, there is quite obviously no singular 'physiological age'. Monitoring the development of a unique physiological system cannot provide a complete description of the progress of the whole organism towards maturity, as there is a degree of variation both between and within somatic, dental, sexual, and skeletal indices of development (Marshall, 1974; Shock, 1966). However, in any population of children, particularly through adolescence, much variability is reduced when individuals are grouped by any similarities in development rather than by chronological age (Shock, 1966; Tanner, 1978).

1.4. Shape Change in Human Development.

1.4.1 Foundations

Until the study of growth entered the scientific realm in the Nineteenth Century, an appreciation for, and quantification of the changes in body proportions which accompany development from infancy through to adulthood was the province of artists (Maresh, 1964; Zeger and Harlow, 1987). It was the Belgian astronomer, Adolphe Quetelet (1871), who first demonstrated to the scientific world, shape changes due to alterations in linear segment proportions as part of the basic pattern of human growth.

1.4.2 Differential growth

Auxologists have since re-iterated the fact that differential growth of anatomical components characterize shape to be as much a variable of growth as age and stature (Bookstein, 1978; Healy and Tanner, 1981; Hiernaux, 1968; Huxley, 1932; Jensen, 1987; Leitch, 1976; Malina, 1978; Medawar, 1945; Stratz, 1909; Tanner, 1962; Tanner, et al., 1976; Thompson, 1917; Zeller, 1936; Zuk, 1958). Among the derivatives of the comparatively recent large-scale longitudinal growth studies have been descriptions of the differences in rates of growth of various dimensions of the body, including the timing of the growth spurt and the relative maturities of each (Attalah, 1980; Cameron, et al., 1982; Harrison and Marshall, 1970; Hauspie, 1979; Maresh, 1964; Marshall and Ahmed, 1976; Marshall and Harrison, 1971;

Meredith, 1978; Roche, 1974; Tanner, et al., 1976; Welon and Bielicki, 1979). Although by no means universal (Cameron, et al., 1982; Jensen, 1987), a fairly generalized sequence of growth in segments of the axial and appendicular skeleton is apparent (Hauspie, 1979; Tanner, 1977), which results in recognizable differences of form throughout development. The sequences are cephalo-caudal, and distal-proximal respectively.

1.4.3 Quantification of shape, shape change, and developmental status

Godin and Stratz

Many have attempted to define human shape, either subjectively or empirically, and in doing so ascribe developmental status to a child. Among the first were Godin (1903, cited by Tanner, 1962) who used ratios of segmental volumes and lengths to characterize physiological age, and Stratz (1909) whose height-scaled planar drawings of a male figure from birth to maturity have been repeatedly used by investigators and educators in this field (Graber, 1966; Krogman, 1943; Leitch, 1976; Medawar, 1945; Maresh, 1955). Williams and Scammon (1945) further developed Stratz's scaling technique to show proportionality differences of physiques ('iconometrography'). Mathematical treatment of Stratz's system, allowing quantitative analysis of the changes in vertical proportions over time, was proposed by Medawar (1945), although he concluded that shape "does not admit of definition in the language of real numbers".

D'Arcy Thompson

Based on the premise that organic transformation is continuous and variable in space and time, D'Arcy Thompson (1917) demonstrated the differential growth gradients of organisms (as well as shape differences among species) through a deformation of coordinates on the Cartesian grid. This system has only latterly been quantified mathematically to model human growth and development by Goldstein and Johnston (1978), producing a higher order polynomial which is difficult to interpret in biological terms. In his monograph describing geometrical techniques for the measurement of biological shape and shape change, Bookstein (1978) stated that "it seems impossible to extract quantity from the Cartesian grid as Thompson formulated it, in any straightforward way".

Huxley

The introduction of bivariate allometry to the study of differential growth by Huxley in 1932 was among the early attempts to quantitatively describe changes in shape. Some of the contemporary criticisms of the Huxley's model are that it does not partition out size from shape (but rather, implies differences in shape associated with size), and that restriction of analyses to bivariate functions afford a poor appreciation of what may be more complex contrasts between forms (Reyment, et al., 1984).

Zeller

Visual recognition of physical shapes corresponding to developmental progress was promoted in Germany by Zeller (1936) who used the term Gestalt, denoting configuration, to encompass both the specific relationships of different body parts to each other and the total form. Simon (1959) reported the successful anthropometric quantification of this inspectional method for testing the hypothesized developmental parallels between school performance and physique among young children.

Healy and Tanner

More recently, multivariate morphometrics, a term coined by Reyment, et al. (1984), has emerged as the science of measurement and description of biological growth and form. The concept was introduced by Jolicoeur and Mosimann (1960), who used principle component analysis as a multivariate extension of Huxley's allometric quantification of shape differences. Most commonly used in problems of taxonomy and phylogeny, application and interpretation of appropriate multivariate techniques is a topic of much discussion in these areas of study (Corruccini, 1978a and 1978b; Gould, 1966; Lestrel, 1974; Sprent, 1972; Reyment, et al., 1984; Reyment, 1985; Zegura, 1978; Zegel and Harlow, 1987).

Speculations concerning the utility of some multivariate techniques in quantifying shape and shape change in human development have been presented by Healey and Tanner (1981), who regarded principal components analysis as appropriate for identification of shape vectors and their anthropometric components in adults. The experience of these authors in defining shape components suggests a close examination of the data is necessary to avoid biases brought about by large differences in variance due to measurement error or to the magnitude of the measures themselves. It is also suggested that those linear compounds which define shape in the adult physique are not likely to define shape in children, nor its subtle changes with growth.

Meszaros

The Hungarian group of Meszaros, Mohacsi, Szabo, and Szmodis (1986) have recently reported a system for assessment of biological development by anthropometric variables. Based on quarter-year cross sectional averages of stature, body mass, and sum of biacromial breadth, forearm girth, and hand circumference for 25,000 children; the subject's measures are each rated for the age equivalent to the nearest quarter-year. Developmental age is then estimated as the mean of chronological age plus the three variable ratings, with some adjustments where stature deviates more than a year from the average. When testing the validity of their system against skeletal age ratings, the authors found correlations of .88 .86, and .85 for boys aged 11, 12 and 13 years respectively. The relative simplicity and effectiveness of this system suggest that superior models can be generated from a similar, biologically rational approach, using more valid fundamental criteria such as developmentally-adjusted anthropometric norms.

Chapter 2 STATEMENT OF THE PROBLEM, ORGANIZATION OF THE THESIS, AND DEFINITION OF TERMS

2.1 Statement of the problem

It is recognized that a need exists for a system of appraising developmental status which is accurate, safe, non-invasive, prospective, inexpensive, portable, and requires minimal training. Such a system's validity would be in its ability to reflect the developmental status of at least one physiological component, such as peak height velocity age. As prescribed by Marshall (1966a), such a scheme should also ideally be applicable to all stages of development, rather than limited to a short period when specific benchmarks are apparent .

Differential growth of segmental masses throughout development results in a constantly altering body form. These morphometric variations should be more characteristic of developmental status than of chronological age, as they reflect underlying developmental physiology rather than any simple function of time. Therefore this variation in morphology could be used in modeling developmental status throughout childhood and adolescence. The use of anthropometric parameters to characterise developmental status might offer further advantages over existing systems as it generates information regarding tissue masses relevant to movement mechanics, muscle function, metabolic events, pubertal timing, and stature and physique potential.

2.2 Objective

The objective of this work was to design a comprehensive anthropometric system for assessing physique status of boys aged 7 to 16, which would better reflect the timing of specific developmental events (PHV and skeletal age at chronological age 11) than does chronological age.

In order to meet this objective, four general problems were investigated as follows:

1.0 Specification of anthropometric prototypes characterising developmental status, involving three subproblems:

1.1 Augmentation of select data from the Saskatchewan Growth and Development Study by photogrammetric assessment of limb segmental lengths.

1.2 Identification of age at peak height velocity (PHVa) as a marker of developmental status by curve-fitting.

1.3 Organisation of data on annual intervals aligned on PHVa.

2.0 Identification of anthropometric variables discriminating among the developmental age prototypes, involving two general approaches:

2.1 Proportionality assessment

2.2 Principal components analysis

3.0 Exploration of models for estimation of developmental status from selected anthropometric variables, involving four techniques:

3.1 Multiple linear regression analysis

3.2 Non-parametric designs:

3.2.1 distance from adult reference target

3.2.2 minimal sum of differences from developmental prototype.

3.3 Discriminant function analysis

3.4 Anthropometric maturity assessment charts.

4.0 Evaluation of above models using technique-specific criteria:

4.1 Standard error of residuals for prediction of developmental markers (PHVa, skeletal maturity) by multiple regression.

4.2 Correlation of non-parametric predictions with indices of skeletal maturity and PHVa.

4.3 Estimates of misclassification and within-group variance for discriminant analyses.

2.3 Organization of the Thesis

The layout of this thesis follows the logical sequence of experimentation required for the construction of the proposed predictive systems. Chapters 3 through 7 describe work which provided an essential basis for the analytical procedures addressed in Chapter 8. While unable to establish adequately the proposed models, the functions explored in Chapter 8 drew critical conclusions regarding suppositions of the relationships between physique and maturity. Chapter 9 describes a comprehensive anthropometric maturity assessment system which, while a rational extension of the analyses of the previous chapter, avoids the misinterpretations produced by mathematical generalizations

To understand the outcome and conclusions of this thesis, the current chapter (Chapter2) along with Chapter 8: sections 8.2.4 through 8.3, and Chapters 9 and 10 are essential. However, to appreciate fully the biological and statistical inferences on which the final system and concluding statements were established, the complete work should be reviewed.

2.3.1 Tables

As the present work is a component of ongoing investigation in the Saskatchewan Growth and Development Study, detailed reporting, including subject identification in tabulated data was warranted. In most cases such data were listed in the appendices.

2.3.2 Figures

The study of longitudinal growth is multidimensional,

where for every X_{ijk}

$i = 1, \ldots .120;$

$j = 1, \ldots 24;$

$k = 7, \ldots 16;$

given i= number of subjects;

j= anthropometric variables;

k= chronological ages.

And where $Y_i = (Y_{i1}, Y_{i2})$;

given 1= index of maturity based on PHV age;

2= index of maturity based on skeletal age ratings at age 11.

Consequently, many graphical analyses and descriptions generated between 10 and 48 figures from the same procedure. In these cases, a sampling of the best descriptors was chosen for inclusion in the text.

2.4 Definition of Terms

The literature covering growth and development contains a number of terms which are often used interchangeably. This practice has created a degree of ambiguity of meaning. For the extent of this document (with the exception of the literature review), the definitions listed below will be followed.

1. GROWTH:

There appears to be no agreement in auxiological literature as to the definition of growth, or more specifically, the distinctions between growth and development. Some follow D'Arcy Thompson's denotation of growth as change in 'magnitude and direction':

> "To terms of magnitude, and of direction, must we refer all our conceptions of form. For the form of an object is defined when we know its magnitude, actual or relative, in various directions; and Growth involves the same concepts of magnitude and direction, related to the further concept or 'dimension' of Time."
>
> D'Arcy Thompson, 1945

> "a fundamental attribute of living organisms, manifested by change in size of the individual. Change in size is usually positive but adverse conditions can lead to negative growth. Growth is usually the resultant sum of the growth of component parts, which rarely grow at the same time and rate. Few dimensions of an organism grow at a rate equal to a simple power of time."
>
> Richards and Kavanaugh, 1945

Others include differentiation or development as processes within growth:

> "Growth is a process in which quantitative and qualitative changes in body structure occur during a period of almost two decades. "
>
> Hauspie, 1979

"Growth is a term used to describe the process of growing - the increase in size and development of a living organism from a simple to a more complex form or from its earliest stages of being to maturity. Growth is not simply a uniform process of becoming taller or larger, it involves change in shape and body composition and may involve replacement of tissues (the ductus arteriosus), tissue substitution (cartilage with bone) and alteration of modification of specific tissues (puberty)."

Rallison, 1986

For the purposes of this thesis, growth will be defined as the increase (or decrease) in size of an organism and/or its constituent anatomical components and tissues.

2. DEVELOPMENT and MATURATION

"Development is related to growth but can take place without change in magnitude (growth) ..... implies differentiation, changes of proportion, and changes in complexity".

Garn, 1952

"the terms development, maturation, and growth are used synonymously but are not identical. Development is a superordinate concept which subsumes growth and maturation. Maturation is the process leading to the condition of ripeness or maturity."

Connolly and Prechtl, 1981

"Maturation is metamorphotic and distinct from growth .... cannot be measured in time or distance units."

Acheson, 1966

"development implies increase in skill and complexity of function, that is, a series of changes by which an embryo becomes an organism .... therefore includes differentiation of various parts of the body to perform different functions."

Rallison, 1986

The definition of development will be the process of differentiation of tissues and function which procedes from an embryo to adult state. Maturation will be synonymous with development. Maturity or Adulthood will refer to the state achieved on completion of sexual and skeletal development.

3. PUBERTY and ADOLESCENCE

"adolescence is .... the period of transition from childhood to adulthood. It begins with a biological event, puberty, but its termination is variably defined and difficult to determine. ...... Commonly viewed within the context of sexual maturation and statural growth, adolescence begins with acceleration in rate of growth prior to attainment of sexual maturity, then merges into a deccelerative phase."

Malina, 1978

"adolescence is ..... the period of 'ripening' which extends from puberty to maturity. A period of time in which certain events take place in contradistinction to puberty which is the moment of beginning of adolescence."

Crampton, 1944

"Puberty: from 'pubertas' (age of manhood), refers to the point of time when the asexual life is changed to the sexual, and the ability to procreate is established. It is not a stage or a period of time but a division between two periods having no more duration than the division between one year and the next. It is practically impossible to determine this moment with exactness. It is only by external and objective signs that we know that puberty is approaching, is about here, or is past."

Pubescence denotes a process covering a period of time, the completion of which is vaguely understood to be puberty."

Crampton, 1944

Puberty will be defined as the transition between childhood and adolescence.

Adolescence will be the term used to describe the highly developmental phase between the initiation of secondary sexual development (puberty) and adulthood.

4. DEVELOPMENTAL AGE : this term describes an adjustment to a child's chronological age by the number of years which separate the normative age of a specific biological maturity event, and the age at which it was experienced by that individual child. For example, a boy who has reached his peak height velocity at age 12 would be described as having an advanced developmental age, as the norm for this event is around 14 years. In terms of peak height velocity, his developmental age is 14.

5. MATURITY-ADJUST(ED) : this is defined as the manipulation of anthropometric and other longitudinal growth data, such that individuals are re-aligned on a time scale reflecting a common feature of biological maturity instead of the more usual chronological age scale.

6. SIZE: this has been defined as the absolute dimensions of the anatomical features, or the composite of the human body, relative to those of an external reference.

7. SHAPE: strictly defined, shape denotes the appearance with regards to the outline of the surface of the body. Healy and Tanner (1981) have expressed shape differences as those which remain once differences in size have been accounted for. As an example, two individuals can be similar in shape or proportions, but different in size. For the purposes of this document shape has been defined as the proportions of the component anatomical features of the body relative to one another.

8. PHYSIQUE: similar to shape, this is a general term for the outer conformation of the body.

9. HEIGHT VELOCITY: the first derivative of a distance curve showing the rate of change in stature with age, usually expressed as cm.year^{-1}.

10. PEAK HEIGHT VELOCITY (PHV): the apex of the adolescent stature growth spurt, or that point where the growth in stature (cm.year^{-1}) is greatest.

Chapter 3 THE SASKATCHEWAN CHILD GROWTH AND DEVELOPMENT STUDY DATA

Few complete large-scale pure longitudinal studies of growth from childhood to maturity have been carried out to date (see Malina, 1978 for list; Tanner, 1985 for comments). Among these is the Saskatchewan Child Growth and Development Study which was conducted from 1964 to 1973 by R.L. Mirwald and D.A.Bailey of the University of Saskatchewan. This study consisted of an original sample of 207 seven-year-old boys who were randomly selected on a stratified socio-economic basis from the elementary school system in the City of Saskatoon. Each was put through a comprehensive battery of physiological and physical performance tests, as well as comprehensive anthropometric measurement, and somatotype photography at annual intervals as close as possible to the date of the previous year's testing. Between the ages of 11 and 12, each subject underwent hand-wrist radiography for the assessment of skeletal age. Of the original subject sample, complete longitudinal data were acquired for 104 boys across the 10 year study. Partial data, missing only 1 measurement year, were acquired for a further 32 subjects. While not every one of the 136 subjects had a full measurement, radiograph, and photograph complement, sufficient data for the purposes of this research were available for approximately 125 subjects. These data have been made available to the Kinanthropometry Research Associates at Simon Fraser University by Professors Bailey and Mirwald. A full description of the study appears elsewhere (Bailey, 1968).

3.1 Anthropometric Data

A total of 25 anthropometric variables were measured annually (see Table 3.1). The exceptions were femur and humerus breadth which were only measured from 1967 onward.

Table 3.1. Anthropometric Measures Taken in Saskatchewan Growth and Development Study

1. Heights: stature
   sitting height
2. Body Mass
3. Girths: shoulder
   chest (inspired and expired)
   gluteal
   upper arm
   forearm
   wrist
   thigh
   knee
   calf
   ankle
4. Chest depth
5. Breadths: biacromial
   chest
   bi-iliac
   elbow
   knee
6. Skinfolds: iliac
   abdominal
   tricep
   chest
   subscapular
   front thigh

The techniques used in the original study were redefined from original photographs using the most recent statement of conventions and nomenclature by Ross and Marfell Jones (1990) as follows:

1. Body mass or weight: the force obtained on a Toledo balance weighing machine calibrated in mass units when the subject was weighed in minimal clothing.

2. Stature: the distance from the vertex to the floor when the subject's head was oriented in the Frankfort plane, that is, when the orbitale-tragion line was perpendicular to the long axis of the body when the subject was standing erect.

3. Sitting Height: vertex to the top of a box set in front of a wall mounted stadiometer, the subject's feet were placed on an adjustable support so the tibia was flexed to a 90 degree angle at the knee.

4. Leg length: Stature (2) minus sitting height (3).

5. Shoulder girth: perimeter distance at the level of the greatest lateral protrusion of the deltoid, perpendicular to the long axis of the torso.

6. Chest girth: maximal perimeter distance at the level of the nipples,? perpendicular to the long axis of the torso, end tidal.

7. Gluteal girth: the perimeter distance at the greatest potuberance of the gluteal muscles, about the level of the pubis symphysium.

8. Arm girth: the arm is flexed to an angle of 90 degrees at the elbow, the girth is the perimeter distance at the level of the greatest circumference, perpendicular to the long axis of the relaxed pendant upper limb.

9. Forearm girth: maximal perimeter distance of the forearm, when the arm is held forward volar surface upward and the tape is perpendicular to the long axis of the radius.

10. Wrist girth: minimal perimeter distance of the wrist obtained proximal to the syloidius ulnare and radiale when the tape is perpendicular to the long axis of the radius.

11. Thigh girth: perimeter distance of the the thigh, within 2 cm of the gluteal fold with the tape perpendicular to the long axis of the femur.

12. Knee girth: perimeter distance of the knee, at the level of the patella and medial condyle of the femur, perpendicular to the long axis of the lower exremity when the subject is standing.

13. Calf girth: maximal perimeter distance of the calf when the subject is standing and the tape is perpendicular to the long axis of the tibia.

14. Ankle girth: minimal perimeter distance of the ankle obtained proximal to the sphyrion mediale, perpendicular to the long axis of the tibia.

15. Biacromial breadth: maximum diameter of the shoulders when sliding caliper branches are applied to the most lateral aspects of the acromial processes when the subject is standing erect with the arms hanging by the sides and palms against the thighs.

16. Transverse chest breadth: maximum diameter of the chest at approximately the level of the nipples, when the branches of a widespreading caliper are applied from the front pointing downwards across the ribs.

17. Biiliocristal Breadth: maximal diameter of the iliac crest when the branches of a widespeading caliper are applied from the front pointing upwards to encompass the most lateral aspects of the ilium.

19. Humerus breadth: biepicondylar diameter of the humerus, when the arm is flexed to an angle of 90 degrees at the shoulder and the forearm flexed at 90 degrees at the elbow with the calpers applied at a 45 degree angle upwards to bisect the angle at the elbow.

20. Femur breadth: bicondylar diameter when the subject is seated and the leg flexed to 90 degrees at the knee and the calipers are applied with the branches pointing downwards to bisect the angle at the knee.

Although not used as variables in the analyses, three skinfold thicknesses were used to correct arm, chest, and thigh skinfolds with measures at triceps, subscapular and front thigh sites as follows:

21. Triceps skinfold: The caliper thickness of the raised fold on the posterior surface of the arm at the mid acromion - olecranon distance.

22. Subscapular skinfold: The caliper thickness of a raised fold raised immediately inferior to the angle of the right scapula parallel to the long axis of the body.

23. Front thigh skinfold: The caliper thichness of a raised vertical fold at the estimated mid- inguinal-paroximal patella distance obtained on a seated subject.

To ensure accuracy of the longitudinal data, the study employed the same research technician throughout the ten years of data collection "who provided a consistent standardization and continuity for the calibration of equipment, training of testing personnel, and application of the anthropometric measurement technique" (Mirwald, 1980). Anthropometric landmarks and techniques were described in written material as well as in specific photographs and slides, and the same equipment was used throughout the study.

The procedure was to measure each site in triplicate, then use the median value of the three measures. These were then checked for error by comparing them with the original measurement, and the last of the series, and where warranted, remeasured.

Recorded data were cleaned by scanning for outliers (beyond 3 standard deviations) and subjectively evaluating whether there were physiological rationale for the measures or whether they were recording errors.

3.2 Radiographic Data

Between the ages of 11 and 12 years radiographs of the left hand and wrist were taken for the purposes of assessing skeletal maturity. All x-raying was done with parental consent and was carried out by the Department of Diagnostic Radiology, University Hospital, University of Saskatchewan, during the week of January 27 to 31, 1969.

Each radiograph included the bones of the fingers, wrists and approximately 1.5 inches of the radius and ulna of the left hand.

Three experienced raters independently estimated skeletal age (SA) using the Greulich Pyle Atlas method (Greulich and Pyle, 1959). No subject information other than identification code and sex were known to the raters, with the chronological age revealed only after the x-ray had been evaluated. The mean of the three ratings was used as the estimated SA for a given child at the age the exposure was taken. If any of the three raters disagreed by ±12 months with each other, that radiograph was re-analysed by all three raters, and a final SA was decided upon. Final intra-observer reliability was r=0.92 (Bailey, 1968).

3.3 Somatotype Photographs

Somatotype photographs of each subject were taken at the time of the physical and anthropometric measurements. The photographic equipment was fixed into position at the University of Saskatchewan, thereby ensuring standard set-up from year to year. The camera used was a Rolleicord Schneider, with a Kreuznach Xenar lens (1:35:75). Kodak Verichrome Pan ASA125 black and white film was used, with the F stop set between 11 and 16, and exposure time set at 1/15 sec. The camera was mounted on a 1 meter tripod with the lens center an additional 5 cm from the floor. The distance from the camera to the central plane of the subject (as determined by the center of rotation of the pedestal) was 157 inches. A 6x8 foot background grid composed of 3 inch squares stood 18 inches behind the center of rotation of the pedestal. The pedestal was 18 inches in diameter and 3 3/4 inches from its upper surface to the floor. Pedestal heelplates were fixed 10 cm behind the center of rotation, 4 cm apart, with two angled plates directing the feet 10° each from the camera-center of heelplate line.

The procedure for posing subjects was generally that of Dupertuis and Tanner (1950). Each subject was posed in the somatotype position and photographed from the anterior, rotated 90° counter-clockwise for a right lateral exposure, then rotated again for a posterior image. For the first four years of the study (1964-1967), subjects were posed with their hands in a modified 'anatomical' position, with palms open toward the camera, and arms outstretched at an angle of about 30-45° from the trunk. In all subsequent years the hand positioning was that of the more standard somatotype pose, palms toward the body and arms angled at about 10°.

55mm negatives of these photograph series were made available for the current study.

3.4 Discussion

The Saskatchewan Growth and Development Study provided one of the best pure longitudinal assemblies of anthropometric data on boys aged 7 to 16 available. In addition, the attendant physiological data offered oportunities for future analyses of the relationships among physique, maturity, and performance.

Chapter 4 PHOTOGRAMMETRIC ESTIMATION OF SEGMENTAL LENGTHS

4.1 Introduction

Limb segmental lengths (upper arm, forearm, hand, lower leg, and foot) were not measured in the Saskatchewan Study. However, as anthropometric variables which have been consistently shown to exhibit significant proportional changes throughout growth and development (Attalah, 1980; Krogman, 1970; Malina, 1978; Meredith, 1939; Shuttleworth, 1939, Simmons, 1944; Tanner, et al.,1976), these data were felt likely to be important for the construction of the proposed developmental age functions.

As described in Chapter 3, somatotype photographs were taken of each subject at each measurement occasion throughout the Saskatchewan study. These photographs availed the required limb segmental lengths through measurement of the photographic image, or photogrammetry.

4.2 Objectives of somatotype photogrammetry

The objectives underlying measurement of the somatotype photographs were as follows:

- to obtain measurement estimates of segmental lengths for the upper arm, lower arm, hand, lower leg (tibia), and foot to augment the Saskatchewan study anthropometric data for use in this and future research.

- to derive formulae for each segment which would predict anthropometric values from photogrammetric estimates. These anthropometric equivalents would then be tested along with the directly measured variables for usefulness as predictors of developmental status.

4.3 Principles of Photogrammetry

The practice of using photographs as permanent records of human physique was introduced to North America by Sheldon (1940) in establishing his system of somatotyping. As this was a technique of visual inspection rather than precise measurement, acquisition of detail in the images was perhaps not a necessity. However, Sheldon did establish photogrammetry as a viable anthropometric method, contrary to the doubts of many before him (Cameron, 1978; Gavan et al., 1952). In 1949, Tanner and Weiner demonstrated that photographs can serve as substitutes for the living subject in yielding reliable anthropometric measurements of small detail.

There are certain advantages to using photographs for the purpose of human anthropometry. The 'subject' is stationary, does not change his posture, nor do his tissues compress under the forces of measurement tools. The time taken to pose the subject and photograph him is considerably less than that required for comprehensive anthropometry, so that large groups can be photographed in field studies, and measured later on, in more relaxed circumstances. Of great importance is the permanence of photographic records. This permits retrospection for the purposes of obtaining additional measures and of checking doubtful values, which in classical anthropometry would require deletion or interpolation of data (Attalah, 1980). Gavan, et al.(1952) went so far as to suggest that "a large part of the error inherent in traditional systems of measurement and observation can be eliminated by the use of photogrammetry".

4.3.1 Potential errors

Among the most obvious shortcomings of photogrammetry is the inability to accurately estimate girths. While Tanner and Weiner (1949) attempted to measure arm and leg circumference from photographs, these produced the lowest correlations with *in vivo* values of their entire test.

Parallax

Another problem associated with the restriction to two dimensions in measuring photographs is that of parallax. This is a distortion of relative dimensions caused by differences in the distance from the lens to the object being photographed. There are two potential sources of parallax error in photogrammetry. The first is caused by the curvature of the lens, resulting in any plane of the subject being closer to the center of the lens than to the edges. The second, and likely greater parallax is due to the relative departures of the body's contours from its central plane, on which the lens is focused. For example, in the lateral view, the hand is closer to the camera lens than is the forearm, and in turn, the upper arm, and the trunk. This will obviously distort the relative measures of these segments. The further the distance from lens to subject, the less parallax distortion will occur. Tanner and Weiner (1949) estimated the error due to parallax at 10 meters from the lens to central plane of the subject to be 1% for every cm the measurement taken lies from that central plane.

Posing

Some characteristics which prove advantageous to photogrammetry can also create problems to the acquisition of reliable data. The immobility of the subject's permanent image requires that the pose be standardized for the purposes of those measures being sought. In one of the foundation papers on this technique, Tanner and Weiner (1949) found the correspondence between *in vivo* measurement and photogrammetry to be good.

The error in repeated measures of photogrammetry was reported to be predominately (67%) due to differences in posing. From this evidence, Dupertuis and Tanner (1950) recommended a less casual approach to posing of subjects than that established by Sheldon (1940). Reports on the reliability of photogrammetry of limb lengths have included no mention of posing problems confounding these measurements (Harrison and Marshall, 1970; Marshall and Harrison, 1971; Marshall and Ahmed, 1976; Marshall and Attalah, 1979). The original implication of Tanner and Weiner (1949), that breadths may be among the most sensitive measures to posing artefacts was reiterated by Healy and Tanner (1981) who had attempted to quantify a number of transverse and anteroposterior breadths from photographs for the purposes of modelling human shape.

Landmark selection

The advantage of incompressible, essentially homogeneous 'tissue', of photographs also precludes the identification of most boney landmarks requiring palpation *in vivo.* For this reason, the datum points commonly used for photogrammetry are different from those of traditional anthropometry and the segments thus measured are correspondingly different (Cameron, 1978; Marshall and Attalah, 1979; Harrison and Marshall, 1970). While Tanner and Weiner (1949) reported the associations between measures by these two techniques to be good, Cameron (1978) maintains that the correlations between measures of the two are too low for direct carry-over from photogrammetry to the living body.

Selection of photogrammetric landmarks is based on consistency of their identification on all subjects, and of visibility in standard photographs. Harrison and Marshall (1970) suggest as suitable markers, a skin crease at joint level; a change in direction on the photographic outline; or the center of a small, well-defined constant highlight.

Table 4.1 lists the datum points suggested for limb measurements using both anthropometric and photogrammetric techniques.

Table 4.1 Datum points for limb measurements using both anthropometric and photogrammetric techniques.
(from Attalah and Marshall, 1986)

Limb Segment	Anthropometric datum points	Photogrammetric datum points
Upper arm	inferior border of the acromial angle to lateral superior margin of head of radius	lower lateral end of clavicle to centre of skin crease at elbow
Forearm	lateral superior margin of head of radius to articular surface of distal end of radius	centre of skin crease at elbow to base of thenar eminence
Leg (calf)	from upper-most point on medial condyle of tibia to distal border of medial maleolus	intersection of skin crease at knee with shadow of biceps femoris tendon to the most prominent point of the lateral maleolus

4.3.2 Relationship of photogrammetry with direct anthropometry

Marshall and Attalah (1979) examined the relationships between limb lengths measured by both direct and photogrammetric anthropometry over a cross-sectional sample of 1768 girls and 995 boys aged 4 to 16 years. After dividing their sample into pre-pubescent (age 4 to 8.99 years) and pubescent (age 9 to 15.99 years) subsamples, they found both techniques to give essentially the same mean measures for upper arm and forearm lengths, in all subsamples. This is in spite of the declaration of Harrison and Marshall (1970), that the datum points of the upper limb are the most difficult to select, and error due to incorrect identification would be most likely in these measures. Leg measures differed to a significant extent and differentially in the two age groups. Although the authors did not explain the age changes, the former was accounted for in light of distance between the two landmarks at the leg datum points. The skin crease at the knee is reported as being slightly higher than the upper medial end of the tibia. The lateral and medial maleoli are also at different levels.

4.3.3 Reliability of photogrammetry

Reliability studies, preliminary to photogrammetric estimates of limb proportions, have confirmed the claims of Tanner and Weiner (1949) that this is a highly repeatable technique (Harrison and Marshall, 1970; Marshall and Ahmed, 1976). The former reported standard deviations of the differences between pairs of repeated measures, taken as percentages of the measurement mean to be (±) .49, 1.71, 1.28, .45, 2.07, and 1.50 for the total arm length, upper arm, forearm, total leg length, thigh, and lower leg respectively (Harrison and Marshall, 1970). The study of Marshall and Ahmed (1976) on arm lengths describes standard error of measurement from duplicate measures of 197 photographs, of 2.3mm for the upper arm, and 2.0mm for the forearm. These are similar to the acceptable measurement error for standard anthropometric measurement of limb lengths (Borms, et al., 1976). No published tests of reliability can be found for photogrammetric measure of foot and hand length.

4.4 Photogrammetric Derivation of Segmental Lengths

Standard somatotype photographs of the anterior, right lateral, and posterior plane, including a scaled background grid were available for most subjects at each occasion of his measurement in the Saskatchewan Study. Serial segmental length data were collected from these annual somatotype photographs by the following procedure.

4.4.1 Materials and methods

4.4.1.1. Saskatchewan Growth Study somatotype photographs

The procedures for taking the somatotype photographs have been described in Chapter 3. It is important to note that these photographs were not taken for the purpose of physical measurement at a later date. Consequently, conditions of lighting, background, and posing were neither consistent nor necessarily optimal for this procedure. For example, the change in posing created the potential for systematic error in both the measurement and subsequent predicted segmental lengths. This is addressed later in this discussion.

4.4.1.2 Equipment

Fifty-five milimeter negative transparencies of the three poses for each child were measured for segmental lengths. Transparencies were mounted in a metal frame, on an Omega Dichoric II photographic copy stand fitted with an f/4,0-80mm Rodenstock Rodagon lens. Images were projected on an even white surface to a magnification of approximately 4.75x, which was approximately 0.12x life size. In order to assure the same magnification at each photogrammetry session, the projection distance was adjusted so that a central square of background grid measured precisely 9.2 mm.

A 15 cm Mitutoyo Digimatic caliper, capable to .01mm was used for the measurements. This caliper was recalibrated at zero after each 3-image measurement set.

Measurement data were entered directly into a spreadsheet program (Excel™) on a Macintosh™ micro-computer set up adjacent to the copy stand.

4.4.1.3 Landmarks

As conventional anthropometric landmarks cannot be identified in photogrammetry, it was proposed to use those datum points outlined in Table 4.1 by Attalah and Marshall (1976). However, preliminary inspection of the photographs suggested that many would not show all these landmarks. A new set of photogrammetric datum points was developed (as shown in Table 4.2), and tested for repeatability. All measurements were taken on the right side of the subject.

Table 4.2 Datum points for photogrammetry of limb segment lengths.

Exposure	Segment	Photogrammetric Landmarks
anterior	upper arm	from the apex of the shoulder curvature to the mid-arm crease
	lower arm	mid-arm crease to base of the thenar eminence
	hand	base of the thenar eminence to tip of most extended digit
	calf/tibia	distal point of patellar fold, equivalent to the point of inflexion of the curve of the medial femoral epicondyle to the tip of the medial maleolus
right lateral	foot	mid point of heel (calcaneous) curvature to tip of longest toe
posterior	calf	center of knee crease, point where vertical ligament extension intersects knee crease

As previously mentioned, posing of the subjects changed somewhat over the 10 years of data collection. During the first 4 years (1964 to 1967), the hands were posed in the anatomical position, with the arms generally spread to an angle of about 30 to 45 degrees from the torso. In many cases this resulted in supination of the lower arm making the mid-arm crease difficult to detect, as well as causing the hands to abduct. Throughout the study, posing of the hand was imprecise such that many were either hyperextended or cupped inward (see below).

Shoulder landmark:

Being a soft tissue landmark, variations in arm position, and in adiposity and muscularity made the true shoulder curve rather variable in a few subjects.

Mid-arm crease:

This landmark became less evident as the subjects matured, though was replaced by the clear insertion point of the biceps bracchi, which is at the same position as the arm crease.

Base of the thenar eminence:

The landmark was clearly identifiable in most subjects regardless of age, pose or body composition.

Tip of most extended digit:

Many images showed hands which were curved inward at the palm, both with and without, bent fingers. Also, some hands were clearly held at angles outside the plane of the lower arm. Where the left hand appeared to be better than the right in its alignment, it was chosen as the measured hand. When neither hand was held correctly, an attempt was made to divide the (right) bent hand into two measurable segements, and record the sum of these.

Distal point of patellar fold: equivalent to the point of inflexion of the medial epichondyle curve (anterior calf). The former was a clear landmark in most subjects past the first few years. In the younger ages, the fold was not obvious, so the inflection of the medial epichondyl curve was the sole landmark.

Tip of the medial maleolus:

This landmark was clearly indentifiable except in the obese and those wearing socks.

Foot measures:

This was a clearly identifiable landmark except in cases where the heel was partially obscured by the heelplate of the pedestal. This rarely covered the point of the curve established as the landmark.

4.4.2 Pilot study testing reliablility of photogrammetric techniques

A pilot study of the photogrammetric procedure was felt necessary for a number of reasons:

1. The creation of new landmarks for some of the photogrammetric lengths required assurances that these generated repeatable measures.

2. The usefulness of photogrammetric stature as a scaling measure, and the most reliable of the two calf/tibia measures needed to be tested.

3. The very large number of photographic measurements (5 or 6 segments per boy-year for 124 boys over 10 years) warranted examination of measurement error in order to assess the validity of using single or duplicate measures, as opposed to the triplicate measurement protocol of conventional anthropometry.

4. An estimate of the degree of parallax distortion in the images was needed in order to establish if correction functions where necessary.

4.4.2.1 Procedure

In a randomly selected subsample of 20 subjects, each annual set of images was measured in random sequence, on three separate occasions, [20 boys x 3 photographs (7 lengths +3 grids) x 10 years x 3 repeated measures]. For each of the three images (anterior, right lateral, and posterior), a square of the background grid lying close to the majority of landmarks being measured in that exposure was measured and recorded for the purpose of assesing parallax error.

A. Reliability

Measurement reliability for each segment was estimated by the technical error of measurement (TEM) suggested by Johnston et al (1972), where:

$$\text{TEM}= \sqrt{\frac{\Sigma d^2}{2n}}$$

and, Σd is the sum of the difference between the measurements of any two sets.

This function is used in preference to correlation coefficients or the standard error of residuals because it evaluates true differences without assuming similarity of means and variances between the measurement sets. In this manner, systematic measurement error is identified as a technical error.

By calculating Σd for each combination of measurement sets (s1-s2, s1-s3, s2-s3), three TEM's were estimated for each variable. The measurement of relative error (the coefficient of variation or CV) for a variable is the mean of the three technical errors calculated as a percentage of the mean variable measurement.

B. Accuracy

The more frequently the measurement is repeated, the closer the mean of the measures approaches the 'true' dimension. The standard error of the estimate [$\sigma_1 \sqrt{(1-r^2)}$] calculates how close to the first measure, subseqent measures are likely to be, assuming $\sigma_1 = \sigma_2$ and $\mu_1 = \mu_2$. The standard error of measurement (σ_{meas}) described by Tanner and Weiner (1949) is used to determine how close to the true value (the mean of an infinite number of readings) one's further measurements are likely to be, where:

$$\sigma_1 = \sigma_2 \text{ and } \mu_1 = \mu_2$$

$$\sigma_{meas} = \sigma_1 \sqrt{(1-r)}$$

As with other standard error estimates, the interpretation of this is that 95% of subsequent measurements will fall within ± 2 σ of the 'true' value.

4.4.2.2 Results

A. Reliability Estimates

The technical error of measurement, expressed as percentages of the mean measure for each variable are shown in Table 4.3.

Table 4.3 The technical error of measurement (TEM) and the coefficient of variation (CV%) for three repeated photogrammetric estimates of segmental lengths (n=197).

measurement sets	upper arm	lower arm	hand	calf (ant.)	stature	foot	calf (post.)
1...2							
TEM(mm)	1.247	0.944	0.675	1.079	9.557	0.496	1.434
CV(%)	3.684	3.084	3.239	2.432	4.706	1.553	3.198
1..3							
TEM(mm)	1.221	0.934	0.916	0.960	9.898	0.561	1.354
CV(%)	3.608	3.050	4.399	2.155	4.873	1.755	3.019
2...3							
TEM(mm)	1.058	0.792	0.689	0.735	2.565	0.344	0.993
CV(%)	3.205	2.587	3.306	1.651	1.263	1.077	2.216
mean							
TEM(mm)	1.175	0.890	0.760	0.925	7.340	0.467	1.260
CV(%)	3.499	2.907	3.648	2.079	3.614	1.462	2.811

In comparing the mean TEM for each segment across the years of the study, analysis of variance (ANOVA) indicated no significant differences over chronological age (Table 4.4). It was concluded from this analysis that there was no apparent systematic influence of subject maturity or time-span of the growth study on technical error of any of the segmental lengths.

Table 4.4 ANOVA for TEM of each photogrammetric segment across time.

Segment	Source	df	F-test	P value
Upper arm	between subj.	17	1.453	0.1184
	within subj. (over time)	9	1.475	0.1618
Lower arm	between subj.	17	1.498	0.1011
	within subj.	9	0.779	0.636
Hand	between subj.	17	1.391	0.1467
	within subj.	9	0.942	0.4904
Calf	between subj.	17	0.574	0.9071
	within subj.	9	1.011	0.4335
Foot	between subj.	17	1.041	0.4176
	within subj.	9	1.686	0.0968

B. Accuracy

The standard errors of measurement for segmental lengths in the pilot sample of 197 randomly measured photograph sets are listed in Table 4.5.

Table 4.5 Standard error of measurement for photogrammetry of segmental lengths.
Where:
$r = (r_{1,2} + r_{1,3} + r_{2,3})/3$ and $s = (s(\text{set } 1) + s(\text{set } 2) + s(\text{set } 3))/3$ (N=197)

variable	std error meas (mm)	coeff of var (%)
upper arm	1.225	3.619
lower arm	0.920	3.004
hand	0.587	2.817
calf (ant.)	0.828	1.859
stature	5.643	2.778
foot	0.424	0.861
calf (post.)	1.816	4.054

3. Parallax

No systematic parallax error was measurable from these photographs in that, under the conditions of this measurement, differences in grid size nearer the edges (foot and hand measurements) in contrast to the center (upper arm) of the transparencies were not obvious. No adjustment for parallax was subsequently made to the reported measures.

4. Calf measurements

A two-tailed t test ($p < .0001$) established the anterior calf measure to be more reliable than that of the posterior calf. The former was then used for all subsequent calf photogrammetry.

4.4.2.3 Discussion

It is evident from the TEM and CV% (Table 4.4), that upper limb measures are in general less reliable than those of the lower limb. This supports the findings of Harrison and Marshall (1970). All the variables exceeded the 1% reliability tolerance established for anthropometric lengths by Borms, *et al* (1976). While this does not invalidate the use of these measures in subsequent predictions, the error of these predictions will likely incorporate a larger portion of photogrammetric error than anthropometric error.

While stature proved to be as reliable as some of the other measures, the strength of photogrammetric estimates to predict anthropometry was insufficient for the purposes of individual scaling ($R^2 = .981$; SER=2.617). As observed by Harrison and Marshall (1970), it was not possible to accurately assess the position of the crown of the head under the hair, nor to correct for variations in posture.

It is evident from Table 4.5 that photogrammetric estimates from single measurement for all variables except the foot would be highly inaccurate. As stature was measured only for the purposes of testing as a scaling device, and has been rejected on other grounds, this inaccuracy is of no relevance. Similarly, posterior calf has been rejected in favor of anterior calf, which is shown to be superior in both accuracy and reliability.

An earlier photogrammetric study by Harrison and Marshall (1970) described reliability in terms of CV where upper arm, lower arm, and calf errors were .49, 1.71, 1.5 percent respectively, considerably lower than those obtained in this study. This is not surprising, as these authors rejected photographs where datum points were unclear. As mentioned previously, Marshall and Ahmed (1976) obtained s_{meas} of 2.3mm and 2.0mm respectively for the upper and lower arm. As these were not described as CV, there was no opportunity to compare the magnitude of their errors with the current study.

It was concluded from this pilot work that upper arm, lower arm, hand, and anterior calf could not be accurately estimated form single measurements. Single photogrammetry of the foot was considered to be sufficiently accurate for use in subsequent predictive equations.

4.4.3 Photogrammetry of remaining Saskatchewan subjects

The same general procedures were followed for the remaining subsample as were outlined for the pilot group. The differences were that stature and anterior calf were no longer measured, and the remaining segments were measured only twice. The exception was foot length, which was measured only once for each of the remaining subjects. A single grid was measured on each transparency to ensure standard magnification.

The following table (Table 4.6) summarizes the measurement of the entire Saskatchewan photographic data.

Table 4.6 Summary of photogrammetric measurements on Saskatchewan data

data	subjects	lengths	repeated measures	
1. Pilot study:				
	20 (x 10 years)	anterior:		
	(n=197*)	- upper arm		
		- forearm		
		- hand		
		- calf	3	
		lateral:		
		- stature		
		- foot		
		posterior:		
		- calf		
Total pilot photogrammetric measurements:				4,137
2. Remainder:				
	104 (x 10 years)	anterior:		
	(n=1,006*)	- upper arm	2	
		- forearm		
		- hand		
		- calf		
		lateral:		
		- foot	1	
Total remainder photogrammetric measurements:				9,054
Total photogrammetric measurements:				13,191

*photographs for some boy-years were not available.

After collation of the repeated measures, the data were plotted to identify outliers and were cleaned as follows:

1. misplaced decimal points were moved
2. other obvious keystroke errors were corrected

The arithmetic means of the cleaned data were then recorded as the photogrammetric values to be used in further analyses.

4.5 Prediction of anthropometric lengths

While it was possible to use the photogrammetric lengths directly in the creation of developmental age prediction equations, the research objective was to establish a practical tool which relied solely on surface anthropometry. The photogrammetric lengths therefore required transformation to their anthropometric equivalents.

4.5.1 Method

Two approaches could have been used to accomplish this end. The more direct method would have been to geometrically scale-up each measure according to the known dimensions of the background grid and the distances from the camera lens to the subject and the background grid. The resulting lengths would be the 'life-size' equivalents of the photogrammetric lengths, but not necessarily the facsimile of true anthropometric lengths. The chosen method was to determine the relationship between lengths measured by direct anthropometry and by photogrammetry under the same conditions as the Saskatchewan study, and apply these relationships to the photogrammetric data.

4.5.1.1 Subjects

Fifty-three Caucasian boys between the ages of 6 and 17 were recruited from summer sports and mini-university programs run by Simon Fraser University. The study procedure was described to each boy before he was asked personally if he would participate. Those in agreement were given an informed consent letter to be signed by a parent or guardian. Where necessary, follow-up phone calls were made to clarify procedures or as reminders to return informed consent documents. Of 53 subjects approached, 45 (85%) returned informed consent and were used in the study. The distribution of ages in this sample are listed in Appendix A-1. All measurement and photographic procedures were cleared by the Simon Fraser University ethics committee, as part of general approval of the Kinanthropometry laboratory procedures.

4.5.1.2 Photographic procedure

Every attempt was made to photograph these subjects under identical conditions to the Saskatchewan study. Those parameters considered essential to duplicate are listed in Table 4.7, which compares the photogrammetric set-up of the Saskatchewan study with that of the SFU study.

Table 4.7 Photographic procedures for Saskatchewan Growth and Development Study and SFU sample

Procedure	Saskatchewan study	SFU sample
Camera	Rolliecord	same camera
Film	ASA 125	ASA 125
F stop	11-16	11-16
Exposure time	1/15 sec	1/15 sec
Distances		
- floor to camera	1 meter	1 meter
- camera to subject	157 inches	157 inches
- subject to grid	18 inches	18 inches
Backdrop		
- grid	3 inches	3 inches
Pedestal		
- center to heel plate	10 cm	10cm
- angle of foot plates	10°	10°
Lighting	6 front 660 watt hooded photoflood lamps	overhead fluorescent

Subjects were posed in the standard somatotype alignment for which pictures were taken of the anterior and right lateral view. To help evaluate if systematic error was inherent with the change of somatotype pose in the early years of the Saskatchewan study (cf Chapt.3), a subsample (n=30), predominantly composed of the younger subjects, was photographed in both the standard position and the anatomical position of the anterior view.

4 .5.1.3 Anthropometric procedure and error measurement

Duplicate measures of direct lengths were taken for the right side upper arm, forearm, hand, calf, and foot of each of the SFU subjects. Where the second measure was ± 2% of the first, a third measure was taken.

Landmarks were those described by Martin et al(1988) as outlined in Table 4.8.

Table 4.8 Anthropometric landmarks for direct lengths

Length	Landmarks
upper arm	- superolateral aspect of the acromion to the posterior surface of the olecranon process of the ulna
lower arm	- the most posterior point overlying the olecranon to the most distal palpable point of the styloid process of the radius
hand	- styloid process of the radius to the tip of the middle finger
lower leg	- proximal medial tibial border to tip of medial maleolus
foot	- pternion to acripodion

As direct length measurement using a modified tape (Carr, 1990) is a relatively new procedure, an estimate of technical error was carried out. Table 4.9 lists the technical error of measurement (cm) and the coefficient of variation (%) for each of the direct lengths across the 45 subjects. When compared with the technical error of projected length measures which have been shown to range from .39 cm to .68 cm (Chumlea, 1983; cited in Martin et al,1988), it can be concluded that this is a highly reliable technique for each length.

Table 4.9 Technical error of measurement (TEM) and coefficient of variation for direct lengths.

Length	TEM (cm)	Coeff var (%)
upparm	0.152	0.544
lowarm	0.150	0.685
hand	0.158	0.940
calf	0.105	0.321
foot	0.100	0.424

4.5.1.4 Photogrammetry procedure and error measurement

The identical procedure was used to measure the photographs of the SFU sample as was used in measuring the Saskatchewan photographs. The measurement error of the SFU sample is described in Table 4.10

Table 4.10 Technical error of measurement (TEM) and coefficient of variation (CV) for standard (n=42) and anatomical (n=30) poses for photogrammtery of SFU sample.

SEGMENT	TEM (mm)	Coeff var (%)
upper arm	0.683	1.901
upper arm (anat)	0.809	3.290
lower arm	0.423	1.369
lower arm (anat)	0.787	3.604
hand	0.421	1.981
hand (anat)	0.303	2.021
calf	0.608	1.303
foot	0.194	0.597

These data show that upper limb measurement of anatomically posed subjects would appear to be less reliable than those measures on subjects in the standard somatotype pose. However, analysis of variance (ANOVA) for combined upper limb measures comparing standard with anatomical pose showed no significant difference (F=2.79, p=.2068). This supports the earlier finding that there were no age trends (which for the upper limb segments would also be posing trends) in the error of the Saskatchewan photogrammetry.

The photogrammetric (measurement) errors for the SFU sample were considerably less than those for the Saskatchewan sample. This could have been due to a number of factors. The SFU photographs were measured after the entire Saskatchewan sample had been completed so there was likely a learning effect which improved the reliability of this sample. Being relatively small, the SFU sample did not show any ambiguous data as were found in the larger sample. As such, no outliers were likely to have been unintentionally included. Single outliers show up as large differences in repeated measures, which in turn exaggerate the technical error and coefficient of variation. While the Saskatchewan data were cleaned of obvious outliers, it was difficult to justify altering or deleting data where repeated measures were within 4 or 5 mm of each other. Other differences were in photographic lighting, distortion caused by the age of the Saskatchewan transparencies, and perhaps the quality of film used.

4.5.2 Equations for the prediction of segmental lengths from photogrammetry.

Linear regression equations for each photogrammeteric variable predicting its anthropometric equivalent were produced using the StatView™ micro-computer statistical package.

The change of photographic pose described previously necessitated a number of predictive formulae covering each possible route to anthropometric estimates as shown in Table 4.11. The regression equations are outlined in Table 4.12.

Table 4.11 Prediction routes for derivation of anthropometric lengths from photogrammetric data.

Variable	Years	Prediction Route(Y= ax+b)
Upper limb: - upper arm - lower arm - hand	64-67	1. Anatomical(x) predicting anthropometric length (Y).
Upper limb: - upper arm - lower arm - hand	64-67	2. Anatomical(x_1) predicting standard pose (Y_1, x_2), then standard pose (x_2) predicting anthropometric length (Y_2).
Upper limb: - upper arm - lower arm - hand	68-73	Standard pose(x) predicting anthropometric length (Y).
Lower limb: - calf - foot	64-73	Either pose (x : equivalent in these variables) predicting anthropometric length (Y).

Table 4.12 Regression equations for the prediction of anthropometric lengths from photogrammetry.

Segment	Years*	Indep. var.(x)	Dep. var.(Y)	Intercept	slope(b)	R2	DF
Upper arm	64-67	photogramm.(anat)	1. anthropom.	0.863	0.772	0.933	28
	64-67	photogramm.(anat.)	photogramm.(stand.)	-2.949	1.101	0.942	27
	64-73	photogramm.(stand.)	2. anthropom.	4.159	0.672	0.925	44
Lower arm	64-67	photogramm.(anat)	3. anthropom.	2.148	0.644	0.907	28
	64-67	photogramm.(anat.)	photogramm.(stand.)	1.122	0.953	0.966	27
	64-73	photogramm.(stand.)	4. anthropom.	1.973	0.038	0.874	44
Hand	64-67	photogramm.(anat)	5. anthropom.	1.681	0.717	0.875	28
	64-67	photogramm.(anat.)	photogramm.(stand.)	3.181	0.861	0.866	27
	64-73	photogramm.(stand.)	6. anthropom.	1.332	0.723	0.882	44
Lower leg	64-73	photogramm.	7. anthropom.	2.44	0.679	0.959	43
Foot	64-73	photogramm.	8. anthropom.	1.901	0.685	0.982	42

* measurement years of Saskatchewan data in which equations could be used.

4.5.2.2 Evaluation of equations

From the coefficients of determination for each regression in Table 3.13, it can be seen that, for the prediction of anthropometric lengths, foot ($R^2 = 0.982$) and lower leg ($R^2 = 0.959$) are superior to the upper limb equations.

Of the upper limb segments, upper arm was the strongest ($R^2 = 0.933$ for anatomical equation; $R^2 = 0.925$ for the standard pose prediction). Hand length was not as well predicted as the other lengths, though lower arm predicted by the standard pose equation is slightly worse.

For the upper limb lengths, the anatomical pose would appear to be slightly superior to the standard pose for the prediction of anthropometric equivalents in all cases, except the hand.

The choice of the most appropriate regression route for the upper limb segments reached beyond their relative predictive powers. It was also important to determine how well the lengths predicted by each route fit the estimated growth curve, and whether there were any significant differences in their means and variances.

The appropriateness of each photogrammetric route to anthropometric equivalents for the upper limb segments was also judged by appending the derived curves to those formed by the variables from years 1968-onwards, for the entire Saskatchewan data set (n=124). These plots are included in Appendix A-2. It can be seen that there are very few differences in the shape or slopes of any of the pairs of curves. The pairs also appear to merge equally well with the rest of the data.

Table 4.13 outlines a series of paired two-tailed T-tests comparing the means of the two regression routes. It is evident that there are no significant differences in the two regression routes, for any of the upper limb segments.

Table 4.13 Paired two-tailed t-test for anthropometric upper limb lengths predicited from photogrammetry by two regression routes*

Variable	mean	std dev	df	T-value	p
Upper arm					
route 1	28.006	3.662	1203	26.62	.000
route 2	27.871	3.812			
Lower arm					
route 1	21.870	2.584	1203	-19.2	.000
route 2	21.894	2.575			
Hand					
route 1	16.827	2.012	203	20.98	.000
route 2	16.742	2.116			

---

*Refer to Table 4.11 for description of the routes.

4.5.3 Conclusions regarding derivation of anthropometric equivalents from photogrammetry

4.5.3.1 Choice of predictive equations

Although only marginally, the direct prediction of anthropometric upper and lower limb lengths from anatomically-posed photogrammetric measures was concluded to be superior to prediction of standard photogrammetric lengths, and in turn, anthropometric equivalents. For hand length, the standard formula appeared best. Therefore, formulae 1,3, 6,7, and 8 from Table 4.12 were used to derive these segmental lengths for the Saskatchewan sample.

4.5.3.2 Error

Error in these predicted segmental lengths comes from a number of sources (see Table 4.14). In the identification of anthropometric variables to be used in developmental age predictive formulae, consideration had to be given to the amount of error embedded in these derived lengths, and to the seriousness of the errors in the context of formulae based on group characteristics. Given the relative measurement error and lack of predictive strength of the hand measurement, it was felt at this stage, not to be a sufficiently valid measure to include in predictive functions. It was, however, moved through the remaining analyses together with all other variables, in order to continue to assess its performance relative to the other measures.

Table 4.14 Error sources in estimating anthropometric lengths from photogrammetry.

Photogrammetric error
    1. posing (photography set-up)
    2. parallax
    3. landmark identification
    4. measurement (observer bias, reading errors, caliper errors)
    5. interaction (of above errors)

Anthropometric error
    1. landmark identification
    2. representativeness of subjects
    3. measurement
    4. interaction

Predictive error
    1. lack of, or inconsistent relationship between photogrammetric and anthropometric lengths

Chapter 5 DATA TRANSFORMATIONS

5.1 Proportionality Scaling

One of the difficulties in characterising the shape of an object or organism is the artefact imposed by size. Shape can be defined as the allometric relationships of the component parts, whereas size is the absolute dimensions of these parts relative to those of an external reference (Healy and Tanner, 1981).

It was felt that size might confound the estimation of shape characteristics of developmental progress; for example, that a tall child may artificially appear mature. As a means of investigating and ultimately avoiding this problem, where noted, analyses were done on the regular unscaled data, as well as on the data transformed by a procedure known as proportionality deviation analysis (Ross and Wilson, 1974). This method will size-dissociate anthropometric data by geometrically scaling it to stature, then expressing it as standard scores of a metaphorical or 'phantom' model. The technique has been successfully used to describe longitudinal anthropometric proportionality changes in infants (Faulhaber, 1978) and growing children (Ross and Wilson, 1974).

The phantom specifications relevant to the present research are shown in Table 5.1 The calculation of proportionality scores or phantom z-values is described in Table 5.2.

Table 5.1 'Phantom' reference values

Variable	P	s
Stature	170.18	6.29
Sitting height	89.92	4.50
Lengths		
Leg	81.06	4.05
Upper arm	32.53	1.77
Forearm	24.57	1.37
Hand	18.85	0.85
Calf	36.81	2.10
Foot	25.50	1.16
Girths		
Shoulder	104.86	6.23
Gluteal	94.67	5.58
Forearm	25.13	1.41
Wrist	16.35	0.72
Knee	36.04	2.17
Calf	35.25	2.30
Ankle	21.71	1.33
Corrected girths		
Arm: (mid acromiale-radiale g.) * (3.14-(triceps sf/10))	22.05	1.91
Chest: (mesosternale g)* (3.14-(subscapular sf/10))	82.46	4.86
Thigh: (thigh g.)*(3.14-(fr.thigh sf/10))	47.34	3.59
Breadths and Depths		
Biacromial	38.04	1.92
Transverse.chest	27.92	1.74
Biiliocristal	28.84	1.75
Chest depth (AP,mesosternale)	17.50	1.38
Biepicondylar humerus	6.48	0.35
Biepicondylar femur	9.52	0.48

P is the phantom defined value for a given variable
s is the phantom defined standard deviation for that variable

Table 5.2 Calculation of Proportionality Z-values

$$Z = ((v((170.18/h)^{d}))-P)/s$$

where:

Z	is the proportionality or z-value
v	is the size of any measured value
170.18	is the 'phantom' stature constant
h	is the subject's stature at time t
d	is a dimensional exponent
P	is the 'phantom' value for the measured variable v
s	is the 'phantom' standard deviation for the measured variable v

5.2 Data Interpolation and Curve Fitting

For a number of the analytical procedures in this work, it was necessary that the anthropometric data be representative of the subjects at a coordinated point of development (such as age at PHV), of measurement (such as age at which hand-wrist x-ray was obtained), or of time (such as annual intervals).

Two curve fitting procedures were considered for these purposes, the Preece-Baines Model 1 (Preece and Baines, 1978), and the method of Akima (1970).

The Preece Baines (PB) algorithm is among a series of logistic models which are generally regarded as the best fitting parametric functions of serial growth data in general use (Tanner, 1981a; Gasser, et al., 1984). While not strictly designed for the purpose of interpolation, the PB function fits a smooth curve through longitudinal data, from which interpolated estimates can be derived. Having been constructed to fit serial stature data, it was uncertain as to how well the PB model would handle the growth curves of other anthropometric variables.

The Akima function, on the other hand, was designed to interpolate as well as to carry-out smooth curve fitting. It does not assume any functional form of the curve, but rather bases its estimates on a relatively small number of datum points, without taking into account the entire set. The piecewise function assumes that the slope of a point in question is determined locally by the coordinates of the two points on either side of it. A third degree polynomial representing the curve between any two points is calculated using the coordinates and slopes of those points. An anticipated weakness of this procedure would be the failure to capture rapid changes in growth velocity at take-off and toward maturation. The function also necessitates estimates of datum points at each end of the curve based on the slope of the curve immediately adjacent to the end points. This might generate false estimates where end points are at stages of growth such as those mentioned above. Finally, a function based on local procedures might be highly sensitive to measurement error.

5.2.1 Method

Subsets of 5 each, early, middle, and late maturing subjects (refer to Chapter 6 for the derivation of maturity status), were selected for comparison of the two curve-fitting functions. All 24 variables were fitted by both functions for each of the 15 subjects and interpolated to annual intervals before and following age at peak height velocity.

With the maximum acceptable residual mean square of the fit set at 0.1, the PB function was unable to fit the data for certain variables in some subjects. Specifically leg length, chest girth, wrist girth, transverse chest, and humerus and femur breadth could not be fit on three occasions each, showing no particular bias toward maturation type. As the Akima function does not presume a singular curve shape, there was no question of failure to fit a curve.

5.2.2 Results

A sample of the new estimates were plotted along with the raw data to evaluate the relative faithfulness of each function to the original measures. (Figures 5.1 through 5.3). These few were chosen as examples of how the two procedures handled stature as well as variables dissimilar to stature, and variables for subjects at the maturational extremes (based on age at PHV).

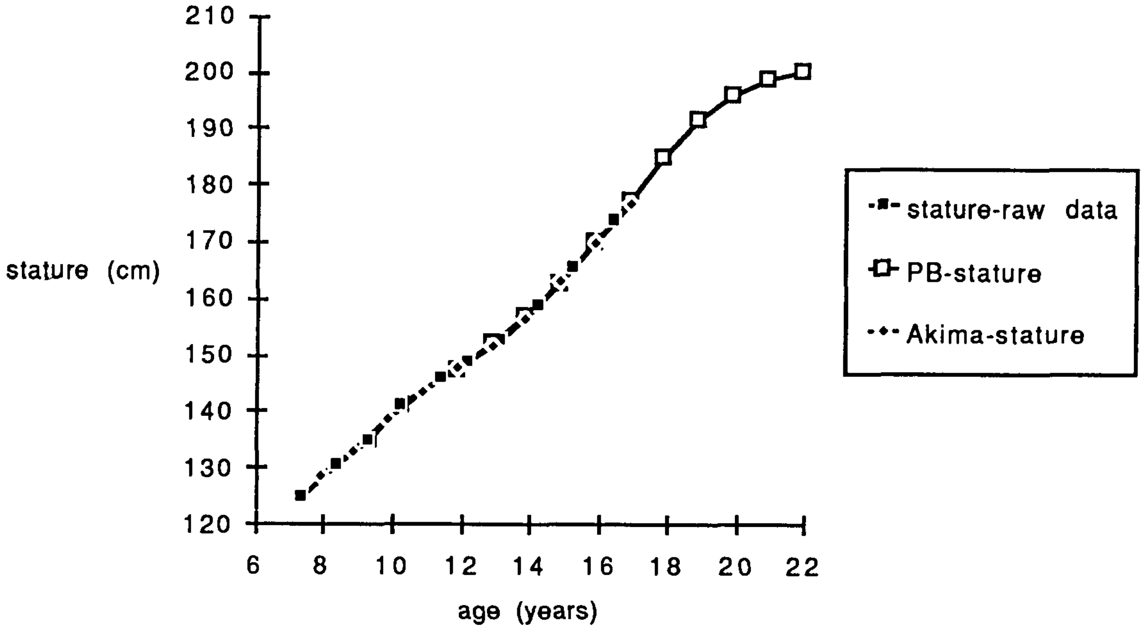


Figure 5.1 Comparison of PB and Akima curve-fitting for stature in a late maturing subject

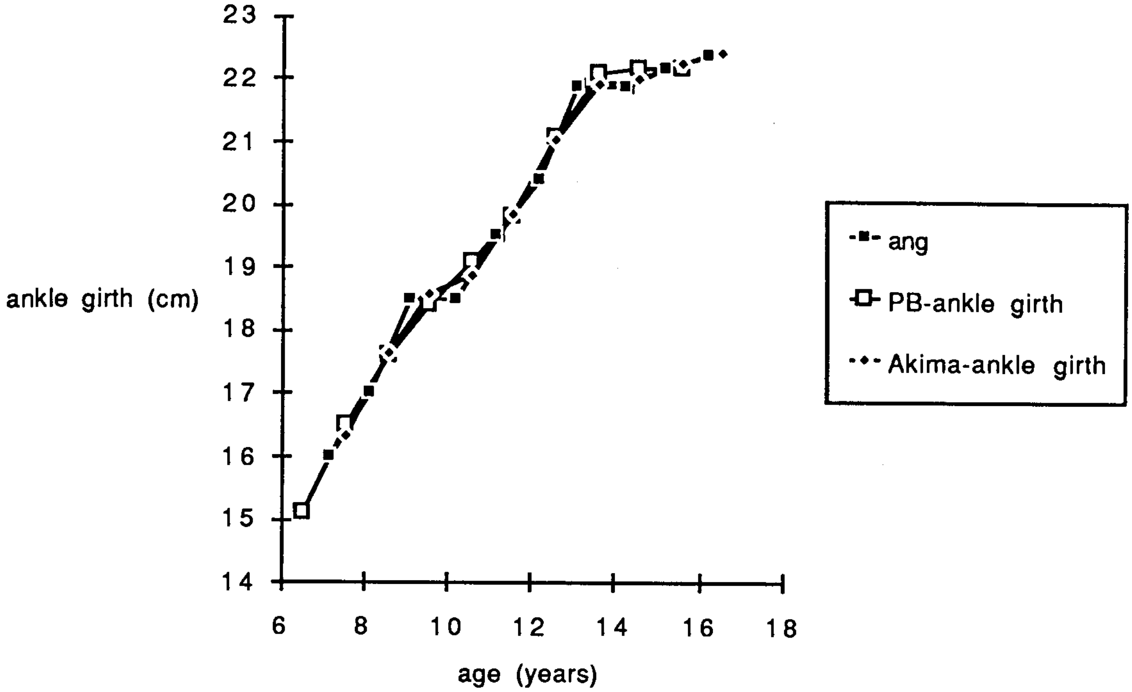


Figure 5.2 Comparison of PB and Akima curve-fitting for ankle girth in an early maturing subject

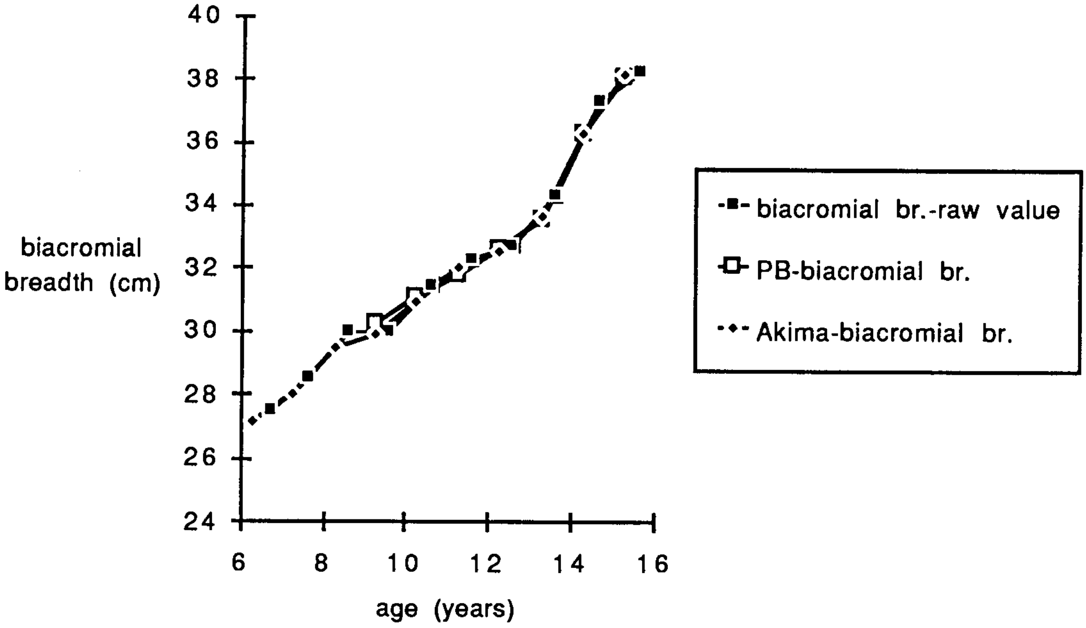


Figure 5.3 Comparison of PB and Akima curve-fitting for biacromial breadth in an average maturing subject.

5.2.3 Discussion

Figures 5.1 and 5.3 outline how well both curve-fitting functions can interpolate and smooth when the data follow the patterns characteristic of stature velocity. Figures 5.2 and 5.3 also show how the PB function might be accused of over-smoothing. The burst of growth around age 8, with almost zero velocity in the following year is characteristic of the mid-growth spurt (Tanner and Cameron, 1980). The Akima function partially followed this pattern, whereas the PB algorithm ignored it. On the other hand, these deviations of the standard curve could equally be measurement errors, in which case it was the Akima function which produced the misestimate.

It was concluded from this exercise that while PB function may do a superior job at data smoothing for some variables, it is inappropriate and frequently impossible, to force the shape of the stature growth curve onto all measures (Roche, 1989). The PB function also tended to extrapolate the anthropometric data for apparent late maturers to values of questionnable dimension. While the Akima function failed in some cases to truly smooth the data, it appeared to be adequately true to the original nature of the growth curve of each variable as to not miss important velocity fluctuations. Unless otherwise indicated, all required data smoothing was done using the Akima function.

5.3 Missing Data

Full data sets were not available for every child used in this study. Where data were being smoothed, it was possible to also estimate missing measurements if they were not situated at either end of the data set. Otherwise missing data were treated as such, and no attempt was made to derive their estimates.

5.4 Variables selected for developmental functions

Of the 25 anthropometric variables available from the the original Saskatchewan data assembly, a subset of 19 was used for all analytical procedures. Three of these were skinfold-corrected girths derived from the girth as originally measured, corrected for overlying adipose tissue, estimated from the appropriate skinfold. Along with the five photogrammetrically-derived segmental lengths, the complete variable listing is found in Table 5.3. This list also indicates the abbreviations used in the remainder of this work.

It was decided at the outset that measurements of adiposity would not be included in the analyses other than to correct specific girths for overlying subcutaneous adipose tissue. While a number of investigators have reported associations between amount and distribution of adipose tissue with maturity (Garn, 1972; Beunen, et al,1982; Deutsch, Mueller, and Malina, 1985; Katz, et al,1985), it is the nature of adiposity to be highly influenced by genetics and lifestyle, and as such it was deemed as a likely confounder in maturity modeling.

Table 5.3 Anthropometric variables used in analytical procedures

Variable	Source	Abbreviation
Stature	SGDS	STAT
Sitting height	SGDS	SITHT
Lengths		
Leg	SGDS	LEG
Upper arm	Photo	UA
Forearm	Photo	FA
Hand	Photo	HA
Calf	Photo	CA
Foot	Photo	FOOT
Girths		
Shoulder	SGDS	SHG
Gluteal	SGDS	GLG
Forearm	SGDS	FAG
Wrist	SGDS	WRG
Knee	SGDS	KNG
Calf	SGDS	CAG
Ankle	SGDS	ANG
Corrected girths		
Arm: (mid acromiale-radiale g.) * (3.14-(triceps sf/10))	derived/SGDS	CAGR
Chest: (mesosternale g)* (3.14-(subscapular sf/10))	derived/SGDS	CCHG
Thigh: (thigh g.)* (3.14-(fr.thigh sf/10))	derived/SGDS	CTHG
Breadths and Depths		
Biacromial	SGDS	BIAC
Transverse.chest	SGDS	TRCH
Biiliocristal	SGDS	BIIL
Chest depth (AP,mesosternale)	SGDS	APCH
Biepicondylar humerus	SGDS	HUM
Biepicondylar femur	SGDS	FEM

SGDS: Saskatchewan Growth and Development Study
Photo: photogrammetrically-derived
derived/SGDS: measurements corrected for overlying adipose tissue (both taken from SGDS)

Similarly, body mass was not included in the variable subset. Besides being reflective of adiposity, weight for a given height would likely capture all the variance of girths and breadths. These measures would appear redundant in mathematical equations which included the highly correlated variable, weight. Resulting models would give little information on the nature of physique at different stages of maturity, other than the relationship of weight to stature.

5.5 Chronological Age

Throughout this document chronological age has been used in specific analyses on a cross-sectional basis. The following specifications describe the decimal age ranges which fall into each chronological age.

Age	Decimal age range
7	6.0 to 7.499
8	7.5 to 8.499
9	8.5 to 9.499
10	9.5 to 10.499
11	10.5 to 11.499
12	11.5 to 12.499
13	12.5 to 13.499
14	13.5 to 14.499
15	14.5 to 15.499
16	15.5 to 17.0

Chapter 6 DEVELOPMENTAL MARKERS AND MATURITY ADJUSTMENT

6.1 Developmental Markers

6.1.1 Age at peak height velocity

The introductory chapter outlined a number of criteria by which developmental status can be estimated. Where longitudinal data are available, retrospective identification of the age at which maximal growth in height or peak height velocity (PHV) occurred has proven to be one of the more stable means of determining relative maturational status (Marshall, 1966). It is an identifiable parameter for most individuals, reflecting neither chronological age, size; nor does it occur at a fixed percentage of adult size (Zacharias and Rand, 1983). PHV occurs on average about 2 years following the onset of puberty in males (Marshall, 1966).

As a pure longitudinal study, it was proposed that the age at PHV could be identified for most subjects in the Saskatchewan database.

6.1.1.1 The Preece-Baines growth model

Of the 200 or so published mathematical formulae which propose to model some aspects of growth, about 6 are widely used for the study of human growth and development (Bogin, 1980). The principle aim of these models is to condense lengthy and potentially noisy growth data to a few parameters which will sufficiently describe the important trends of an individual's growth pattern. These functions will both smooth the data as well as summarize it. Once reduced to a few parameters, serial growth data can be more readily analysed for associations with biological markers of maturity. Such models are especially useful where serial growth data are collected at irregular intervals, and where data sets for some individuals are incomplete (Preece and Baines, 1978).

As described in Chapter 5, the Preece-Baines series of non-linear curves (Preece and Baines, 1978) are generally regarded as the best fitting parametric models of serial growth data in general use (Tanner, 1981a; Gasser, et al., 1984).

In comparing graphical curve generation with the Preece-Baines model 1 (PB1), Brown and Crisp (1987) reported both curves generated the same age at PHV while the PB1 generated a lower velocity at this point. Hauspie, et al.(1980) similarly compared PB1 with graphic smoothing of serial stature data reporting some differences in parameter means but insignificant differences in age at PHV. Therefore, for the purposes of identification of age at PHV, the PB1 function was considered ideal.

The PB1 function program was written for the purposes of analysis of the Saskatchewan data, under the direction of Drs. Mirwald and Bailey at the University of Saskatschewan. Programmed in Turbo Pascal, the PB1 curve can be fitted using the Marquardt algorithm for least squares estimation of nonlinear parameters (Marquardt, 1963). Among other functions, the program can be customized to alter the number of curve-fitting iterations, the step size of each iteration, and the acceptable redidual mean squares. The output includes identification of age at PHV in decimal years as well as other growth parameters derived by the PB1 function.

6.1.1.2 Fitting Saskatchewan growth data to PB1

Ten year stature data for 125 subjects were individually entered into the PB1 program. The function was unable to fit these data for only 2 subjects and it was evident from a later graphical display, that these two apparently grew linearly, with no evidence of velocity fluctuation. Individual PHV age rankings are listed in Appendix B. The descriptive statistics for age at PHV for the remaining 123 subjects are listed in Table 6.1 below.

For twelve of the subjects, the PB1 function estimated a PHVage beyond the final measurement age of that individual. Nine of the twelve were assessed as having growth parameters estimated by the PB function which were outside the range of normal anthropometric expectation. These subjects were noted as potential outliers in all subsequent analyses and are identified in Appendix B-2.

Table 6.1 Descriptives for age at peak height velocity

Statistic	Age (n=123)	Age (n=114)
Mean	14.359	14.154
Standard Deviation	1.367	1.094
Maximum	18.43	16.86
Minimum	11.56	11.56

6.1.2 Skeletal Age

Skeletal age (SA) provided a second, though perhaps more limited, marker of developmental status of the individuals in this sample. While SA is a well established and valid estimate of skeletal progress toward maturation (*cf* Chapter 4), it was assessed at only a singular point in the study, at about the age of 11 years for each subject.

Radiographs of the left hand-wrist region were taken between the ages of 11 and 12 years for most subjects, and rated for skeletal age using the Greulich Pyle method. These procedures are described in Chapt. 3.

6.2. Identifying Early and Late Maturing Subjects.

6.2.1 Identification of early and late maturing subjects using PHVage

Tanner and Davies (1985) have published clinical growth standards which define early and late maturers as those falling outside two standard deviations of the mean. This criteria would reduce the early and late subsamples to only one or two children, which might heavily bias subsequent analyses. Quite arbitrarily, those subjects having PHVages greater than 1 standard deviation above the mean were considered to be 'late maturers' and those falling below 1 standard deviation beneath the mean, to be 'early maturers'. Appendix B-1 lists the early and late maturing subjects according to the PHVage criterion.

6.2.2 Identification of early and late maturing subjects using skeletal age

Developmental status using skeletal age ratings is commonly expressed as the Maturity Index (MI) where:

MI= skeletal age (months)/ chronological age at x-ray (months)

The mean, standard deviation, maximum, and minimum MI and SA for the Saskatchewan data are listed in Table 6.2.

Table 6.2 Descriptives for maturity index (MI) and skeletal age (SA) (n=121)

	MI	SA(months)	SA(years)
mean	0.967	134.910	11.243
std dev	0.110	16.074	1.340
max	1.180	163.00	13.583
min	0.660	95.00	7.917

Again, early and late maturers were defined as those falling outside ± 1 sd of the mean MI. Appendix B-2 lists the early and late maturing subjects at age 11 as defined by the MI. It should be noted that these are only estimates within a single age-frame and do not necessarily indicate that a child with a low MI at age 11 is a 'late maturer' throughout his development.

6.2.3 The relationship between PHVage and skeletal age

A comparison of the descriptive data for PHVage in Table 6.1 with that for SA in Table 6.2, shows that in this sample the variance for PHVage (± 1.367 years) is similar to that for SA at age 11 (± 1.34 years).

However, in comparing the subjects on the two maturity listings in Tables B-1 and B-2 it would appear that PHVage and skeletal age rating circa chronological age 11 are only vaguely estimating the same 'maturity factor'. There are 10 subjects (45% of the PHVage cohort), who appear to be early maturers by both criteria. Although only 4 late maturers (24% of the PHVage cohort), are common to both groups, when the outliers are removed and the criterion adjusted, a total of 5 of the remaining 12 subjects (42%) are considered late maturers by both PHvage and MI. A listing of all subjects maturity-ranked according to both the PHVage and MI criteria can be found in Appendix B-3.

By regressing MI on PHVage for the 110 subjects for whom both parameters were available, it is again evident that only a weak association exists between the two maturity indices (Figure 6.1). PHVage explains only 18% of the variance in (r^2 = 0.176) of skeletal age at around chronological age 11 (expressed as a maturity index).

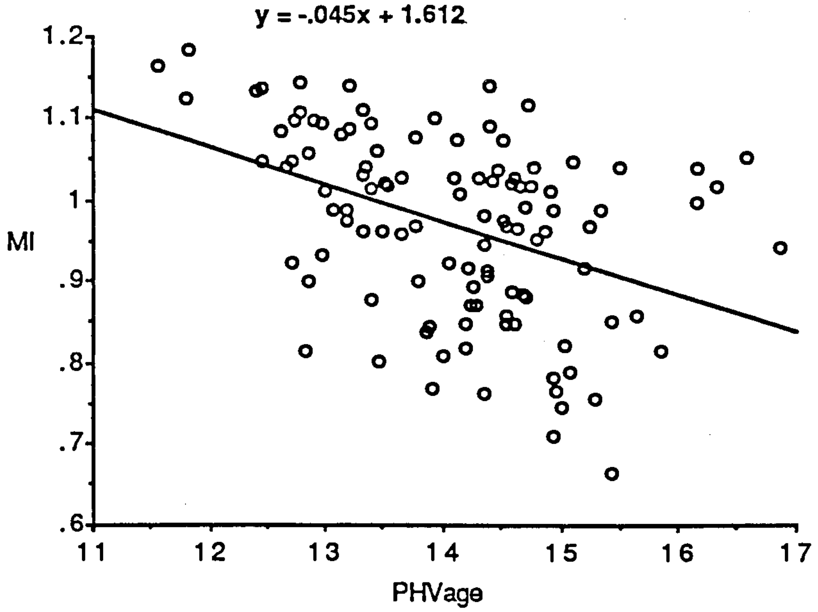


Figure 6.1 Regression of Maturity Index (MI) on PHVage around age 11 years.(n=110)

6.2.4 Discussion

As outlined in Table 6.3, the mean age of PHV for the Saskatchewan sample appears to reflect those reported in the literature. Although, perhaps at the upper limit, the association of PHVage with skeletal maturity is within the range described by other samples (*cf* Table 6.4).

Table 6.3 Mean age of PHV from a sample of longitudinal studies of growth in boys

Study	n	mean PHVage	reference
Wroclaw	177	13.9	Bielicki,Koniarek, and Malina,1984
Leeds	34	13.74	Buckler,1984
-	228	14.06	Marshall and Tanner, 1970
Harpenden	55	13.9	Bielicki,Koniarek, and Malina,1984
-	86	13.77	Nicolson and Hanley, 1953

Table 6.4 Association of skeletal age and age at PHV.

Reference	n	skeletal age	r
Bielicki,Koniarek, and Malina,1984	177	11	0.32
Nicolson and Hanley, 1953	86	11.25	0.105
Bielicki, 1976	121	11(girls)	0.05
Bielicki, 1976	121	12(girls)	0.12

6.3 Maturity Adjustment on PHVage

Among individual children, the process of maturation is highly variable in its timing, intensity and duration. A common practice in longitudinal studies of child growth is to maturity-adjust the data such that it is aligned on some common biological parameter of maturation rather than the chronological age scale. Where available, the parameter most frequently used is the age at peak height velocity (Malina,1978). Figure 6.2 shows the maturity adjustment of stature along PHVage, where the new time scale becomes chronological years before and following PHVage.

It was proposed that aligning the Saskatchewan growth data on PHVage would, in essence, create a series of maturity-adjusted physique prototypes for annual intervals along the new age scale. These would be more realistic accounts of shape characteristics of common maturity than could be derived from measures at chronological ages.

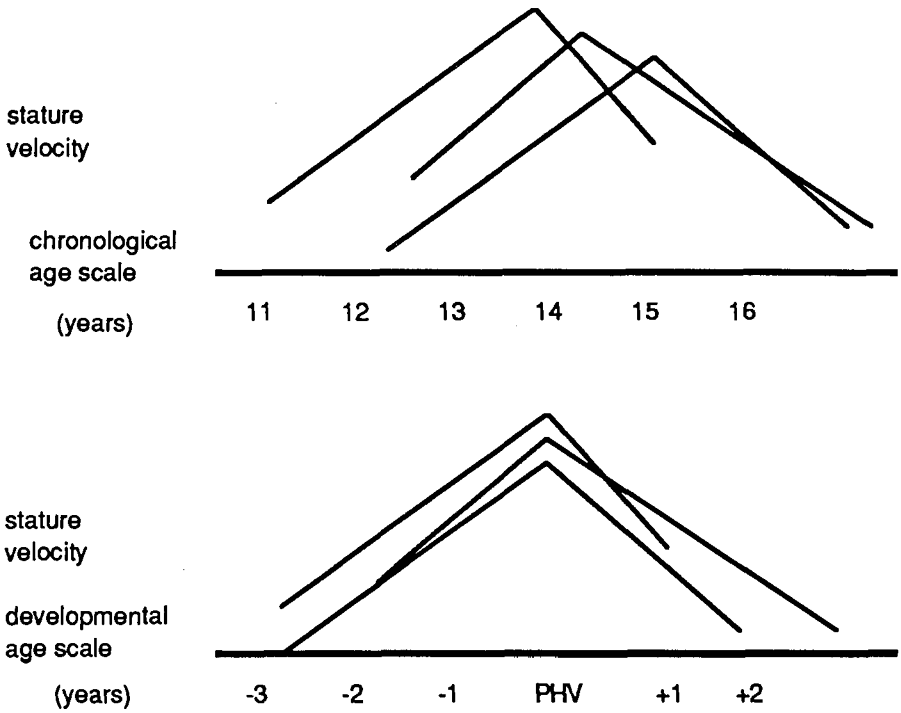


Figure 6.2 Stature aligned on PHVage.

The first step in the alignment procedure was to identify age at PHV for each case. This was explained in the preceding section of this chapter. Subsequently, every variable for each case was interpolated to annual intervals before and following PHVage using the Akima (1970) function. The final manipulation was to physically shift each variable matrix so that the PHVage vectors aligned. The new time scale became years before and after PHVage as outlined in Table 6.5, starting with 9 years prior to PHVage (PHVm9), and ending at 4 years post age at PHV (PHV4) .

Table 6.5 Maturity-adjusted and chronological age* scales

Maturity-adjusted scale	Chronological age scale* (years)
PHVm9	5
PHVm8	6
PHVm7	7
PHVm6	8
PHVm5	9
PHVm4	10
PHVm3	11
PHVm2	12
PHVm1	13
PHV	14
PHV1	15
PHV2	16
PHV3	17
PHV4	18

* given the mean PHVage of around 14

Due to the variety of PHVages, many different ranges of the maturity-adjusted ages were found among the sample. For example, a late maturing subject may have data ranging from PHVm9 to PHV, whereas an early maturing child would have data from PHVm5 to PHV4. The number of subjects at each end of the scale was small and for this reason, many of the analyses using the maturity-adjusted data were restricted to the developmental range from PHVm6 to PHV2.

Chapter 7 ANTHROPOMETRIC CHARACTERISTICS OF DEVELOPMENTAL STATUS

In order to build a model which would assess the developmental status of an individual child, it was necessary to identify the nature of physique characteristics of the sequence of development. Being a multidimensional concept, shape-change over time is not readily described by simple multivariate methods (Reyment, et al, 1984). It was proposed that an element of the complexity could be controlled by reducing the number of variables to those which uniquely offered critical information regarding the specified objective.

7.0 Identifying Anthropometric Characteristics of Maturity

Two different approaches were used in this investigation. The first was to examine the physique of children of the same chronological age, though at different stages of development. Those variables which showed the largest gross anthropometric differences between early and late maturing cohorts would likely characterise developmental status in a generalized sample.

The second approach was to control for development, identifying the apparent anthropometric changes which occurred from one year to the next.along the developmental span. Where the first method predominantly examined point differences, this approach sought information about serial change.

7.1 Physique Differences in Early and Late Maturers at the Same Chronological Age.

Proportionality deviation analysis (Ross and Wilson, 1974) was chosen as a tool which would readily identify point differences in anthropometric dimensions between early and late maturing subjects (refer to Chapter 4 for rationale).

7.1.1 Method

Subsamples of 12 each, of the early and late maturing subjects were assembled on the bases of both PHVage and skeletal maturity. Those subjects meeting both criteria (refer to Chapter 6) were selected first, after which subjects appearing to be similarly near the maturational extremes were added to make up the full cohorts.

For these observations, it was important that the data were representative of identical chronological ages so the 23 anthropometric variables were first interpolated to anniversary values using the procedure outlined by Akima (1970). At each chronological age (7 to 16 years), the variables were then transformed to proportionality z-values according to the method of Ross and Wilson (1974).

The variables which were considered most likely to differentiate maturity at each age were considered to be those showing the greatest absolute difference between z-values of early and late maturers. Where :

for variable X: $Z_{dif} = \surd(Z_e - Z_l)^2$

where:

Z_e is the variable mean z-value for the early maturing subsample

Z_l is the variable mean z-value for late maturing subsample

An estimate of the variables which might best discriminate developmental status across the entire age span was made by ranking the mean of the z-value differences for each variable, from age 6 to age 17, where:

for variable X: $MZ_{dif} = ((\Sigma \sqrt{}((Z_e - Z_l)^2))/10)$

where:

Σ : sum from age 7 to age 16

Z_e is the mean variable z-value for the early maturing subsample

Z_l is the mean variable z-value for late maturing subsample

7.1.2 Results

For each chronological age, the 23 variables were ranked according to their discriminatory ability. Appendices C-1 and C-2 list the ranked z-value differences for these variables at each chronological age.

It was apparent from these analyses that a few variables persist with larger relative differences between early and late maturing subjects across the age range. Corrected arm girth is the most striking, ranking first or second at all ages except age 7 where it ranks 5th. Calf girth is prominent from ages 7 to 13, then ranks much lower through the remaining years. Ankle girth appears to be a superior discriminator in the earlier years, then substantially loses its power after the age of 13. Other variables, such as upper arm, hand, and foot lengths, gluteal girth, and femur breadth tend to fluctuate, for at least a few years, around the upper ranks of difference.

A somewhat similar variable list emerged from the estimates of mean Z-value differences across the age range (Table 7.1).

Table 7.1 Ranked mean z-value differences (MZ_{dif}) between early and late maturers

Variable	MZ_{dif}
A.P. chest b.	0.413
Humerus b.	0.640
Bi-iliocristal b.	0.685
Transverse chest b.	0.845
Chest girth	0.961
Sitting height	1.110
Thigh g.	1.119
Leg l.	1.183
Forearm l.	1.199
Knee g.	1.199
Biacromial b.	1.289
Hand l.	1.305
Wrist g.	1.316
Upper arm l.	1.336
Calf l.	1.340
Shoulder g.	1.351
Ankle g.	1.384
Gluteal g.	1.392
Femur b.	1.687
Forearm g.	1.746
Calf g.	1.811
Foot l.	1.877
Corr. arm g.	3.040

7.1.3 Discussion

Using proportionality deviation analysis, a number of anthropometric variables were concluded to be the more likely candidates for functions designed to predict developmental status, whether the functions were age-specific, or generalized across the age range. These variables were:

Girths:	Corrected arm
	Forearm
	Wrist
	Gluteal
	Calf
	Ankle
Breadths:	Femur
Lengths:	Upper arm
	Calf
	Foot

7.2 Principal Components of Maturity-Adjusted Ages

Principal components analysis was employed with two specific objectives in mind. First, it was proposed that by explaining as much of the total variance as possible in a few principal components at each PHV-aligned age, a clearer picture of maturity-related shape characteristics would be evident. The variables with high loadings on each factor would presumably be the more useful in subsequent model construction. The second objective was to determine if different principal components, depicting physique alterations due to developmental changes, would evolve across the maturity-adjusted scale.

7.2.1 Method

All anthropometric data were aligned on PHV to derive maturity-adjusted ages (as described in Chapter 6) for each of 90 subjects in a stratified random subsample. The SPSS^X FACTOR command using principal components analysis extraction method and VARIMAX orthogonal factor rotation were run on the full data matrices (Norusis,1988). Both raw and proportionality-scaled data were examined to determine whether controlling for size (stature) would permit better expression of shape variation across the developmental scale.

7.2.2 Results

The following is a summary of the resulting rotated factor matrices for each maturity-adjusted age from PHVm6 to PHV2 for both the raw and proportionality scaled data.

Raw data

PHVm6: Three principal components explaining 80.5% of the data variance evolved with girths and lengths as the obvious common features of the first two. The third factor was dominated by the two boney breadths (humerus and femur) and AP-chest breadth. Transverse chest and biiliocristal breadth correlated most strongly with the girth component, whereas biacromial breadth loaded on the length component. The highest loading variables on the first factor were forearm and calf girth . The second factor was lead by forearm length and leg length.

PHVm5: Only two factors emerged at this 'age', quite distinctly girths and lengths, accounting for 76% of the variance. AP-chest breadth was now loaded on the girth factor, while humerus and femur breadth had slighlty stronger associations with lengths. Forearm and gluteal girths topped the first component. Leg length and stature now loaded highest on the length component.

PHVm4: Very similar factors developed as in the previous year. Two principal components, explaining 72% of the variance, divided girths and lengths, this time with the boney breadths more heavily loaded on girths. The variables having the strongest correlations with each factor were identical to those at PHVm5.

PHVm3: Girth and length factors again accounted for a total of 72% of the variance. The only difference between this and the previous year was the emergence of forearm, shoulder, gluteal, knee, and corrected arm girths as as the highest loadings on the girth component.

PHVm2: About 78% of the variance was explained by the girth and length factors with calf and forearm lengths becoming the leading, though not clearly dominant, variables on the second component. Biacromial breadth was almost equally loaded on each factor.

PHVm1: Only slight changes from the previous year were evident.

PHV: A third principal component responsible for only 4.2 of the 78.7% explained variance emerged. This factor correlated almost exclusively with biacromial and transverse chest breadth. The other two factors were as previously described.

PHV1: Biacromial breadth uniquely dominated the third component, with transverse chest slipping back in among the girths. Leg and calf length, along with stature loaded highest on the second factor. The dominant girths became forarm, calf, shoulder, corrected thigh, and corrected chest.

PHV2: Seventy-eight percent of the data variance was explained by the 3 principal components. The girths, as usual, had the highest eigenvalue, explaining over half the variance. The highest girth loadings were with shoulder, corrected thigh, gluteal, and forearm girths. Calf length, stature, forearm and lengths dominated the second factor. AP-chest breadth was equally correlated with the girth component as it was negatively correlated with the third, biacromial-dominated factor.

Proportionality scaled data

PHVm6: Six factors were needed to account for 78% of the transformed data variance. Again, girths formed the first principal component, with lower limb girths dominating. The second component was a mixture of boney breadths, chest measures and corrected arm girth. The elements of stature formed the third component, with leg and calf length negatively correlated, and sitting height highly positively loaded. Trunk breadths (biacromial, transverse chest, and biiliocristal) made up the fourth component. Upper limb segmental lengths composed the fifth. Foot length did not correlate highly with any of the first 4 factors, yet loaded highly, and uniquely on the sixth.

PHVm5: There was a general merging of the previous factors to 4, although some of the loadings were quite weak. Only 69% of the variance could be explained by combined factors with eigenvalues above 1.0. The first principal component was again composed exclusively of girths, lead by gluteal, corrected thigh, and calf girth. Breadths and corrected chest girth made up the second component, stature elements the third, and upper limb along with foot length, the fourth component.

PHVm4: A few of the breadths (AP-chest, humerus,femur) along with corrected chest girth which formerly loaded on the second component were found to be now correlated with the girth elements. This moved the stature elements to the position of the second principal component, with upper trunk breadths (biacromial and transverse chest) forming the third. The fourth component was the same as the previous year. Biiliocristal breadth did not correlate with any of the factors.

PHVm3: The first principal component further absorbed transverse chest and biiliocristal breadth, leaving the stature elements to form factor two, the limb segmental lengths as factor three, and biacromial breadth to exclusively load highly on the fourth factor.

PHVm2 to PHV2: The factor breakdowns showed little change from that at PHVm3.

7.2.3 Discussion

The above analyses suggested that perhaps size does mask, or at least dominates the variance of shape across this particular developmental scale. For the unscaled data, the two factors, girths/breadths and lengths accounted for most of the variance until the onset of puberty at around PHVm2 when biacromial breadth emerged on a third factor, and held at least until two years post PHV. One might anticipate more variety in the way of shape components throughout maturation than simply the three elements. The same three components were identified by Skibinska (1977) as characterising shape of adult males. A look at the communalities at each year showed stature along with shoulder, gluteal, and knee girths as consistently having the greatest proportion of their variances explained by the common factors.

With the stature-scaled proportionality data, a slightly clearer impression of the shape changes occuring with maturation seemed to emerge. In spite of an ambiguous start, it appeared that the relatively immature physique is distinguished by independent features of shoulder and limb girths; trunk and boney breadths; stature elements (sitting height, leg, and its component calf length); and foot along with upper limb segmental lengths. As PHVage is approached, the independence of the breadth component starts to weaken, with all but biacromial breadth eventually associating with girths. Unfortunately, no further pattern evolved. From three years prior to PHVage to two years post PHVage, the components and their variable loadings were static.

These analyses would suggest that it may be difficult to model the shape changes accompanying development using unscaled data. However, whereas the proportionality scaled data may be useful, this may be limited to the early stages of development. A parsimonious set of variables which might discriminate shape changes throughout development would be gluteal or knee girth, biacromial breadth, leg length, and upper arm or foot lengths.

7.3 Summary and Discussion

Both scaling for stature and principal components analysis were recognized by Healy and Tanner (1981) as useful techniques for the characterisation of human shape. Whereas the premises of these two techniques were quite different, a similar list of variables emerged as those more likely to assist in the discrimination of maturational differences. Many of these were highly correlated with each other. One distinct difference was the identification of biacromial breadth as a principal component of shape in the circum-pubertal years. While this variable did not account for a large proportion of the shape variance, it was not revealed at all by the proportionality technique.

The variables concluded to be most useful for developmental models were:

- Girths:
  - Shoulder
  - Corrected arm
  - Forearm
  - Gluteal
  - Calf
  - Ankle
- Breadths:
  - Femur
  - Biacromial
- Lengths:
  - Forearm
  - Leg
  - Foot

Chapter 8 MATHEMATICAL MODELS FOR THE ASSESSMENT OF DEVELOPMENTAL AGE

Introduction

This chapter describes a series of forty formal analyses, based on five general approaches founded on the assumption of similar size and shape characterising developmental status. None of these approaches was considered sufficiently acceptable for clinical use since it was apparent that individual variablility defied generalization which would account for stature velocity and skeletal age phenomena. These outcome, however, lead to a unique system whereby physique could be appraised in relation to normative, early, and late maturing prototypes at each chronological age from 7 to 16 years, as described in Chapter 9.

The present chapter is organized in such a manner that a tabulated synopsis of all experimental functions along with the criteria for their acceptance (section 8.1), is followed by the full description of each model attempted (section 8.2). Ancillary analyses which contributed to either the creative aspects or conclusions of these explorations are also included in this section.

8.1 Synopsis of modeling functions and criteria for acceptance.

Table 8.1 Summary of approaches used to establish developmental status using anthropometric characteristics.

Approach	Formal experiments	trials*
Conventional:		
Multiple linear regression		
	Y=PHVage	
	x=5 z values	4
	x= 5 raw variables	4
	x= all z values	1
	x= all raw variables	1
	Y=skeletal age	
	x= all raw variables	1
Discriminant analysis	Y=PHVage	
	x= all raw variables	5
	Y=skeletal age	
	x= all raw variables	5
Novel:		
Target adult reference	Stature-scaled variables	10
	Sitting height scaling	1
	Knee girth scaling	1
Minimum sum of differences	PHVage-adjusted prototype	1
Stanine/sigma scores	Sum of all variables	2
	Sum of 9 common variables	2
	Sum of 9 different variables	2

---

* the majority of these experiments were carried out for each of the ten age levels (from 7 to 16); these numbers have not been counted as trials.

8.1.1 Criteria for acceptance of models

Each approach offered different statistics by which overall acceptability could be judged. The criteria for acceptance of any model was that it must be able to:

1) predict developmental status better than chronological age and stature;

2) predict with a probability greater than chance; and

3) explain at least two-thirds of the variance of maturity (r>0.8)

In addition, it was expected that the model should be superior in its predictions at ages closer to maturity than at younger ages.

8.2 Anthropometric Modeling of Developmental Status

8.2.1 Multiple regression analysis

8.2.1.1 PHVage as the dependent variable

A series of multiple linear regression functions was fitted by least squares and tested against the strength of chronological age alone to predict PHVage. It was proposed that a function was adequate if the standard error of the residuals (SER) was usefully reduced from that for age predicting PHVage, across the entire sample, or in any subsample.

Overall Method

The complete anthropometric data set was plotted on a Sun System using New S Language (A.T.&T. Bell Laboratories) to check the assumptions of linearity and normality. Three dimensional plotting with rotation of the axes gave no indication that the data were other than multivariate normal. As is shown in Figure 8.1 the assumption of linearity does not appear to be violated. Thus, there was no indication that polynomial transformations would be necessary for the regression analyses.

The dependent variable, developmental age or the PHVage index (Y_{ij}) was derived from PHVage where for subject (i) :

$$Y_{ij} = \text{age}_{ij} - \text{PHVage}_i$$

given:

$$i = (1, \ldots, 120)$$
$$j = (7, \ldots, 16)$$

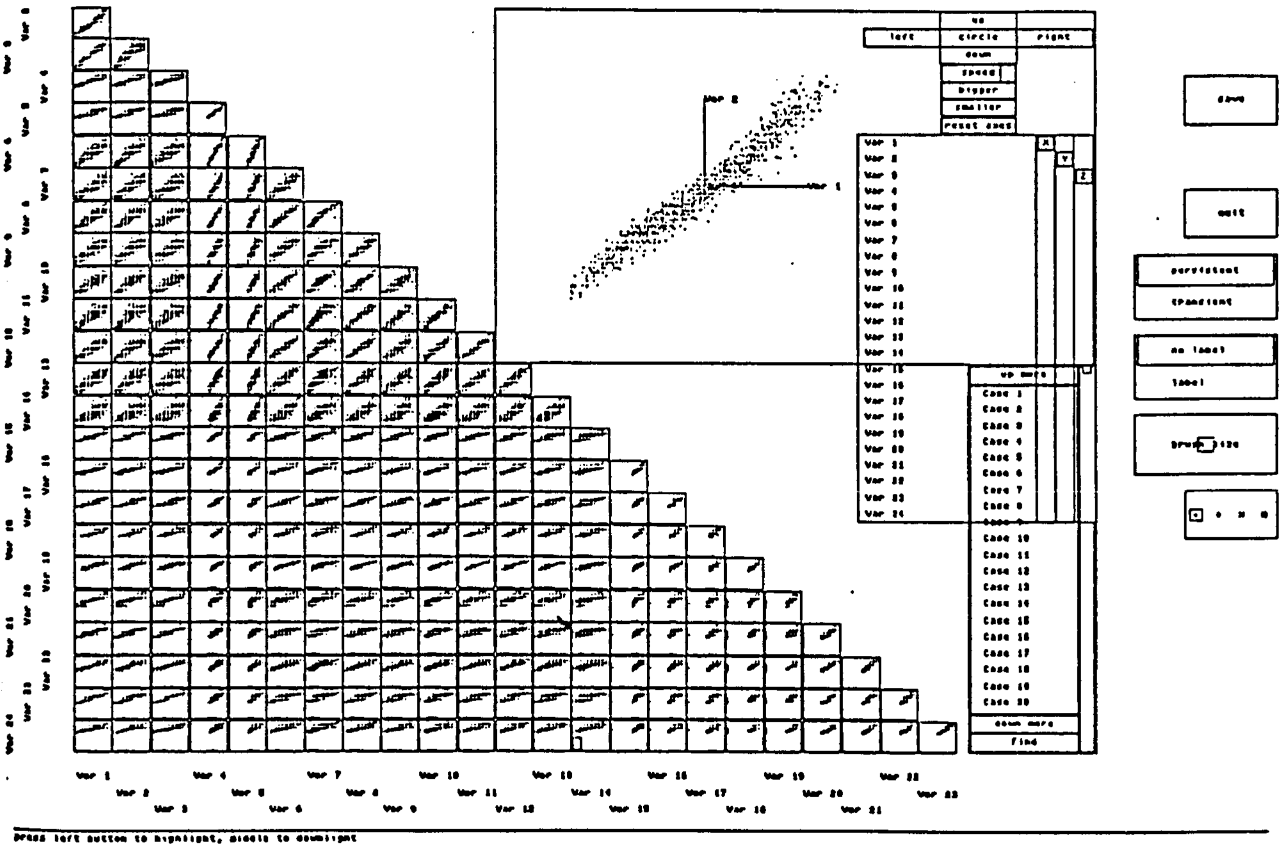


Figure 8.1 Multivariate plot of the full anthropometric set suggesting linear relationships among all variables.

Although this was a longitudinal data set, for the purposes of regression, there was a potential to use each child-year as a cross-sectional 'case'. While this made maximal use of the available relationships, it also introduced highly correlated elements among the dependent and predictor variables. The cross-validation technique described by Geisser (1975) was used to established whether this lack of independence was problematic. The stability of the residual standard errors was tested by removing a single subject and conducting the regression on n=119, for n+1 iterations. The mean standard error for the 120 iterations became the standard error of the mean function.

Method 1

In the initial analyses, the reduced variable set identified in the previous chapter was further collapsed to a minimal subset of uncorrelated variables representing a cross-section of body tissues and regions. These are listed at the bottom of Table 9.2.

For each child-year from age 7 to 16 (n=1157), developmental age was regressed on the variable subset. Three age groupings were then tested to determine if equations could be better fitted for smaller ranges (age 7 to 10; age 10 to 14; age 14 to 16). These were tested with and without chronological age as an independent variable, to assess if its presence would substantially improve the prediction. The full age range, and three sub-range analyses were then repeated using the z-value transformations of each variable.

Results 1

Table 8.2 shows the mean standard error of residuals (from 120 iterations) for each of the regressions to be no better, and frequently worse, than prediction using chronological age alone. The addition of age to the independent variable subset did not improve the estimate error to any extent.

Table 8.2 Mean standard errors of residuals (SER) from cross-validated regression of developmental age on 5 anthropometric variables* and age.

transformation	age range	n	x var.	meanSER
none	7-16 years	1157	5	1.3104
none	7-9.99 years	396	5	1.4024
none	10-13.99 years	472	5	1.3021
none	14-17 years	283	5	0.9788
none	7-9.99 years	396	5+age	1.3520
none	10-13.99 years	472	5+age	1.2614
none	14-17 years	283	5+age	0.9426
z-value	7-16 years	1157	5	1.3181
z-value	7-9.99 years	396	5	1.5709
z-value	10-13.99 years	472	5	1.6359
z-value	14-17 years	283	5	1.1817
n/a	7-16 years	1157	age	1.3581

*5 variables: stature, skinfold-corrected upper arm girth, forearm length, ankle girth, and foot length.

To explore the possibility that a nonlinear function or interactive term would improve the predictions, a technique known as projection pursuit (Friedman and Stuetzle, 1981) was carried out. In this operation, the entire independent variable matrix is serially transformed, until an adequate fit is derived. Between 8 and 14 transformations were necessary to reduce the error variance by approximately 0.4 years in the age sub-range tests. Before investigating the mathematical nature of these transformations, the functions were evaluated by cross-validation and were found to be highly unstable. The mean SER for each of the three sub-ranges reverted to above 1.4 years.

Method 2

The second regression tactic using PHVage as the dependent variable, was to run a multiple linear regression analysis using least squares estimations and backward elimination (SPSS^{X}, Release 3.0) for the full anthropometric data set plus chronological age. This was done independently for each chronological age, for both the normal and z-value data, in an attempt to assess whether the failure of the initial analyses was the result of independent variable selection.

Backward elimination commences with all the available independent variables in the equation, then, starting with the variable having the smallest partial correlation coefficient, the hypothesis that ß for each of the variables is zero (F test, level of significance $p< .10$) is sequentially tested. Variables unable to meet the criterion F probability are removed and the new coefficients for the remaining variables are retested (Kleinbaum, Kupper, and Muller, 1988).

Results 2

Tables 8.3 a and b lists the multiple R and the SER for each prediction across the age range.

Table 8.3 a Multiple R and SER for regression of PHVage

Age	7	8	9	10	11	12	13	14	15	16
R	0.439	0.361	0.538	0.548	0.55	0.63	0.73	0.83	0.81	0.77
SER	1.17	1.13	1.08	1.199	1.04	0.96	0.85	0.71	0.75	0.82

Table 8.3 b Multiple R and SER for regression of PHVage on z-values

Age	7	8	9	10	11	12	13	14	15	16
R	0.265	0.373	0.410	0.376	0.459	0.39	0.63	0.70	0.71	0.75
SER	1.24	1.159	1.14	1.16	1.103	1.15	1.03	0.91	0.90	0.86

While an apparent improvement on the previous predictions, it was evident from the SER that further diagnostics were not necessary as none of these anthropometric equations were adequately superior to chronological age at estimating PHVage. There was similarly no suggestion that stature-scaled, and standardized data in the form of phantom z-values (Ross and Wilson, 1974), improved the ability to assess developmental status using multiple linear regression.

As such, it was concluded that no specific combination of anthropometric variables, or their stature-scaled derivatives, were found which could predict PHVage substantially better than could chronological age.

8.2.1.2 Regression functions using skeletal age as predicted variable

A second marker of developmental status available with the Saskatchewan Growth Study data was skeletal age assessed at around age 11 years. To appropriately use this numerical estimate as a dependent variable in multiple regression, the data needed to be handled somewhat differently than in the former analyses

Method

Because the skeletal age truly only reflects developmental status relative to the age at which it is measured, the regression had to be restricted to that single chronological age frame. For this reason, each subject was used only once, and a split sample format could be employed instead of the more cumbersome cross-validation procedure. A stratified random sub-sample of 90 children was derived using the SPSS^{X} SAMPLE command. Stratification was on the basis of early, middle and late maturation, with 75% of each maturity level being taken into the regression sample. The remaining cases were held out as the test sample.

In addition, it was necessary to first synchronize the dependent and independent variables, as the anthropometric and skeletal age information were collected as much as 6 months apart in some cases. This required that the anthropometric data be interpolated to the date at which the hand-wrist x-ray was taken for each child. The Akima function for data smoothing (Akima, 1970) was used to individually adjust the data matrix for each case.

Backward elimination of variables was again utilized with only three variables: corrected arm girth, upper arm length, and foot length, remaining in the final equation.

Results

Again, further regression diagnostics were not carried out as the multiple R (R=.689) and the standard error of the residuals (SER=.969), were similar to those for PHVage equations at the same age and were not deemed adequate for the useful prediction of developmental status between the ages of 11 and 12 years.

8.2.2 Non-parametric models

8.2.2.1 Target Physique Models

The results of the principal components analysis of proportionality-scaled data suggested that the nuances of shape change, at least in early stages of development, might be best modeled using this data transformation on the maturity-adjusted prototype.

The Ross/Wilson 'phantom' itself could also provide a mature physique end-point or target, the distance from which might account for developmental status. The fact that proportionality scaling expresses the data as standard scores, makes the values additive and the cummulative variable distance from the mature reference or target, more easily calculated.

Stature-scaled z-values

The objective was to establish a model based on the sum of stature-scaled z-values of select anthropometric variables, which would approximate developmental status as defined by years from PHVage.

Procedure

A random sub-sample (n=90), stratified for early, middle, and late maturers was selected as the experimental group from the Saskatchewan data. Twenty-three variables for each subject were stature-scaled to 'phantom' z-values by the Ross/Wilson procedure (Ross and Wilson, 1970). They were then re-aligned on PHVage for each case in the sub-sample. For each maturity-adjusted age from PHVm7 to PHV2, the mean z-value for the individual variables was calculated.

To identify the variables whose mean z-values proceeded toward maturity in a unimodal fashion, each was plotted against the maturity-adjusted age scale. Those whose deviations proceded in a single direction toward the adult reference were chosen as the maximal subset (Table 8.4). Ten summative models were then derived from these variables (Table 8.4).

The initial criteria for variable selection were the findings of the analytical work described in Chapter 7. However, as is evidenced by the sums for each of the models listed in Table 8.5, it became the primary objective to find a set of variables whose sum declined to PHV2 as consistently, and as sharply as possible.

Femur breadth was removed to the second set of models to determine if its partial presence (PHVm3 to PHV2) was of any consequence.

Table 8.4 Variables used in 'target physique' models

Unimodal to target	Sum(14)	Sum(11)	Sum(9)	Sum(6)	Sum(8)
Girths:					
shoulder	•	•	*		
corr.arm	•	*			
forearm	*	•			
wrist	•				
gluteal	*	•	*	*	•
corr.thigh	*	•	•	*	•
calf	•	•	•	*	•
ankle	*				•
Breadths:					
biacromial	*	*	•		
tr.chest	*	*	•		
AP-chest	*	•	*	*	•
femur	•	•	*	•	•
Lengths:					
forearm	•	•	*	•	•
foot	•	*	*	•	•

The remaining 5 models were identical to the above, with the exclusion of femur breadth.

Table 8.5 Sums of mean variables (n=90) as listed in Table 8.4

Age	sum (14)	sum(11)	sum(9)	sum(6)	sum(8)
PHVm7	20.052	17.387	16.109	8.260	9.774
PHVm6	17.669	15.265	13.954	8.152	9.518
PHVm5	15.339	13.358	12.291	7.239	8.330
PHVm4	12.983	11.608	10.575	6.802	7.605
PHVm3	11.296	10.130	9.208	6.298	7.073
PHVm2	10.146	8.997	8.251	5.792	6.619
PHVm1	9.291	8.035	7.609	5.326	6.154
PHV	7.990	6.850	6.470	4.285	4.971
PHV1	6.735	6.226	5.505	2.789	3.173
PHV2	9.437	8.747	7.397	1.633	2.108

Table 8.6 Sums of mean variables (n=90) as listed in Table 8.4 with exclusion of femur breadth

Age	sum (14^f)	sum(11^f)	sum(9^f)	sum(6^f)	sum(8^f)
PHVm7	18.082	15.417	14.139	6.290	7.804
PHVm6	15.653	13.249	11.938	6.136	7.502
PHVm5	13.621	11.640	10.573	5.521	6.612
PHVm4	11.207	9.832	8.799	5.026	5.829
PHVm3	9.636	8.470	7.548	4.638	5.413
PHVm2	8.604	7.455	6.709	4.250	5.077
PHVm1	7.867	6.611	6.185	3.902	4.730
PHV	6.948	5.808	5.428	3.243	3.929
PHV1	6.142	5.633	4.912	2.196	2.580
PHV2	9.216	8.436	7.086	1.322	1.797

The maturity-adjusted age scale was regressed on each of the models to estimate the best-fitting line through the variable sums. The 10 sums were calculated for each of the 36 children not used in formulating the mean models, and their developmental ages were predicted by the linear equations.

Results

While the estimated years from PHVage were close to accurate for a few of the cases, the majority were incorrect. Many of the sums were so far beyond the scale of the models that the linear extrapolation produced unreasonable estimates. There was no indication of superior prediction at earlier ages, and there was little continuity in the model-estimated ages across time. For example, a child may have been calculated as PHVm3 on one occasion, then as PHVm6 the following year. No single model appeared even marginally superior to the others. This preliminary inspection suggested that statistical analyses of the results were not warranted.

8.2.2.2 Z-values scaled to alternative variables

It was felt that one weakness of the above models was the scaling of all variables to stature. Tallness and shortness are often due to relatively long or short legs, with trunk length showing less variance among individuals of the same developmental status (Ross, et al,1988). In scaling a short child, for example, breadths and girths might be exaggerated to the point of distorting the proportions characterising developmental status. A probable outcome would be inflated sums such as those observed. Similarly, the dramatic nature of the stature growth spurt might result in a variable z-value decreasing over subsequent years if it was not growing at the same relative rate as stature. This offered a possible explanation for the lack of continuity in these models.

To circumvent these theoretical problems, a second tactic, involving z-values scaled on variables other than stature was tested.

The first alternate variable chosen was sitting height. While it is responsible for most of the adolescent growth acceleration (Tanner, 1978), as an alternative to stature, it is perhaps a better indicator of a child's maturity level than of phenotype.

The second alternative was knee girth, chosen because it represents the boney tissue and so does not readily reflect inter-subject differences in nutrition or physical training. Knee girth was also highly loaded on the first principal component throughout the developmental age range (refer to Chapter 7), and it did not appear to undergo a dramatic adolescent growth spurt in these data.

The procedures for scaling were the same as outlined in Chapter 5, with the alternative variables replacing stature to make the equation:

$$Z= ((v^{*} ((Y_p/Y_s)^d))-P)/s$$

where:

Z	is the proportionality or z-value
v	is the size of any measured value
Y_p	is the 'phantom' variable constant
Y_s	is the subject's variable measure at time t
d	is a dimensional exponent
P	is the 'phantom' value for the measured variable v
s	is the 'phantom' standard deviation for the measured variable v

All anthropometric data for the 90 case sub-sample were transformed to both sitting height-scaled z-values and knee girth-scaled z-values. For the two new data sets, variables which unimodally approached maturity were sought by plotting the mean z-values along the maturity-adjusted age scale. Only nine variables met this criteria for sitting height, and 8 for knee girth. These are listed with their mean sums in Table 8.7.

Table 8.7 Sums of variable means for sitting height and ankle girth-scaled z-values (n=90)

Age	Sitting height z-value* sum of means	Knee girth z-value** sum of means
PHVm7	18.489	16.491
PHVm6	18.082	16.05
PHVm5	16.493	13.919
PHVm4	15.355	12.021
PHVm3	14.011	10.683
PHVm2	12.176	9.137
PHVm1	10.653	8.138
PHV	10.025	7.304
PHV1	9.082	6.97
PHV2	8.112	6.973

---

* sum of biacromial and transverse chest breadth; shoulder, corr.chest, gluteal, corr.arm, forarm, corr.thigh, and calf girths.

** sum of sitting height; leg, forearm, and foot length; wrist and corr.thigh girth; AP chest and femur breadth.

Rather than create any reduced models from these two sets, they were first evaluated as maximal models on the 35 test subjects.

Results and Discussion

Once again, a highly erratic pattern of developmental ages was derived by the variable sums. As with the stature-scaled models, no discernable patterns emerged which could offer an opportunity improve to the estimates.

Having theoretically corrected for stature-scaling problems by testing alternative models, it was concluded that either the predictive error emanates from outside the scaling, from generalized scaling itself, or both.

Potentially at fault outside the scaling could be any or all of the following:

1. differences between mean sums for one developmental age and the next (ie. the slope of the line) were small, leaving little room for individual variation before the next developmental age was reached.
2. models may have been unduly weighted by a single variable type such as girths. (Although, this was not the case for the knee-girth-scaled model).
3. the mean maturity-adjusted prototype may not represent any real individual physique.

The issue of scaling warranted more thorough investigation before z-value data were used in any further modeling. Refer to Section 8.3 for this discussion.

8.2.3 Minimal sum of differences models

A second type of model was built on the maturity-adjusted prototype with the objective of avoiding the restrictive assignation of developmental age by having to closely match model variable sums.

The proposed changes were that an individual's anthropometric data would be calculated in terms of distance from the mean developmental protoypes. The estimated developmental age of the subject would be that which produced the minimal sum of these distances, that is, the maturity-adjusted age at which the subject most closely approximated the norm.

Procedure

Again, using the maturity-aligned data for the stratified random sub-sample (N=90), the minimum and maximum value for each of the 24 variables for each maturity-adjusted age (PHVm7 to PHV2) were extracted. An algorithm was written on $SPSS^x$ which took single variables (i) at time (t), from the test subject and transformed each to a percentage of the difference between the maximum and minimum values for each of the maturity-adjusted age prototypes, ($P^t{}_i$). The operation then calculated each percentage as a deviation from modal value, (P_{50}) and summed these deviations for all variables. The general function being:

$$\sum_{i=1}^{n} \sqrt{((P^t{}_i - P_{50}{}^t{}_i)^2)}$$

The result for a given test subject was a 10 by 10 matrix with chronological age forming the columns and sums for each developmental age, the rows. The estimated developmental age was the Y-coordinate for the cell containing the minimal value in each column.

Before any mathematical functions were designed to interpolate precise developmental age predictions from the matrix, the test sub-sample of n=36 was evaluated to determine whether the minimal sums model had solved some of the problems of the preceding paradigms.

Using only integer developmental age predictions, correlations were found among the predicted developmental age and:

PHV-adjusted age, defined as:

(Sample mean PHVage - (CA - PHVage));

Skeletal maturity-adjusted age, defined as:

(CA - ((CA at x-ray - SA)/12));

Where: Mean PHVage=14.13

CA= chronological age

SA= skeletal age rating

Results

The results are reported in Table 8.8.

Table 8.8 Correlations of minimal-sums developmental age with PHV-adjusted age (PHVa), and skeletal maturity-adjusted age (SKa), (n=35).

Chronological age	r 'PHVa'	r 'SKa'
6.5 - 7.5	.019	.341
7.5 - 8.5	.117	.356
8.5 - 9.5	.264	.568
9.5 -10.5	.257	.693
10.5 -11.5	.266	.753
11.5 - 12.5	.334	.721
12.5 -13.5	.570	.706
13.5 -14.5	.611	.658
14.5 -15.5	.424	.641
15.5 -16.5	.396	.580

Discussion

It was evident from Table 8.8, that the physique characteristics captured by the minimal sums prediction model held a greater association with skeletal maturity than with PHVage. The latter relationship was consistently weak until the two years surrounding the average age of PHV. On the other hand, the correlations of the predictions with skeletal maturity were more stable, and reasonably strong, with the exception of the first two age ranges. These correlations also strengthened around the years during which skeletal maturity was assessed.

This modeling format appeared to successfully open-up the range of possible shape and size variation within a given developmental age. This allowed it to predict within more reasonable bounds as well as to overcome the problem of erratic assessments. With the exception of a few subject-years, the estimated ages for each individual never declined from one year to the next.

One of the more serious drawbacks of the current model was its lack of precision in the earliest ages. By default, the minimal sum of differences was most often aligned with a developmental age of 6 (PHVm8). It was also noted that small children could be assigned the developmental age of 6 for three or four years in a row.

Along similar lines, the minimal sums model did not address the appropriateness of the maturity-adjusted prototypes. It was observed that the maximum and minimum values for each age were widely-spread and overlapped considerably on adjacent ages. Before pursuing further paradigms, it was proposed that these prototypes be investigated more thoroughly.

A final concern was cumbersome nature of the model. Over 4,000 operations were necessary for a partial program which did not include the linear functions for interpolating real number ages. It was concluded that a simpler system, utilizing similar concepts could be designed.

8.2.4 Maturity-adjusted prototypes

The nature of the fits for models designed on the maturity-adjusted prototypes suggested that the prototypes were perhaps not characterising shape changes throughout development as well as expected.

One of the assumptions implicit in the aligning of a longitudinal set of measurements on PHVage was that the variance of that data would in turn be reduced. To test this assumption the means and standard deviations of each of the variables were calculated on both the standard age and maturity-adjusted scales. The standard deviations for each variable were plotted simultaneously on the double scale. In addition, the same procedure was carried out for the proportionality-scaled data. A representative sample of these plots make up Figures 8.2 to 8.5

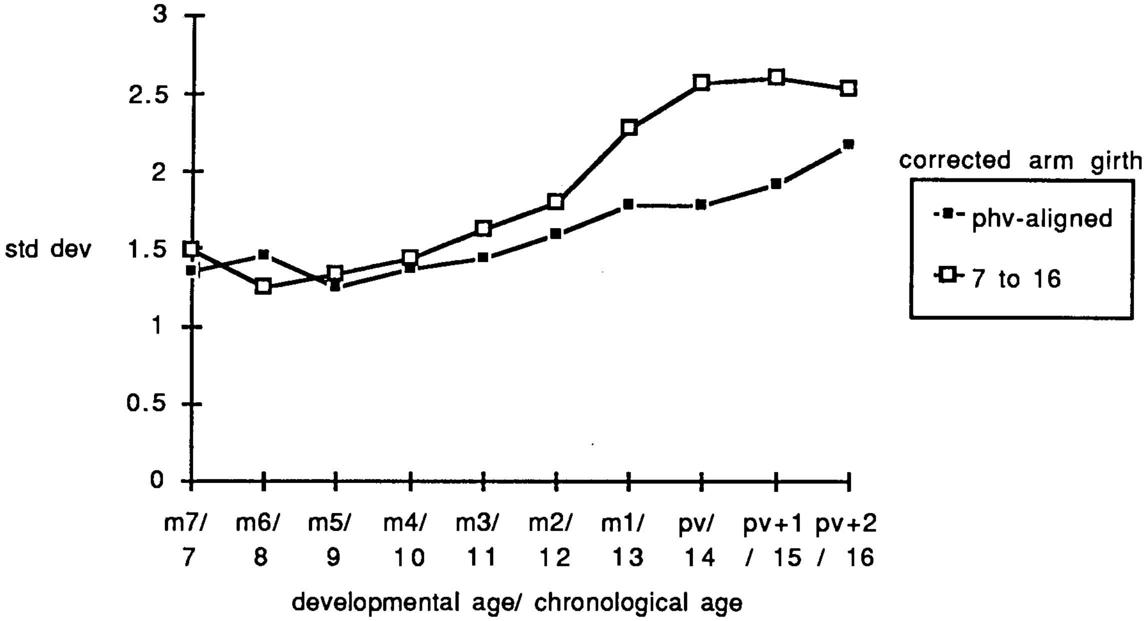


Figure 8.2 Standard deviations for mean corrected arm girth calculated on both the standard and maturity-adjusted age scales.

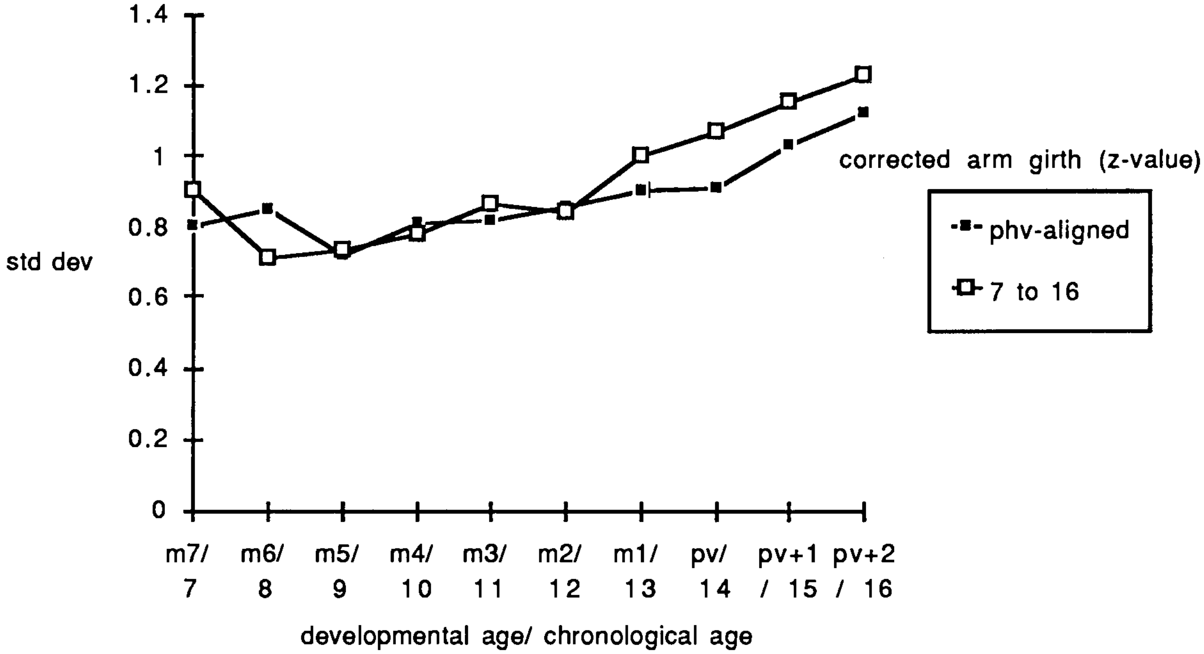


Figure 8.3 Standard deviations for mean corrected arm girth Z-values calculated on both the standard and maturity-adjusted age scales.

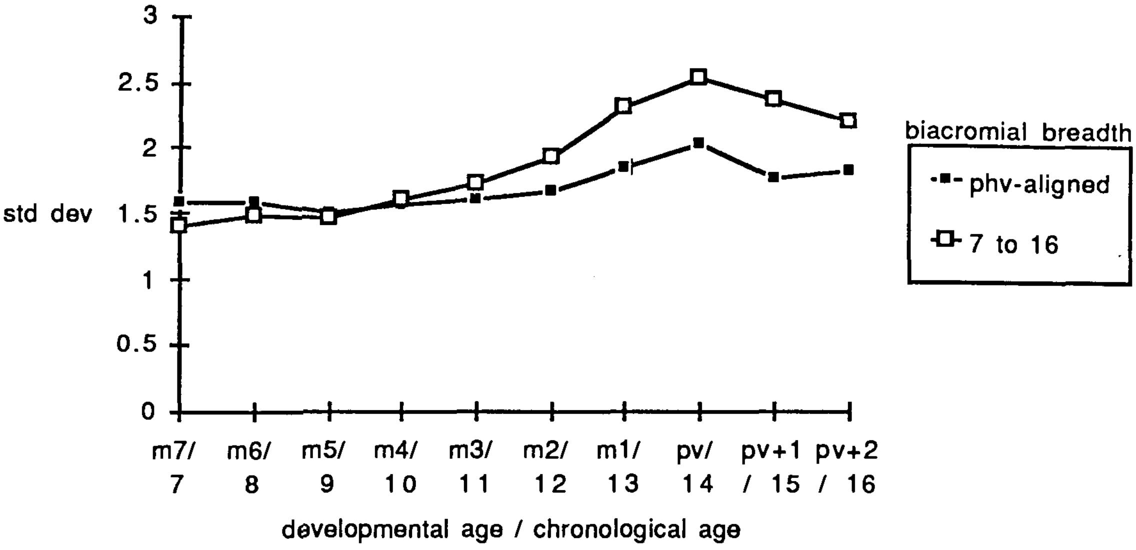


Figure 8.4 Standard deviations for mean biacromial breadth calculated on both the standard and maturity-adjusted age scales.

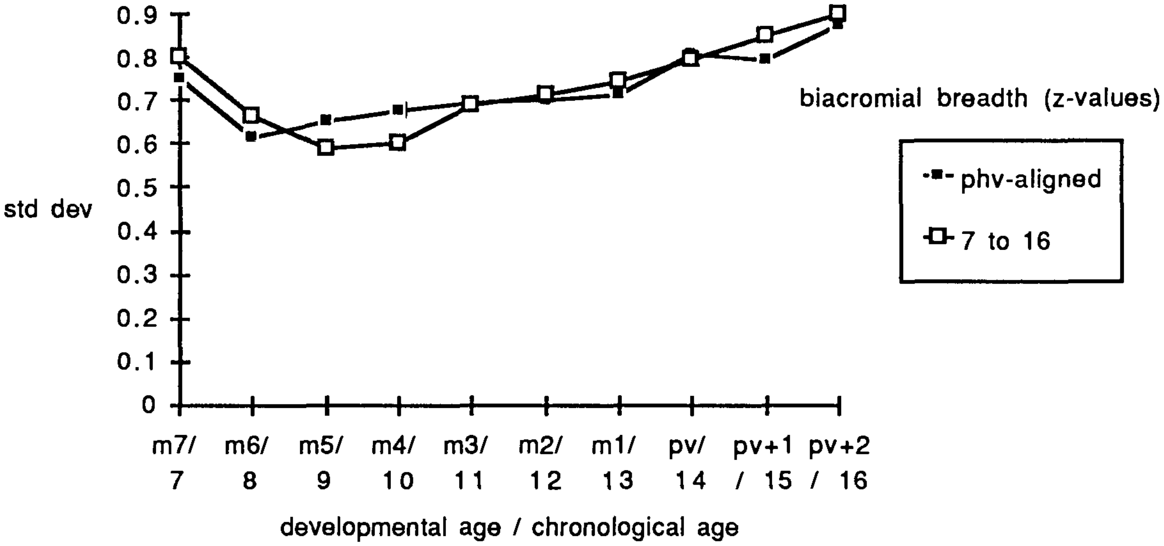


Figure 8.5 Standard deviations for mean biacromial breadth Z-values calculated on both the standard and maturity-adjusted age scales.

Discussion

In general, aligning on PHVage did reduce the variance of each anthropometric measure for the unscaled data. However, the extent of the reduction was not at all consistent. The greatest variance difference appeared at the age of PHV (around chronological age 14) which was to be expected as it was the criterion on which the adjustment was based. Yet at either end of the scales, the differences in variance were not as large. This was particularly extreme at the earlier ages where, for many of the measures, the variance was greater for the maturity-adjusted data.

In the case of the proportionality-scaled data, the aligned and unaligned data variances were close to identical for most of the variables. This phenomenon may be interpreted as an indication that stature or size is a critical element of the shape change which accompanies maturation. These plots suggest that if size is neutralized, many of the physique differences among early and late maturers (of the same chronological age) might not be observable.

In summary, these observations suggested that for unscaled data, the maturity-adjusted prototypes may be useful only at PHVage and for a few years beyond. However, the high degree of variance created at less mature stages of development by alignment on PHVage may confound modeling on the earlier prototype series (PHVm7 to PHVm1).

In contrast to the results of the principal components analysis, these plots also suggested that proportionality-scaled, maturity-aligned data may not be useful for modeling developmental status on physique characteristics.

8.2.5 Normative development prototypes

New developmental age prototypes were constructed on a sub-sample of 33 subjects who were deemed to be 'average maturers' by virtue of the fact that their estimated

PHVages fell within a half year of the mean, and they were appraised at age 11 to have skeletal maturity indices close to unity.

The anthropometric data for each were smoothed along the chronological age scale to annual intervals before and after PHVage. The means and standard deviations for this normative sub-sample provided the new developmental prototypes on which subsequent models were based.

8.2.6 Standard Score/ Stanine models

Building upon the minimal sums paradigm, it was proposed that standard scores of the normative mean would produce a sum of differences more simply than the previous model which dealt with the percentages of maximum-minimum differences. With the objective of enhancing the model's accuracy particularly at the younger ages, it was also proposed that it be structured in such a way as to limit, or buffer the influence of size extremes on predicted developmental status.

By dividing the deviations from the norm into a limited range of scores, the data extremes would be contained. This could be facilitated by any of a number of scoring scales based on the properties of the normal probability distribution. One which divides the normal distribution into 9 categories based on the standard deviation (Ross and Ward,1986) is the 'standard nine' or stanine scale. The 9 divisions of this scale are constructed as described in Figure 8.6

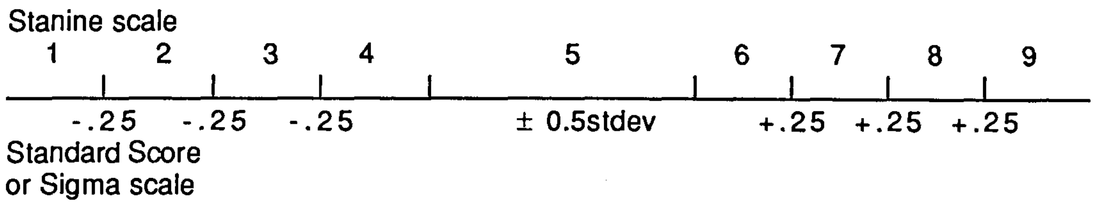


Figure 8.6 The distribution of the stanine scale

8.2.6.1 Procedure

A series of algorithms was written on an EXCEL™ spreadsheet to transform the 24 anthropometric variables for each subject (n=36) to sigma and stanine scores, then sum a specified subset of variables for each year across the age range. Three such subsets were proposed. The first was the maximum model of all 24 variables. The second was composed of nine variables which appeared most frequently in the variable selection analyses (*cf* Chapter 7). The final subset was unique for each chronological age. For each of the early and late maturing sub-sample (*cf* chapter 6), the unscaled means of the 24 variable were compared to determine which showed the greatest early-late contrast. The leading 8 or 9 variables for each chronological age composed the 3rd model subset. The full listing for each subset can be found in Table 8.9

To establish whether the open-ended categorical scale would improve predictive accuracy, both standard scores and stanines were tested. For the standard score summation, all scores were subtracted from the constant 10 to avoid negative sums and averaging.

Each test subject was entered into the system at his chronological age, for which prototype standard scores and model sums were computed. The raw data were then applied to the same functions for the prototypes at ± 1 year from his chronological age, and again for the prototypes at ± 2 years from his entry age. In this manner each child would be tested against a total of 5 developmental norms, two on either side of his chronological expectancy.

A linear function then fit a line through these 5 comparisons to interpolate the estimated developmental age (Y_j), where:

> (X_i,.....X_5), were the means of the variables sums for entry age -2 years, through to +2 years, and
>
> (Y_i,......Y_5), were the corresponding ages of the prototypes.
>
> Given, X_j=5 for the stanine models, and X_j=10 for the standard score models.

The program iterated these functions for all three variable sub-sets, for both stanine and standard scores, for each of the 10 annual measures on every test child (n=36).

To establish how well the best single algorithm assessed early and late maturers, the correlations between the appropriate maturity index and the estimated developmental age were found for the subsamples of the two maturity extremes.

8.2.6.2 Results

The correlations of the estimated developmental ages for each model with both PHV-adjusted age and skeletal maturity-adjusted age were calculated for the test subsample. These are listed, along with the correlation of stature with these two developmental scales, in Tables 8.9 a and b.

Table 8.9 a Correlations standard score and stanine models, and stature with PHvage (n=36).

			Correlations				
Models	stan1	stan2	stan3	std1	std2	std3	stature
AGE							
7	0.231	0.227	0.193	0.115	0.226	0.245	0.205
8	0.325	0.304	0.311	0.136	0.220	0.252	0.259
9	0.218	0.230	0.217	0.288	0.258	0.160	0.305
10	0.152	0.194	0.230	0.223	0.144	0.199	0.308
11	0.254	0.285	0.281	0.214	0.251	0.283	0.349
12	0.307	0.309	0.289	0.241	0.309	0.371	0.427
13	0.447	0.422	0.507	0.475	0.500	0.511	0.533
14	0.532	0.533	0.554	0.521	0.604	0.582	0.612
15	0.485	0.488	0.590	0.368	0.447	0.557	0.547
16	0.334	0.321	0.493	0.316	0.386	0.389	0.344

Table 8.9 b Correlations of standard score and stanine models, and stature with skeletal maturity-adjusted age (n=34)

	Correlations						
Models	stan1	stan2	stan3	std1	std2	std3	stature
AGE							
7	0.706	0.625	0.534	0.621	0.601	0.620	0.573
8	0.683	0.646	0.649	0.496	0.528	0.533	0.561
9	0.681	0.625	0.597	0.682	0.575	0.569	0.589
10	0.646	0.593	0.599	0.633	0.517	0.604	0.603
11	0.722	0.687	0.652	0.582	0.591	0.633	0.641
12	0.757	0.652	0.646	0.726	0.711	0.729	0.650
13	0.738	0.654	0.734	0.740	0.678	0.741	0.640
14	0.716	0.663	0.679	0.512	0.561	0.674	0.628
15	0.673	0.646	0.675	0.445	0.510	0.692	0.608
16	0.589	0.539	0.492	0.607	0.547	0.625	0.504

---

stan: stanine std: standard score

stan1 and std 1: sum of all 24 variables

stan2 and std 2: sum of gluteal, corrected arm, forearm, wrist, knee, calf, and ankle girths; biiliocristal breadth, and forearm length.

stan 3 and std 3: variables are different for each age. Based on maximal early-late differences in unaligned data.

Age 7: gluteal, corr. thigh, calf, knee, ankle girths; AP-chest, biiliocristal breadths, leg length.

Age 8: gluteal, knee, calf, ankle, forearm, and wrist girths; transverse chest and biiliocristal breadth.

Age 9: gluteal, knee, calf, ankle, shoulder, and forearm girths; biacromial and AP-chest breadths.

Age 10: gluteal, knee, calf, ankle, shoulder, and corrected-arm girths; biacromial and AP-chest breadths.

Age 11: gluteal, corr. thigh, knee, calf, ankle, and corrected-arm girths; and AP-chest breadths.

Age 12: AP-chest breadth, sitting height, femur breadth; calf, gluteal, knee, corr. thigh girths; and humerus breadth.

Age 13: sitting height, wrist girth, humerus breadth; calf and gluteal girths; biiliocristal breadth, and ankle girth.

Age 14: sitting height; biacromial breadth; shoulder and corr. thigh girths, humerus breadth, calf and gluteal girths, stature, gluteal girth, forearm length, and corr. chest girth.

Age 15: biacromial breadth, gluteal girth, sitting height, corr. thigh girth, corr. chest and shoulder girths, biiliocristal breadth, and forearm length.

Age 16: biacromial breadth, corr. thigh, shoulder, and gluteal girths; transverse chest breadth, sitiing height; biiliocristal and corr. chest breadths.

Table 8.10 Correlations of predictions from stan1 model and stature, with skeletal maturity-adjusted age in early and late maturing subjects(based on MI).

	Correlations			
	early	stature	late	stature
AGE	(n=23)		(n=19)	
7	.1706	.3962	.6066	.5956
8	.7194	.3497	.6032	.4839
9	.2170	.2511	.6030	.4624
10	.2554	.2956	.5686	.5044
11	.3900	.1453	.5552	.4934
12	.3390	.0585	.5897	.5095
13	.4205	.0077	.5759	.5752
14	.1647	.1418	.6307	.5901
15	.1254	.1993	.4092	.4256
16	.1168	.3211	.1524	.4181

8.2.6.3 Discussion

The results of these 6 models were very similar to those for the minimal sums paradigm. This was expected as the premise was very similar. However, the present models succeeded at improving the associations in the youngest ages. They could also be computed on a relatively constrained spreadsheet.

Once again, the developmental ages estimated on anthropometric characteristics were more highly associated with skeletal maturity than with PHVage. The only PHVage relationship which was remotely satisfactory was that at age 14, although stature alone was more highly correlated with this maturity index than were the more complex anthropometric models.

In association with skeletal maturity, there were only minimal recognizable differences among the six models. The best performing model overall appeared to be the stanine sum of all 24 variables (stan1). Its correlations were somewhat superior to the other stanine sums, and better overall than its standard score counterpart. Most importantly, it had a stronger association with skeletal maturity than did stature alone. Although there were exceptions at specific ages, in general, the use of stanine scores appeared to have marginally improved the associations over standard scores alone.

The fact that the results were so uniform suggested that the number and choice of variables within any given model had relatively little influence on its association with maturity. Where the maximum 'stan1' (24 variable) stanine model appeared the single strongest of its type, the flexible 'std 3' model (9 variables) appeared to be at least as good as the maximal model in the standard score group.

The correlations of the stan1 estimates with skeletal maturity in the early and late-maturing subsamples showed that of the two groups, this particular function clearly favours late maturers. However, the evidence of the stature correlations with the same maturity index suggested, once again, that size was a large component of the physique differences associated with developmental status, and that stature was also less aligned with early maturity than with late.

It is well known that skeletal age is not a static marker of maturity, but one which shows variations of velocity throughout growth (Acheson, 1966; Fry,1971; Houston,1980). For this reason it is fair to suggest that the extrapolation of a single estimate of skeletal maturity based on a radiograph at age 11 is likely to present an unrealistic set of developmental criteria at all ages except age 11. However, given the moderate ability of the single rating to associate with physique at most ages, access to comprehensive assessment skeletal maturity would more than likely improve the apparent estimates made by the models.

8.2.7 The relationship between size and maturity

While the latter models showed modest associations with the index of skeletal maturity, even in the best case (age 12/stan1; r=0.757), morphology could explain only 57% of the maturity variance. It was also notable that stature alone at this age (r=0.65) could explain 42% of the variance.

To shed some light on the relationships between stature and relative maturity, bivariate frequency tables of the two were constructed for the entire Saskatchewan sample (n=120).

For each cross-sectional age, stature was categorized on the basis of percentile ranking on the National Center for Health Statistics standards of height for age in boys (NCHS,1979). Those children whose stature fell above the 75th percentile for their age were categorized as tall, and those falling below the 25th percentile, as short. One standard deviation on either side of the mean was used to categorize the three maturity levels (early, middle, and late) for skeletal age and PHVage as described in Chapter 5. The SPSS^x CROSSTAB procedure was used to produce the contingency tables, a sample of which are found below (Tables 8.11 a and b).

Table 8.11 a Percent frequencies of short, average and tall children by PHVage, at chronological age 7.

row %	Relative maturity		
col%	early PHVa	mid. PHVa	late PHVa
Stature			
short	8.0	64.0	28.0
	12.5	28.1	43.8
average	23.7	60.5	15.8
	56.3	40.4	37.5
tall	19.2	69.2	11.5
	31.3	31.6	18.5

Table 8.11 b Percent frequencies of short, average and tall children by skeletal maturity (Sk), at chronological age 7.

row %	Relative maturity		
col%	early Sk.	mid. Sk.	late Sk.
Stature			
short	4.0	52.0	44.0
	6.3	20.3	68.8
average	17.1	73.2	9.8
	43.8	46.9	25.0
tall	26.7	70.0	3.3
	50.0	32.8	6.3

Once again, it appeared that the PHVage and skeletal maturity indices were differentially associated with stature. PHVage was only weakly related to stature until around the age of 12 when 55.0% of the early maturers were amongst the tallest cohort. As would be expected, this representation rose (to 71.4%) by the age of 14.

It can be seen that even as early as age seven, 69% of the late skeletal maturers were among the shortest cohort, whereas only 50% of the early maturers are considered tall by the set criteria. This pattern of a greater likelihood of late maturers to be short than of early maturers to be tall continued up until age 13. At this point the pattern reversed until age 16.

While a distinct association of relative stature with skeletal maturity was apparent, particularly in the late maturers, stature alone would be of limited use in the estimation of developmental status. Many of the late (skeletal) maturers may have been short, but relatively fewer short children were late maturers. For example, at age 12, seventy-five percent of the late maturers were considered short, while only 37% of all the short children had late skeletal maturity rankings.

8.2.8 Discriminant analysis

The analyses to this point had drawn attention to the fact that the heterogeneity of size and physique at any specific point of developmental could minimize the ablility of mathematic functions to accurately predict a specific developmental marker. It was proposed that prediction of individual membership in the broader categories of early, middle, and late maturity (on either index) would be more successful than trying to estimate exact ages of maturity events.

Discriminant analysis provided a technique whereby an optimal linear combination of weighted anthropometric variables would be chosen so as to maximize the separation, and therefore predictability, amongst the three maturity levels.

8.2.8.1 Procedure

A stratified random subsample of 59 subjects was assessed for relative maturity status based on PHVage as described in Chapter 6. All 24 of the anthropometric variables along with chronological age were used for stepwise entry into the discriminant functions. Three approaches were then tested. The first combined all the data from age 7 to 16 for each child in the subsample, essentially treating them as a cross-sectional sample of 1200 cases. The second divided the data into 3 age categories identical to those used in the regression analyses (*cf* Table 8.2). The final approach analysed each age level separately resulting in 10 functions; from age 7 through age16.

The variable sets were next tested for violation of the assumption of equality of group covariance using Box's M (Norusis, 1988). The data had already been estimated to be multivariate normal (refer to Chapt. 7). Prior probability, or the estimate of the likelihood that a case belonged to a specific maturity category, was based on the proportion of early, middle, and late maturers in the subsamples (approximately 0.16, 0.66, 0.18).

The SPSS^X DISCRIMINANT function uses the minimization of Wilks' lambda as the criteria for variable entry in the stepwise selection procedure. At each step, the variable that results in the smallest Wilks' lambda for the discriminant function is selected for entry (Norusis, 1988). For each age group the function derived a reduced set of weighted variables for which the maximum ratio or eigenvalue:

(between-groups sum of squares/within-groups sum of squares)

was obtained. Once the optimal subsets of variables and their coefficients were identified, the discriminant functions were applied to the remaining subjects (n=56) to estimate the true misclassification rate.

The entire procedure was repeated for the data categorized for maturity status by skeletal age index (n=61 and 58).

8.2.8.2 Results

The functions in which all the data from age 7 to 16 were grouped, failed to pass the Box's M test for equality of covariance matrices, as did the three chronlogical age sub-groupings . None of these was subjected to further analysis.

The individual age categories did not appear to violate any of the tested assumptions, and so the discriminant functions were estimated. Table 8.12 provides a summary of the correct classification rate for grouped cases of the function and subsequent test subsamples.

Table 8.12. Percent of grouped cases correctly classified by discriminant analysis based on PHVage and skeletal maturity (MI).

	PHVage		Skeletal Maturity	
	Function(n=59)	Test (n=56)	Function (n=61)	Test (n=58)
Age	%	%	%	%
7	79.55	41.86	80.95	68.30
8	85.45	55.36	80.00	65.52
9	87.04	45.61	84.48	50.82
10	93.75	41.51	85.42	47.46
11	83.05	50.91	86.67	60.66
12	86.02	55.17	87.27	60.32
13	80.77	64.29	82.14	57.63
14	80.00	55.17	89.47	57.38
15	83.02	67.27	90.38	50.85
16	83.33	58.18	74.58	45.61

While these provide an overall picture of the extent to which the functions could correctly classify all members of each subsample, they do not describe how well early and late maturers were classified relative to the average children. Tables 8.13 a and b summarize the function and test classification percentages for early and late maturers (based on the PHVage and skeletal maturity indices).

Table 8.13 a Percent of early and late maturers correctly classified by discriminant analysis using PHVage.

	Early maturers		Late maturers	
	Function (n=9)	Test (n=9)	Function (n=9)	Test (n=10)
Age	%	%	%	%
7	44.4	14.3	85.7	0.0
8	88.9	22.2	75.0	10.0
9	80.0	50.0	75.0	50.0
10	80.0	20.0	87.5	11.1
11	60.0	10.0	66.7	11.1
12	70.0	20.0	75.0	9.1
13	90.0	62.5	33.3	30.0
14	70.0	63.6	55.6	10.0
15	77.8	40.0	50.0	70.0
16	70.0	20.0	50.0	50.0

Table 8.13 b Percent of early and late maturers correctly classified by discriminant analysis using skeletal maturity (MI).

	Early maturers		Late maturers	
	Function (n=9)	Test (n=11)	Function (n=9)	Test (n=8)
Age	%	%	%	%
7	42.9	0.0	57.1	37.5
8	25.0	18.2	44.4	28.6
9	25.0	23.1	88.9	50.0
10	71.4	0.0	57.1	25.0
11	77.8	23.1	66.7	12.5
12	57.1	30.8	66.7	28.6
13	50.0	0.0	55.6	14.3
14	62.5	23.1	62.5	25.0
15	57.1	21.4	71.4	33.3
16	0.0	0.0	55.6	12.5

The discriminant scores estimated by each function were plotted for both the maturity indices. These provided visual evidence of the lack of clear separation among early, middle, and late maturing groups produced by even the superior function. Figure 8.7 shows the scatterplot for one of the better discriminant functions, that for skeletal maturity at chronological age 14.

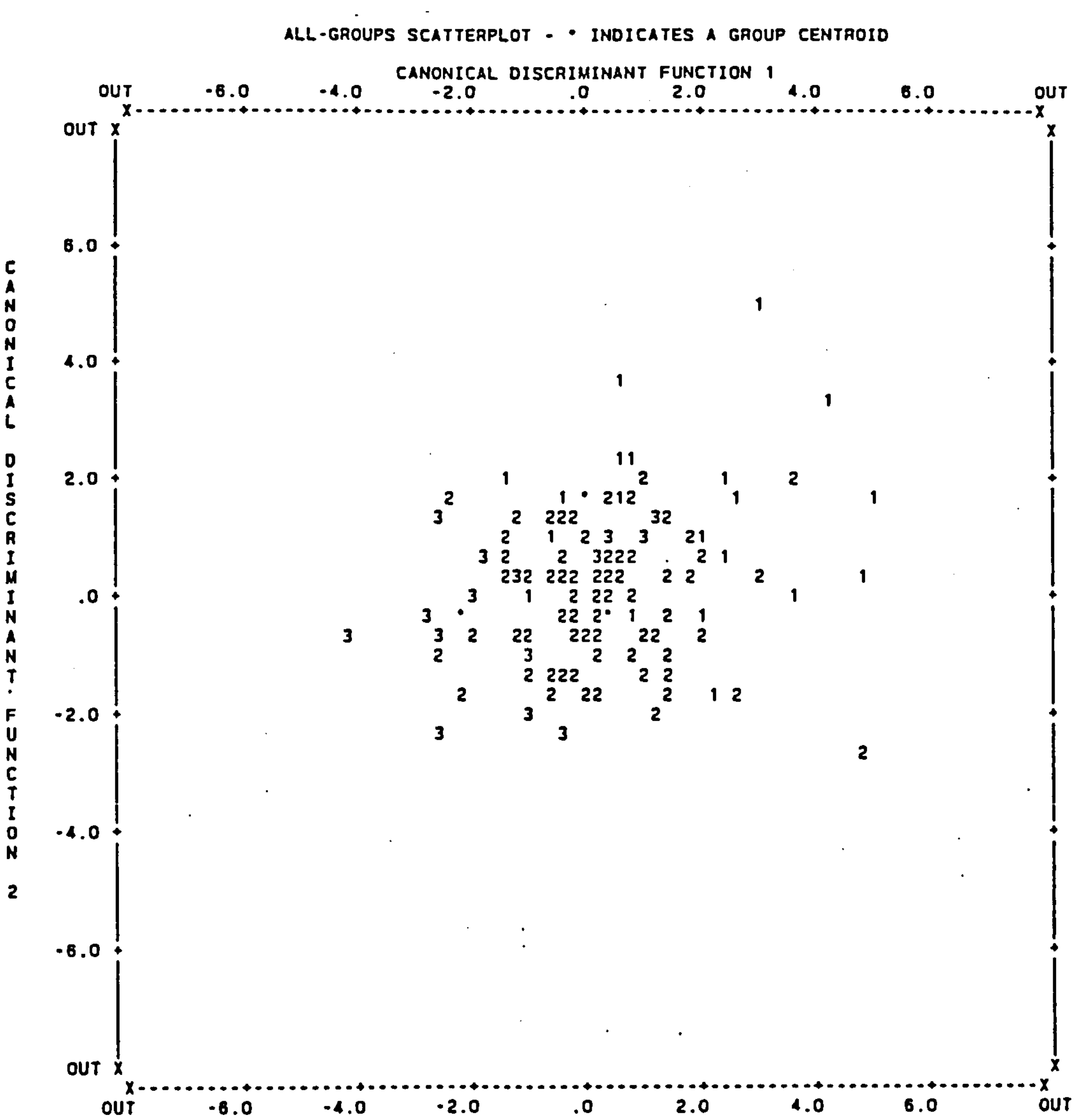


Figure 8.7 Separation of discriminant scores for maturity groupings based on skeletal age. Chronological age 14.
(1=early maturers; 2=middle maturers; 3=late maturers).

The Wilks' lambda statistic (λ) describes the ratio of the within-group sum of squares to the total sum of squares, that is, the proportion of the total variance in discriminant scores not attributable to differences among the three maturity levels (Norusis, 1988). A large value for lambda would suggest that there is a large variance within groups. This statistic for the age functions on both maturity indices (for the entire Saskatchewan sample,n=120) is listed in Table 8.14.

Table 8.14 Wilks' lambda (λ) for the combined discriminant functions predicting maturity level based on PHVage and skeletal maturity (MI).(n=120)

	PHVage	Skeletal Maturity
Age	λ	λ
7	.6676	.6987
8	.8670	.5625
9	.6945	.5466
10	.7028	.6649
11	.6195	.5299
12	.5838	.4545
13	.4687	.4232
14	.4204	.4211
15	.4625	.4337
16	.5673	.5723

8.2.8.3 Discussion

The probabilities of misclassification implicit in Table 8.12 suggest that the discriminant functions derived from the model subsample lose considerable strength applied to another group of individuals. The skeletal maturity functions appeared to be more robust than those based on PHVage, although both produced very high rates of misclassification.

Tables 8.13 a and b showed that neither the PHVage nor the skeletal maturity functions discriminate early and late maturers very well. The only exception might be PHVage classification of early maturers around age 13 and 14 years, and perhaps late around the ages of 15 to 16. It was evident that the modest success of the grouped cases (Table 8.12), was due to the correct classification of the larger group of average maturers.

It was equivocal whether the combined function Wilks' lambda statistics were generally superior for either of the maturity classifications. Most suggested that the anthropometric variance within maturity groupings was very high for both indices.

A graphical confirmation of this is found in a sample of scatterplots of anthropometric measurements against chronological age (Figures 8.8 through 8.10). With relative maturity rating identified, it can be generally seen that the distribution of these measures, even within each maturity grouping, is extremely broad.

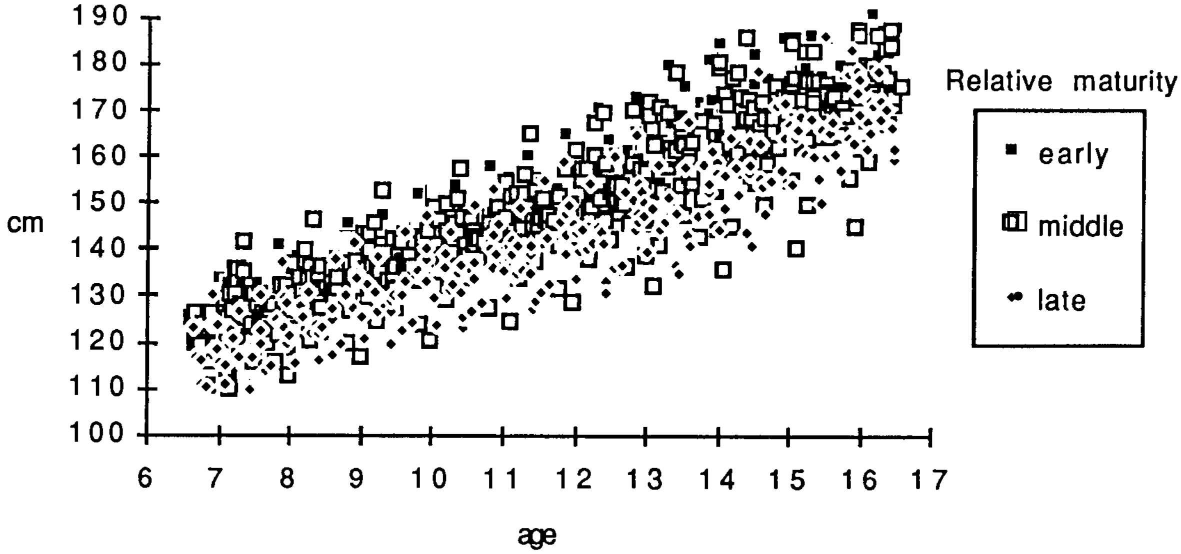


Figure 8.8 Distribution of stature measurement for early (n=18), middle (n=20), and late (n=20) maturing subsamples, based on skeletal age.

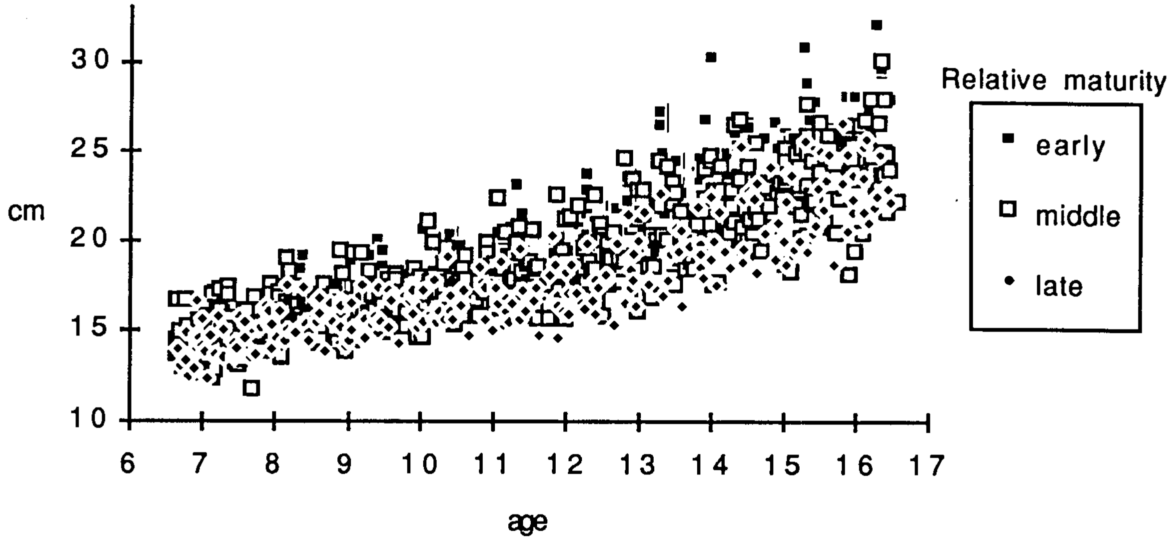


Figure 8.9 Distribution of corrected arm girth measurement for early (n=18), middle(n=20), and late (n=20) maturing subsamples, based on skeletal age.

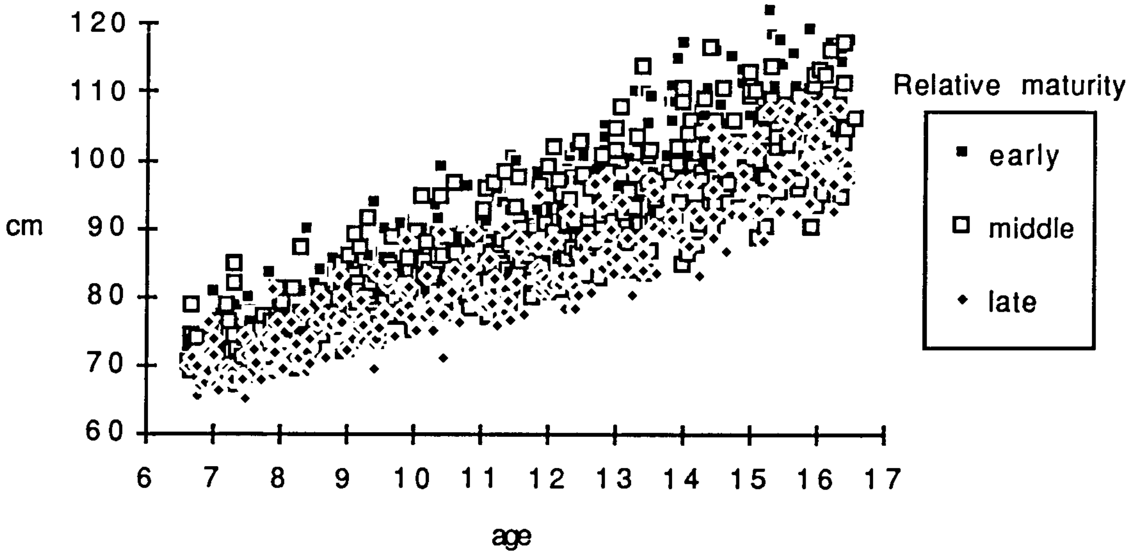


Figure 8.10 Distribution of shoulder girth measurement for early (n=18), middle (n=20), and late (n=20) maturing subsamples, based on skeletal age.

8.3 Conclusions

A number of conclusions regarding size, shape, and maturational status were drawn from this work.

It was noted in a number of the experiments that the two markers of relative maturity status did not share a common association with stature or general physique. Age at peak height velocity was only remotely reflected in anthropometric characteristics throughout growth. Only around the time of the velocity spurt did this association strengthen. In contrast, the index of skeletal maturity appeared to reach as far as the data permitted in its influence on size and shape.

The relationship between PHV and skeletal maturation is poorly understood. However, it appears that the neuroendocrine changes which stimulate the development of the pubertal growth spurt and secondary sex characteristics are independent of the mechanism which regulates skeletal maturity in earlier years. There remains no concensus as to which endocrine functions are driving early skeletal maturation. Somatotropin and thyroid hormone have been suggested (Acheson, 1966;Tanner,1978; Mosier,1981), and more recently, adrenal androgens have been examined in this role (Gasser, et al, 1985; Katz, et al, 1985; Weidemann,1981). It is agreed that in later years, under the common influence of the gonadal hormones, skeletal maturity and velocity of growth become associated (Buckler, 1984; Bielicki et al, 1984; Marshall, 1974).

The suggestion that physique is somehow related to skeletal maturity is not new. Bayley (1943) found boys who were early skeletal maturers (on the basis of age at reaching full skeletal maturity), to be taller than age peers from 10.7 to 17.7. She also noted that biacromial and biiliocristal breadths were larger in early maturers. However, she was unable to conclude that the middle and late maturers could be distinguished on the basis of these measures.

Beunen and his colleagues (1981), examining the data from the Leuven mixed longitudinal growth study, regressed skeletal age and chronological age on 17 anthropometric variables finding skeletal age to account for a large percentage of most body dimensions. In the age range of 12 to 15 the highest relationships were found for body weight and bone lengths, followed by bone widths and body circumferences. This group also noted that for all measures the proportion of the measurement variance explained by skeletal age increased up to age 14 or 15 after which it declined. They concluded however, that the percentages of explained variance were not high enough to be of biological significance. For example, at age 12, stature only accounted for 38% of the maturity variance. This value was very similar to that found in the present study (42%), and those reported by Hewitt and Acheson (1961), who estimated the relationship between stature and skeletal maturity in males to start at about age 4, and intensify up to age 14.

The association of stature alone with skeletal maturity appeared to be stronger in the late maturers than in the advanced individuals. It could be concluded from these limited data, that shortness at all ages from 7 to 16, was more likely to be indicative of late maturation than tallness was of early developmental status. More experimental evidence is required on this differential relationship of tallness and shortness with maturity status.

Related to the lack of generalized association between morphology and PHVage was the apparent inappropriateness of adjusting anthropometric data for maturity by aligning it on age at PHV. First suggested by Shuttleworth (1939), this has become a standard procedure in the analysis of longitudinal data, having been used to reduce the variance of maturity-related phenomena such as appearance of secondary sex characteristics (Tanner, 1981b), physiological parameters of cardiovascular fitness (Mirwald, et al, 1981), as well as circum-pubertal physique and body compositional changes (Bayley, 1943; Parizkova,1976).

In accounting for a single index of maturity, this adjustment ignored the underlying factor of age itself. An 11 year old who is 5 years away from his PHV will undoubtedly have a different physique from a 7 year old who is equally 5 years from this benchmark. The former has, afterall, had 4 additional years of growth. The so-called maturity-adjusted prototypes resulting from this realignment were likely representative of no normative group, and certainly, no individual child.

Without doubt, the principal conclusion from the foregoing work was that at any chronological age, the variance of individual physique is sufficiently vast, that even statistical procedures designed to broadly group children by their relative developmental status, cannot reliably do so. As Shock suggested in 1966, trends in growth can be described for a variety of functions, but individual differences are large; few individual children follow the pattern of growth described by mean values.

Chapter 9 ANTHROPOMETRIC MATURITY ASSESSMENT CHARTS

It was apparent that mathematical systems could not accomodate the wide phenotypic variations in shape and size found at every developmental stage, even under generous precision standards. Thus, an alternative approach to appraising physique and relative maturity status was developed.

By visually displaying all of the available morphological information against age-specific maturity norms, individual differences of size and shape can be examined in the context of the entire physique. In this manner, a few measures showing pronounced deviations from the norm, will not carry the same influence on evaluation of maturity status as they might have done in a delimited mathematical function.

The new approach was based on a series of age-specific normative charts constructed from the reference mid-range maturers identified in the previous chapter (section 8.2.4). These were designed as templates on which any of 25 individual anthropometric items could be plotted. Variable means for early (n=18) and late (n=20) maturing children (based on skeletal age at chronological age 11) were superimposed on each, to provide guidelines for generalized assessment of developmental status. These charts were formatted so that anthropometric data could be plotted as raw values, sigma, or stanine scores. The latter offered a simplified system by which relative variable size could be compared. Two different versions were constructed to allow for both manual plotting of raw values, and alternatively, data transformation, chart construction, and case plotting directly from a microcomputer spreadsheet.

Figures 9.1 through 9.10 show the anthropometric maturity assessment charts for boys from chronological ages 7 to 16 years. The stanine ratings and sigma scores for each are listed in the left-most column. Along each horizontal axis are the raw value means, for normal maturity, for the 8 respective stanine cut-off levels (essentially, sigma scores from -1.75 to 1.75). The means and standard deviations for each variable norm are listed across the bottom axis. Early and late maturing means are plotted as additional guidelines for maturity assessment.

For an individual child, any number of the 25 anthropometric variables can be plotted directly onto these charts. Although, it is evident from some of the following examples, that the more information that can be gathered about a child's physique, the less likely are misleading conclusions. For more specific estimates of maturity, measurements could be plotted on the normative charts for older or younger ages, as appropriate.

A sample of the computer-generated plots are shown in Figures 9.11 to 9.15. Written on Microsoft EXCEL™, the program allows input of raw values for any of 25 anthropometric variables. It transforms these to their respective sigma scores, then plots them along with the early and late maturing means, on the age-appropriate norm.

In both these formats, information on overall or individual variable size can be construed from the vertical placement of the plotted values. Shape, on the other hand is depicted by the oscillations along the horizontal gradients. Examples of how these charts can illustrate the complexities of maturity and physique are also found in Figures 9.11 to 9.15.

The first, (Figure 9.11) shows an early maturing child by the skeletal age criteria, who at age 13.87, meets all the physique expectations for his status. He is tall and approaches the mean early maturing shape characteristics in spite of his overall larger dimensions. One would have little difficulty assessing the developmental status of this individual from only a few of his measures.

The second child, (Figure 9.12) is a boy at age 11.72, whose size is generally in the mid-range at stanines 4 and 5, and whose shape appears to more closely approximate the early maturation pattern than the late one. However, the general presentation is sufficiently convincing that this is an average-maturing individual.

Figure 9.13 shows an individual at age 10.06, whose physique pattern deviates quite widely from the late maturing means. It is apparent that he has long hands and very long, narrow upper arms. However, his overall smallness suggests that he is most likely a late maturer.

The individual plotted in Figure 9.14 showed a unique shape pattern at this early age (7.016 years), and throughout his growth. Other than his average stature, little about his physique, would disclose his relative maturity status. It can be seen with this child, that if only selected girths (gluteal, arm, forearm, wrist, calf and ankle) or lengths (stature, upper arm, and calf) were measured, he might be incorrectly assessed as early maturing.

Finally, Figure 9.15 shows a late maturing boy who is not characteristically short, but in the mid-range for stature. Once again, if only specific breadths (biacromial, transverse chest) and girths (shoulder, chest, thigh, and ankle) were assessed, it might be erroneously concluded that this child was developmentally advanced.

Although, as with the previous case, there is scant information to be found in his relative shape and size which would indicate him to be a late maturer.

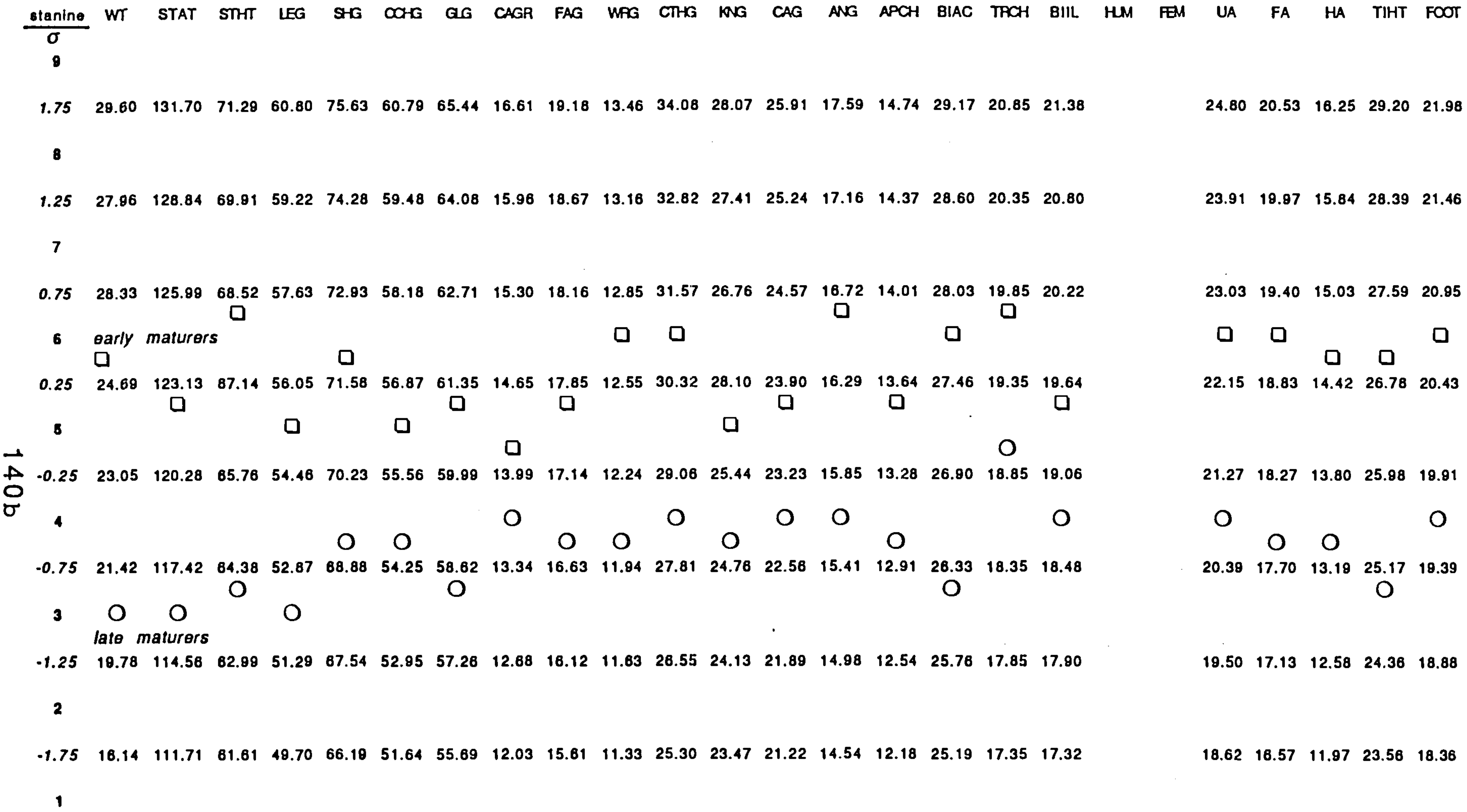
While the above samples were select, they were not artifactual. Similar deviations were seen in these cases at all ages throughout the available range. In these few examples, it can be appreciated that the variables selected by the procedures in Chapter 7 would have little discriminatory capacity in a number of children.

By making no assumptions regarding shape or size constancy at specific stages of development, these new charts offer a meaningful display of physique status relative to the established age-specific maturity norms.

At the same time, they provide the strongest evidence that individual morpohometric characteristics defy mathematical generalizations in the ascription of developmental status.

Table 9.1 Key to anthropometric abbreviations used in Figures 9.1 to 9.15

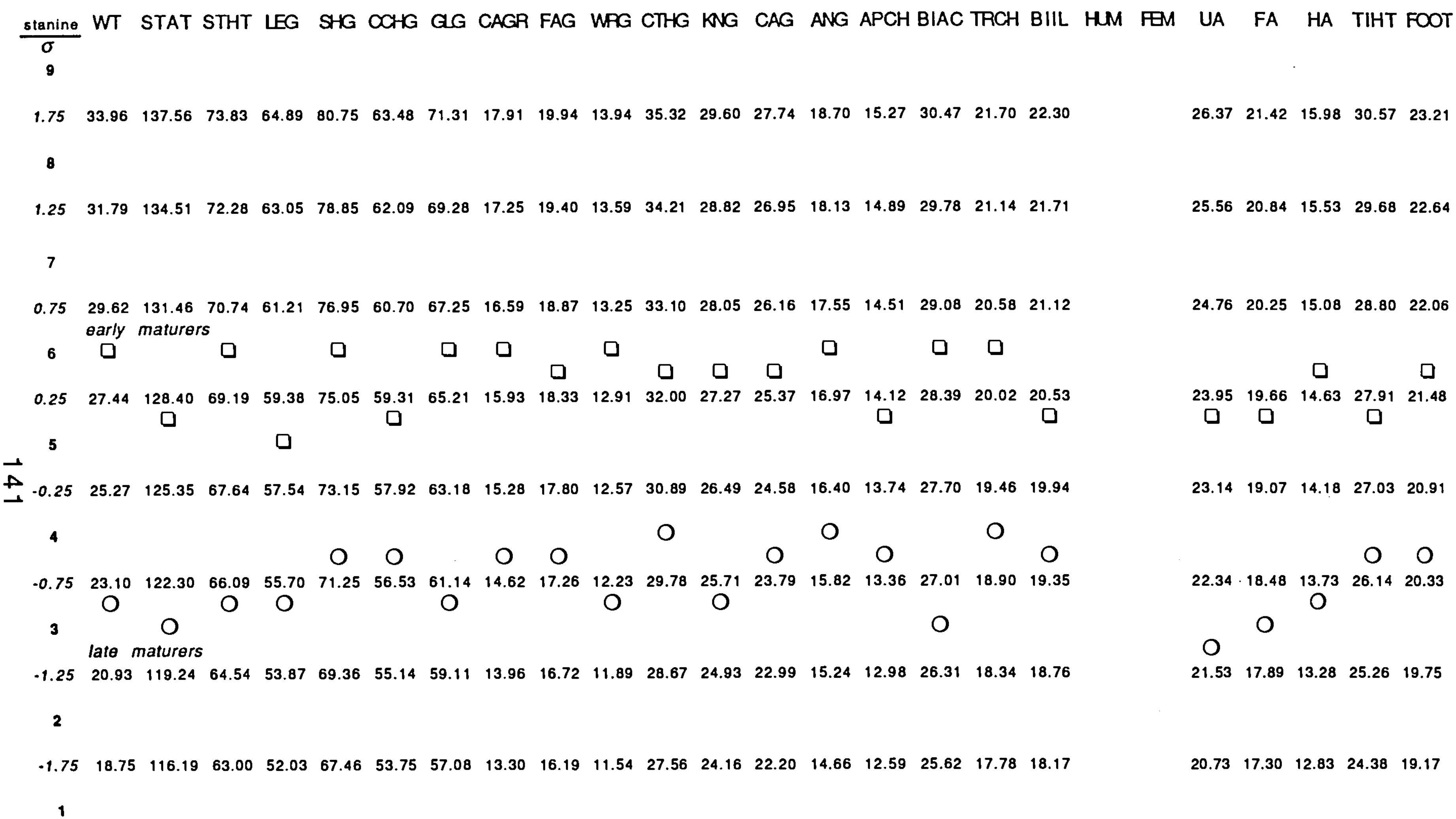
Variable	Abbreviation
Weight	WT
Stature	STAT
Sitting height	SITHT
Leg length	LEG
Girths	
Shoulder	SHG
Skinfold corrected chest	CCHG
Gluteal	GLG
Skinfold corrected arm	CAGR
Forearm	FAG
Wrist	WRG
Skinfold corrected thigh	CTHG
Knee	KNG
Calf	CAG
Ankle	ANG
Breadths and Depths	
Chest depth (AP)	APCH
Biacromial	BIAC
Transverse.chest	TRCH
Biiliocristal	BIIL
Biepicondylar humerus	HUM
Biepicondylar femur	FEM
Lengths	
Upper arm	UA
Forearm	FA
Hand	HA
Calf	TIHT
Foot	FOOT



stanine σ	WT	STAT	STHT	LEG	SHG	OCHG	GLG	CAGR	FAG	WRG	CTHG	KNG	CAG	ANG	APCH	BIAC	TRCH	BIIL	HUM	FEM	UA	FA	HA	TIHT	FOOT
9																									
1.75	29.60	131.70	71.29	60.80	75.63	60.79	65.44	16.61	19.18	13.46	34.08	28.07	25.91	17.59	14.74	29.17	20.85	21.38			24.80	20.53	16.25	29.20	21.98
8																									
1.25	27.96	128.84	69.91	59.22	74.28	59.48	64.08	15.96	18.67	13.16	32.82	27.41	25.24	17.16	14.37	28.60	20.35	20.80			23.91	19.97	15.84	28.39	21.46
7																									
0.75	28.33	125.99	68.52	57.63	72.93	58.18	62.71	15.30	18.16	12.85	31.57	26.76	24.57	16.72	14.01	28.03	19.85	20.22			23.03	19.40	15.03	27.59	20.95
6																									
0.25	24.69	123.13	87.14	56.05	71.58	56.87	61.35	14.65	17.85	12.55	30.32	28.10	23.90	16.29	13.64	27.46	19.35	19.64			22.15	18.83	14.42	26.78	20.43
5																									
-0.25	23.05	120.28	65.76	54.46	70.23	55.56	59.99	13.99	17.14	12.24	29.06	25.44	23.23	15.85	13.28	26.90	18.85	19.06			21.27	18.27	13.80	25.98	19.91
4																									
-0.75	21.42	117.42	64.38	52.87	68.88	54.25	58.62	13.34	16.63	11.94	27.81	24.76	22.56	15.41	12.91	26.33	18.35	18.48			20.39	17.70	13.19	25.17	19.39
3																									
-1.25	19.78	114.56	62.99	51.29	67.54	52.95	57.26	12.68	16.12	11.63	26.55	24.13	21.89	14.98	12.54	25.76	17.85	17.90			19.50	17.13	12.58	24.36	18.88
2																									
-1.75	16.14	111.71	61.61	49.70	66.19	51.64	55.69	12.03	15.61	11.33	25.30	23.47	21.22	14.54	12.18	25.19	17.35	17.32			18.62	16.57	11.97	23.56	18.36
1																									

age	WT	STAT	SITHT	LEG	SHG	OCHG	GLG	CAGR	FAG	WRG	CTHG	KNG	CAG	ANG	APCH	BIAC	TRCH	BIIL	HUM	FEM	UA	FA	HA	TIHT	FOOT
7			lengths						girths								breadths						segmental lengths		
mean	23.87	121.70	66.45	55.25	70.91	56.22	60.67	14.32	17.40	12.40	29.69	25.77	23.57	16.07	13.46	27.18	19.10	19.35			21.71	18.55	14.11	26.38	20.17
SD	3.27	5.71	2.77	3.17	2.70	2.61	2.73	1.31	1.02	0.61	2.51	1.32	1.34	0.87	0.73	1.14	1.00	1.16			1.76	1.13	1.22	1.61	1.03

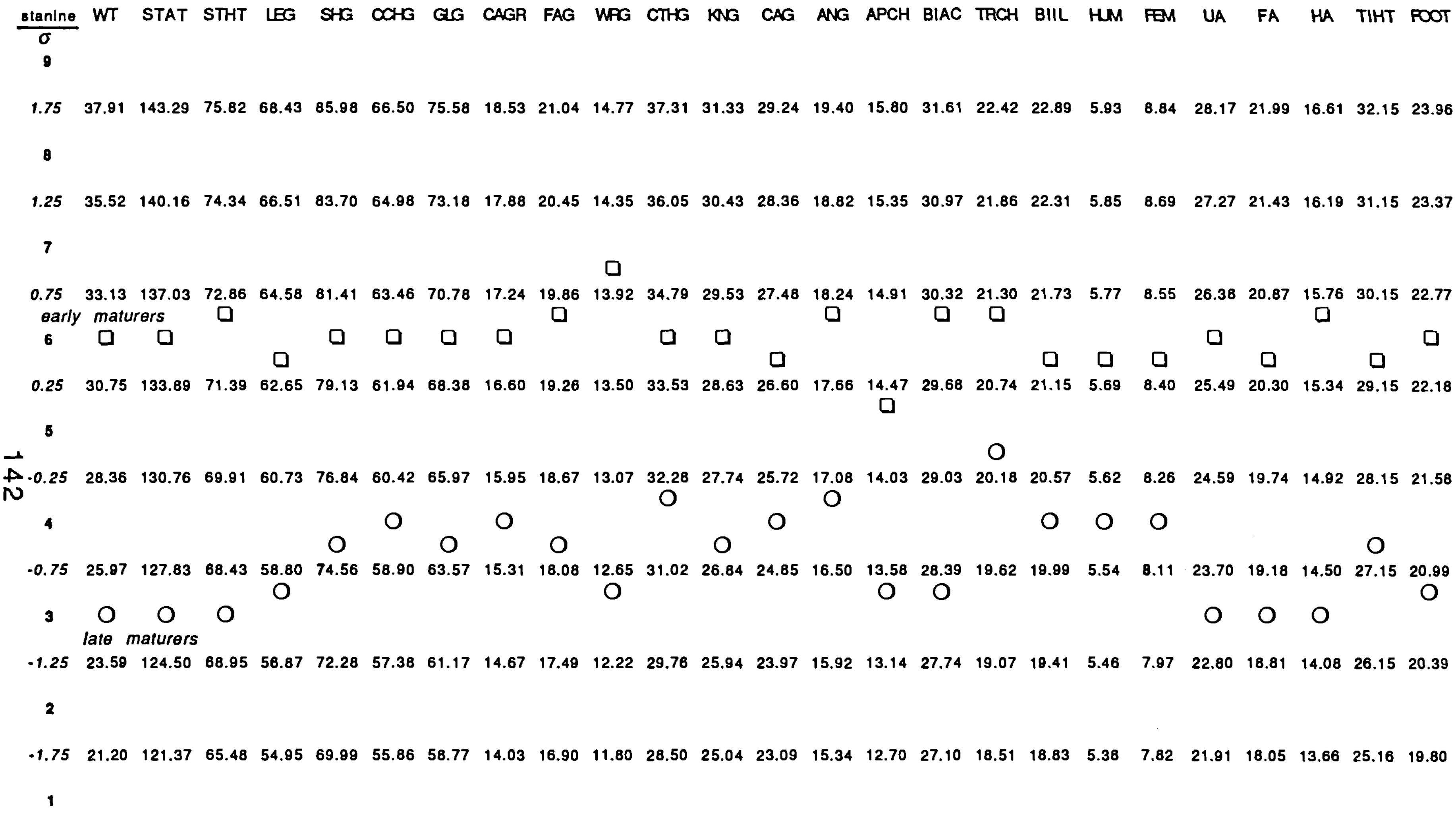
Figure 9.1 Anthropometric maturity chart for chronological age 6.5 to 7.499



stanine σ	WT	STAT	STHT	LEG	SHG	CCHG	GLG	CAGR	FAG	WRG	CTHG	KNG	CAG	ANG	APCH	BIAC	TRCH	BIIL	HUM	FEM	UA	FA	HA	TIHT	FOOT
9																									
1.75	33.96	137.56	73.83	64.89	80.75	63.48	71.31	17.91	19.94	13.94	35.32	29.60	27.74	18.70	15.27	30.47	21.70	22.30			26.37	21.42	15.98	30.57	23.21
8																									
1.25	31.79	134.51	72.28	63.05	78.85	62.09	69.28	17.25	19.40	13.59	34.21	28.82	26.95	18.13	14.89	29.78	21.14	21.71			25.56	20.84	15.53	29.68	22.64
7																									
0.75	29.62	131.46	70.74	61.21	76.95	60.70	67.25	16.59	18.87	13.25	33.10	28.05	26.16	17.55	14.51	29.08	20.58	21.12			24.76	20.25	15.08	28.80	22.06
6																									
0.25	27.44	128.40	69.19	59.38	75.05	59.31	65.21	15.93	18.33	12.91	32.00	27.27	25.37	16.97	14.12	28.39	20.02	20.53			23.95	19.66	14.63	27.91	21.48
5																									
-0.25	25.27	125.35	67.64	57.54	73.15	57.92	63.18	15.28	17.80	12.57	30.89	26.49	24.58	16.40	13.74	27.70	19.46	19.94			23.14	19.07	14.18	27.03	20.91
4																									
-0.75	23.10	122.30	66.09	55.70	71.25	56.53	61.14	14.62	17.26	12.23	29.78	25.71	23.79	15.82	13.36	27.01	18.90	19.35			22.34	18.48	13.73	26.14	20.33
3																									
-1.25	20.93	119.24	64.54	53.87	69.36	55.14	59.11	13.96	16.72	11.89	28.67	24.93	22.99	15.24	12.98	26.31	18.34	18.76			21.53	17.89	13.28	25.26	19.75
2																									
-1.75	18.75	116.19	63.00	52.03	67.46	53.75	57.08	13.30	16.19	11.54	27.56	24.16	22.20	14.66	12.59	25.62	17.78	18.17			20.73	17.30	12.83	24.38	19.17
1																									

age 8	WT	STAT	SITHT	LEG	SHG	CCHG	GLG	CAGR	FAG	WRG	CTHG	KNG	CAG	ANG	APCH	BIAC	TRCH	BIIL	HUM	FEM	UA	FA	HA	TIHT	FOOT
		lengths			girths										breadths						segmental lengths				
mean	26.36	126.88	68.41	58.46	74.10	58.62	64.20	15.60	18.06	12.74	31.44	26.88	24.97	16.68	13.93	28.05	19.74	20.23			23.55	19.36	14.41	27.47	21.19
SD	4.35	6.11	3.10	3.67	3.80	2.78	4.07	1.32	1.07	0.68	2.22	1.56	1.58	1.15	0.77	1.39	1.12	1.18			1.61	1.18	0.90	1.77	1.15

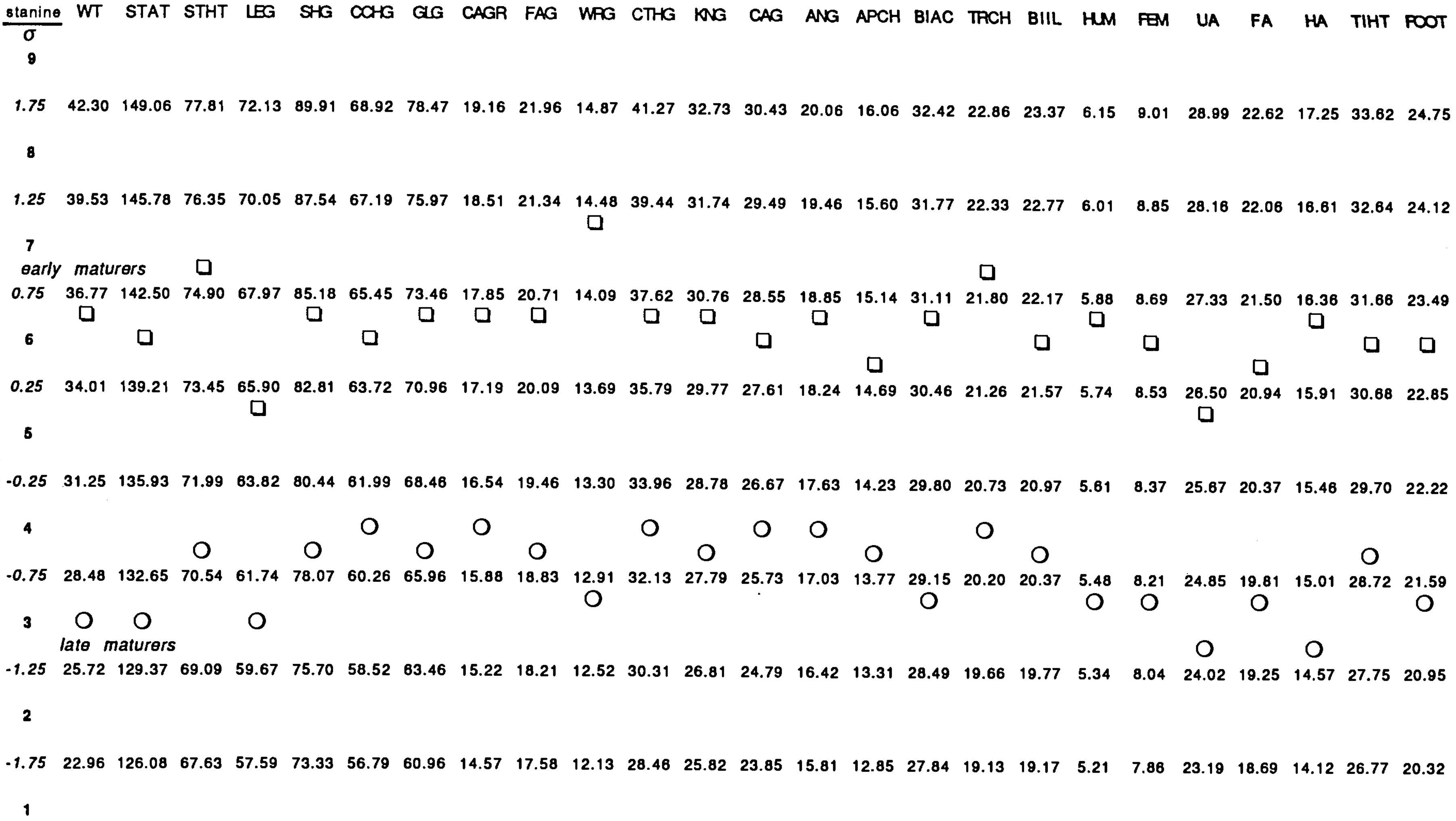
Figure 9.2 Anthropometric maturity chart for chronological age 7.5 to 8.499



stanine / σ	WT	STAT	STHT	LEG	SHG	CCHG	GLG	CAGR	FAG	WRG	CTHG	KNG	CAG	ANG	APCH	BIAC	TRCH	BIIL	HUM	FEM	UA	FA	HA	TIHT	FOOT
9																									
1.75	37.91	143.29	75.82	68.43	85.98	66.50	75.58	18.53	21.04	14.77	37.31	31.33	29.24	19.40	15.80	31.61	22.42	22.89	5.93	8.84	28.17	21.99	16.61	32.15	23.96
8																									
1.25	35.52	140.16	74.34	66.51	83.70	64.98	73.18	17.88	20.45	14.35	36.05	30.43	28.36	18.82	15.35	30.97	21.86	22.31	5.85	8.69	27.27	21.43	16.19	31.15	23.37
7																									
0.75	33.13	137.03	72.86	64.58	81.41	63.46	70.78	17.24	19.86	13.92	34.79	29.53	27.48	18.24	14.91	30.32	21.30	21.73	5.77	8.55	26.38	20.87	15.76	30.15	22.77
6																									
0.25	30.75	133.89	71.39	62.65	79.13	61.94	68.38	16.60	19.26	13.50	33.53	28.63	26.60	17.66	14.47	29.68	20.74	21.15	5.69	8.40	25.49	20.30	15.34	29.15	22.18
5																									
-0.25	28.36	130.76	69.91	60.73	76.84	60.42	65.97	15.95	18.67	13.07	32.28	27.74	25.72	17.08	14.03	29.03	20.18	20.57	5.62	8.26	24.59	19.74	14.92	28.15	21.58
4																									
-0.75	25.97	127.83	68.43	58.80	74.56	58.90	63.57	15.31	18.08	12.65	31.02	26.84	24.85	16.50	13.58	28.39	19.62	19.99	5.54	8.11	23.70	19.18	14.50	27.15	20.99
3																									
-1.25	23.59	124.50	66.95	56.87	72.28	57.38	61.17	14.67	17.49	12.22	29.76	25.94	23.97	15.92	13.14	27.74	19.07	19.41	5.46	7.97	22.80	18.81	14.08	26.15	20.39
2																									
-1.75	21.20	121.37	65.48	54.95	69.99	55.86	58.77	14.03	16.90	11.80	28.50	25.04	23.09	15.34	12.70	27.10	18.51	18.83	5.38	7.82	21.91	18.05	13.66	25.16	19.80
1																									

age 9	WT	STAT	SITHT	LEG	SHG	CCHG	GLG	CAGR	FAG	WRG	CTHG	KNG	CAG	ANG	APCH	BIAC	TRCH	BIIL	HUM	FEM	UA	FA	HA	TIHT	FOOT
		lengths			girths										breadths						segmental lengths				
mean	29.55	132.33	70.65	61.69	77.99	61.18	67.18	16.28	18.97	13.29	32.91	28.19	26.16	17.37	14.25	29.36	20.46	20.86	5.66	8.33	25.04	20.02	15.13	28.65	21.88
SD	4.77	6.26	2.96	3.85	4.57	3.04	4.81	1.29	1.18	0.85	2.52	1.80	1.76	1.16	0.89	1.29	1.12	1.16	0.16	0.29	1.79	1.13	0.84	2.00	1.19

Figure 9.3 Anthropometric maturity chart for chronological age 8.5 to 9.499



stanine σ	WT	STAT	STHT	LEG	SHG	CCHG	GLG	CAGR	FAG	WRG	CTHG	KNG	CAG	ANG	APCH	BIAC	TRCH	BIIL	HUM	FEM	UA	FA	HA	TIHT	FOOT
9																									
1.75	42.30	149.06	77.81	72.13	89.91	68.92	78.47	19.16	21.96	14.87	41.27	32.73	30.43	20.06	16.06	32.42	22.86	23.37	6.15	9.01	28.99	22.62	17.25	33.62	24.75
8																									
1.25	39.53	145.78	76.35	70.05	87.54	67.19	75.97	18.51	21.34	14.48	39.44	31.74	29.49	19.46	15.60	31.77	22.33	22.77	6.01	8.85	28.16	22.06	16.61	32.64	24.12
7																									
early maturers																									
0.75	36.77	142.50	74.90	67.97	85.18	65.45	73.46	17.85	20.71	14.09	37.62	30.76	28.55	18.85	15.14	31.11	21.80	22.17	5.88	8.69	27.33	21.50	16.36	31.66	23.49
6																									
0.25	34.01	139.21	73.45	65.90	82.81	63.72	70.96	17.19	20.09	13.69	35.79	29.77	27.61	18.24	14.69	30.46	21.26	21.57	5.74	8.53	26.50	20.94	15.91	30.68	22.85
5																									
-0.25	31.25	135.93	71.99	63.82	80.44	61.99	68.46	16.54	19.46	13.30	33.96	28.78	26.67	17.63	14.23	29.80	20.73	20.97	5.61	8.37	25.67	20.37	15.46	29.70	22.22
4																									
-0.75	28.48	132.65	70.54	61.74	78.07	60.26	65.96	15.88	18.83	12.91	32.13	27.79	25.73	17.03	13.77	29.15	20.20	20.37	5.48	8.21	24.85	19.81	15.01	28.72	21.59
3																									
late maturers																									
-1.25	25.72	129.37	69.09	59.67	75.70	58.52	63.46	15.22	18.21	12.52	30.31	26.81	24.79	16.42	13.31	28.49	19.66	19.77	5.34	8.04	24.02	19.25	14.57	27.75	20.95
2																									
-1.75	22.96	126.08	67.63	57.59	73.33	56.79	60.96	14.57	17.58	12.13	28.46	25.82	23.85	15.81	12.85	27.84	19.13	19.17	5.21	7.86	23.19	18.69	14.12	26.77	20.32
1																									

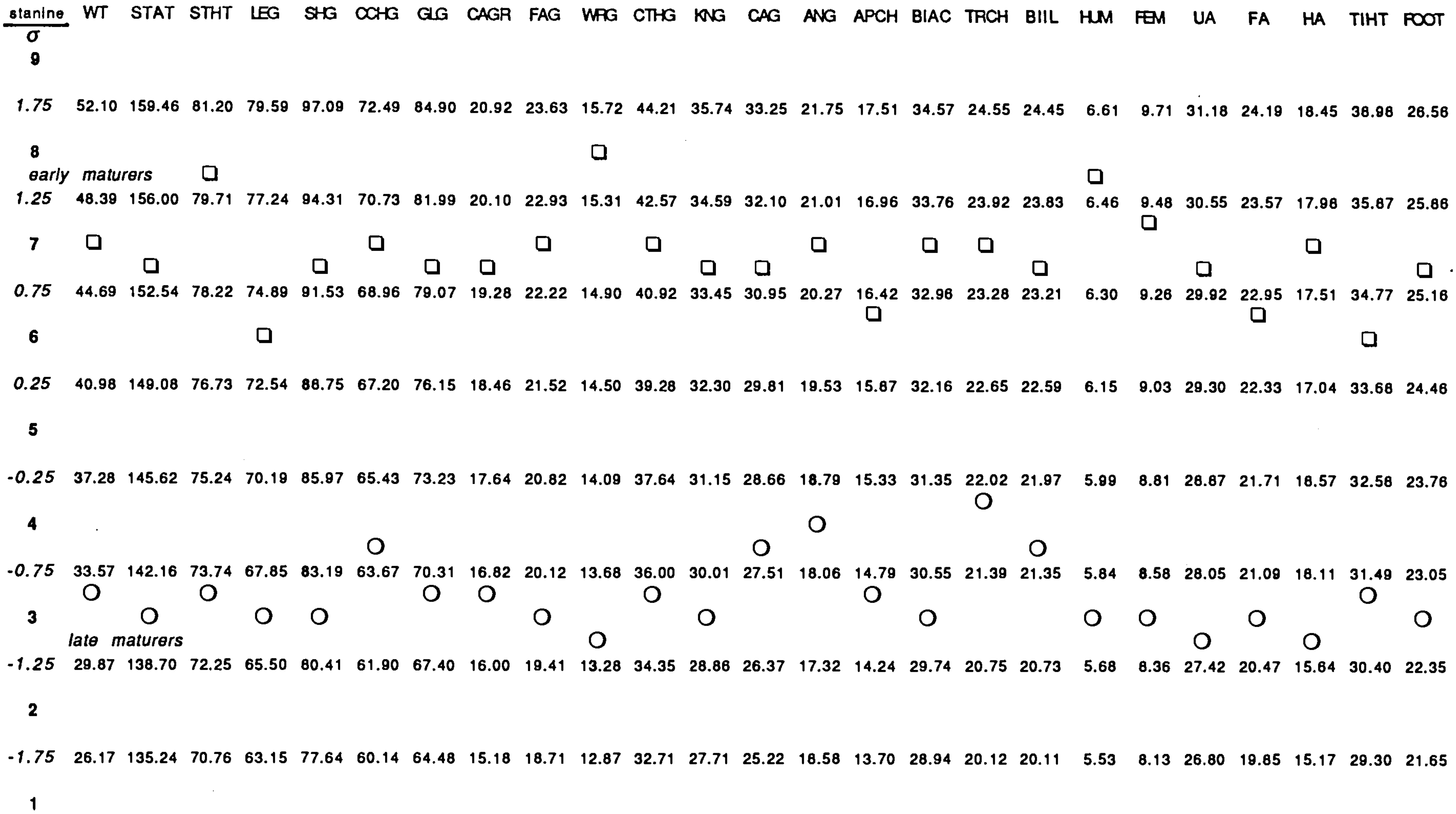
age 10	WT	STAT	SITHT	LEG	SHG	CCHG	GLG	CAGR	FAG	WRG	CTHG	KNG	CAG	ANG	APCH	BIAC	TRCH	BIIL	HUM	FEM	UA	FA	HA	TIHT	FOOT
		lengths			girths										breadths						segmental lengths				
mean	32.63	137.57	72.72	64.86	81.62	62.86	69.71	16.87	19.77	13.50	34.88	29.28	27.14	17.94	14.46	30.13	21.00	21.27	5.68	8.45	26.09	20.65	15.69	30.19	22.54
SD	5.53	6.57	2.91	4.15	4.74	3.47	5.00	1.31	1.25	0.78	3.65	1.98	1.88	1.22	0.92	1.31	1.07	1.20	0.27	0.32	1.66	1.12	0.90	1.96	1.27

Figure 9.4 Anthropometric maturity chart for chronological age 9.5 to 10.499

stanine σ	WT	STAT	STHT	LEG	SHG	CCHG	GLG	CAGR	FAG	WRG	CTHG	KNG	CAG	ANG	APCH	BIAC	TRCH	BIIL	HUM	FEM	UA	FA	HA	TIHT	FOOT
9																									
1.75	46.78	154.58	79.83	75.56	93.34	70.06	81.68	20.14	22.75	15.13	41.74	34.35	31.50	20.88	16.76	33.50	23.53	23.89	6.40	9.49	30.42	23.44	17.91	35.34	25.75
8																									
1.25	43.54	151.15	78.32	73.41	90.80	68.32	79.02	19.39	22.09	14.75	40.31	33.23	30.52	20.19	16.24	32.78	22.95	23.28	6.25	9.26	29.64	22.83	17.44	34.29	25.06
	early maturers																								
7			☐		☐				☐					☐					☐						
	☐						☐	☐		☐	☐		☐												
0.75	40.30	147.72	78.81	71.25	88.27	66.58	76.35	18.65	21.44	14.36	38.89	32.11	29.53	19.51	15.71	32.06	22.36	22.68	6.11	9.03	28.87	22.23	16.96	33.23	24.37
						☐						☐				☐		☐		☐			☐		☐
6		☐													☐		☐								
				☐																	☐	☐		☐	
0.25	37.07	144.29	75.30	69.10	85.73	64.84	73.69	17.90	20.78	13.97	37.46	30.98	28.55	18.83	15.19	31.35	21.78	22.07	5.96	8.80	28.09	21.62	16.48	32.18	23.69
5																									
-0.25	33.83	140.88	73.79	66.94	83.19	63.10	71.02	17.16	20.13	13.58	36.03	29.86	27.57	16.15	14.67	30.63	21.20	21.48	5.81	8.57	27.32	21.01	16.01	31.12	23.00
4						○		○			○						○								
					○		○					○	○	○	○			○							
-0.75	30.59	137.43	72.28	64.79	80.65	61.36	68.36	16.41	19.46	13.19	34.60	28.74	26.59	17.46	14.14	29.91	20.62	20.86	5.67	6.35	26.54	20.40	15.53	30.07	22.32
	○		○						○										○	○				○	○
3		○		○						○						○						○	○		
	late maturers																								
																					○				
-1.25	27.35	134.00	70.77	62.63	78.12	59.62	85.70	15.67	18.62	12.80	33.17	27.61	25.60	16.76	13.62	29.20	20.03	20.25	5.52	8.12	25.76	19.79	15.05	29.01	21.63
2																									
-1.75	24.11	130.57	69.26	60.48	75.58	57.87	63.03	14.92	18.17	12.42	31.75	26.49	24.62	16.10	13.10	28.48	19.45	19.65	5.37	7.89	24.99	19.19	14.57	27.96	20.94
1																									

age	WT	STAT	SITHT	LEG	SHG	CCHG	GLG	CAGR	FAG	WRG	CTHG	KNG	CAG	ANG	APCH	BIAC	TRCH	BIIL	HUM	FEM	UA	FA	HA	TIHT	FOOT
11		lengths			girths										breadths						segmental lengths				
mean	35.45	142.58	74.55	68.02	84.46	63.97	72.36	17.53	20.46	13.78	36.74	30.42	28.06	18.49	14.93	30.99	21.49	21.77	5.89	8.69	27.70	21.31	16.24	31.65	23.34
SD	6.46	6.86	3.02	4.31	5.08	3.46	5.33	1.49	1.31	0.76	2.86	2.25	1.97	1.37	1.05	1.43	1.17	1.21	0.29	0.46	1.55	1.22	0.95	2.11	1.37

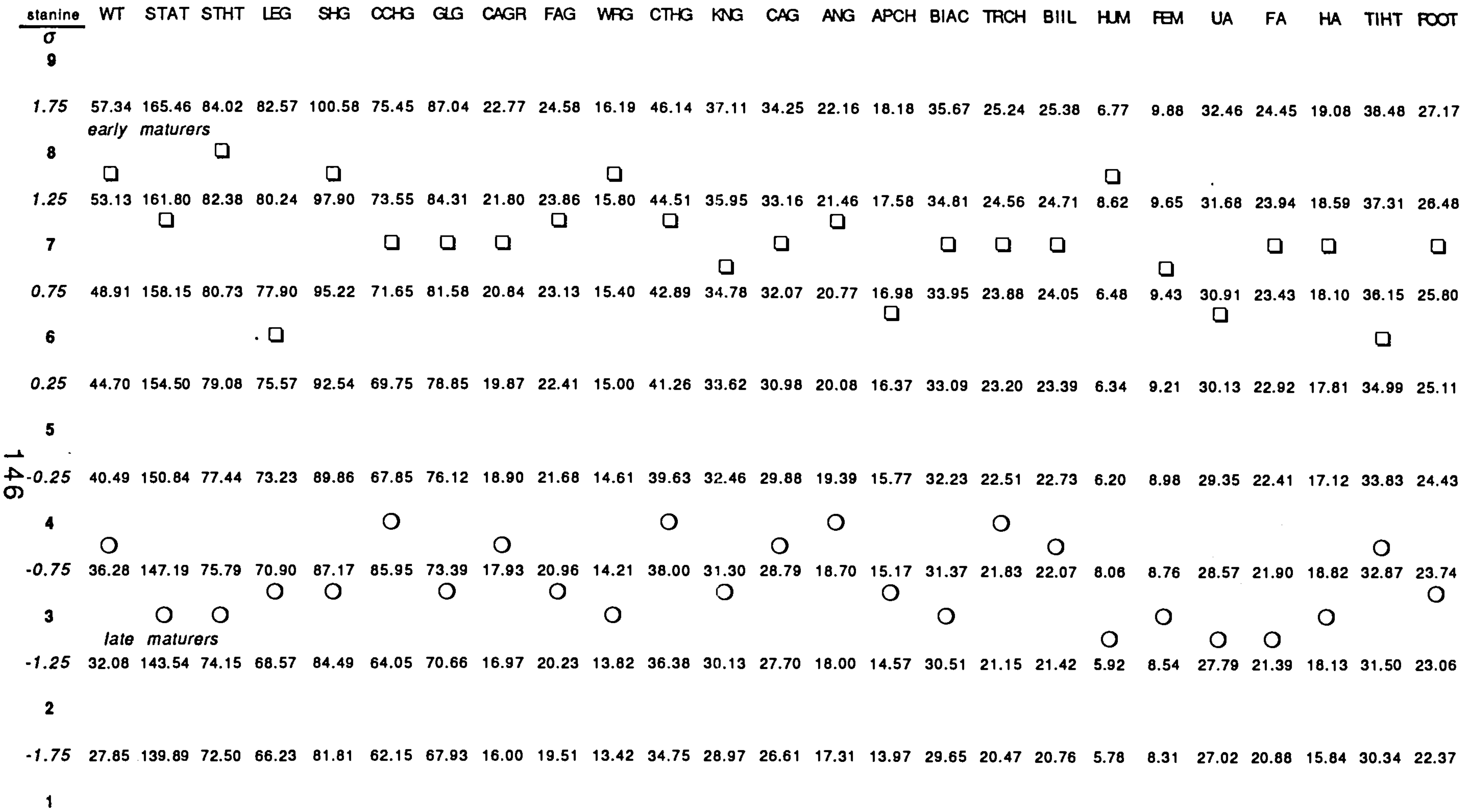
Figure 9.5 Anthropometric maturity chart for chronological age 10.5 to 11.499



stanine σ	WT	STAT	STHT	LEG	SHG	CCHG	GLG	CAGR	FAG	WRG	CTHG	KNG	CAG	ANG	APCH	BIAC	TRCH	BIIL	HUM	FEM	UA	FA	HA	TIHT	FOOT
9																									
1.75	52.10	159.46	81.20	79.59	97.09	72.49	84.90	20.92	23.63	15.72	44.21	35.74	33.25	21.75	17.51	34.57	24.55	24.45	6.61	9.71	31.18	24.19	18.45	36.98	26.56
8																									
early maturers																									
1.25	48.39	156.00	79.71	77.24	94.31	70.73	81.99	20.10	22.93	15.31	42.57	34.59	32.10	21.01	16.96	33.76	23.92	23.83	6.46	9.48	30.55	23.57	17.98	35.87	25.86
7																									
0.75	44.69	152.54	78.22	74.89	91.53	68.96	79.07	19.28	22.22	14.90	40.92	33.45	30.95	20.27	16.42	32.96	23.28	23.21	6.30	9.26	29.92	22.95	17.51	34.77	25.16
6																									
0.25	40.98	149.08	76.73	72.54	86.75	67.20	76.15	18.46	21.52	14.50	39.28	32.30	29.81	19.53	15.87	32.16	22.65	22.59	6.15	9.03	29.30	22.33	17.04	33.68	24.46
5																									
-0.25	37.28	145.62	75.24	70.19	85.97	65.43	73.23	17.64	20.82	14.09	37.64	31.15	28.66	18.79	15.33	31.35	22.02	21.97	5.99	8.81	28.67	21.71	16.57	32.58	23.76
4																									
-0.75	33.57	142.16	73.74	67.85	83.19	63.67	70.31	16.82	20.12	13.68	36.00	30.01	27.51	18.06	14.79	30.55	21.39	21.35	5.84	8.58	28.05	21.09	16.11	31.49	23.05
3																									
late maturers																									
-1.25	29.87	138.70	72.25	65.50	80.41	61.90	67.40	16.00	19.41	13.28	34.35	28.86	26.37	17.32	14.24	29.74	20.75	20.73	5.68	8.36	27.42	20.47	15.64	30.40	22.35
2																									
-1.75	26.17	135.24	70.76	63.15	77.64	60.14	64.48	15.18	18.71	12.87	32.71	27.71	25.22	18.58	13.70	28.94	20.12	20.11	5.53	8.13	26.80	19.85	15.17	29.30	21.65
1																									

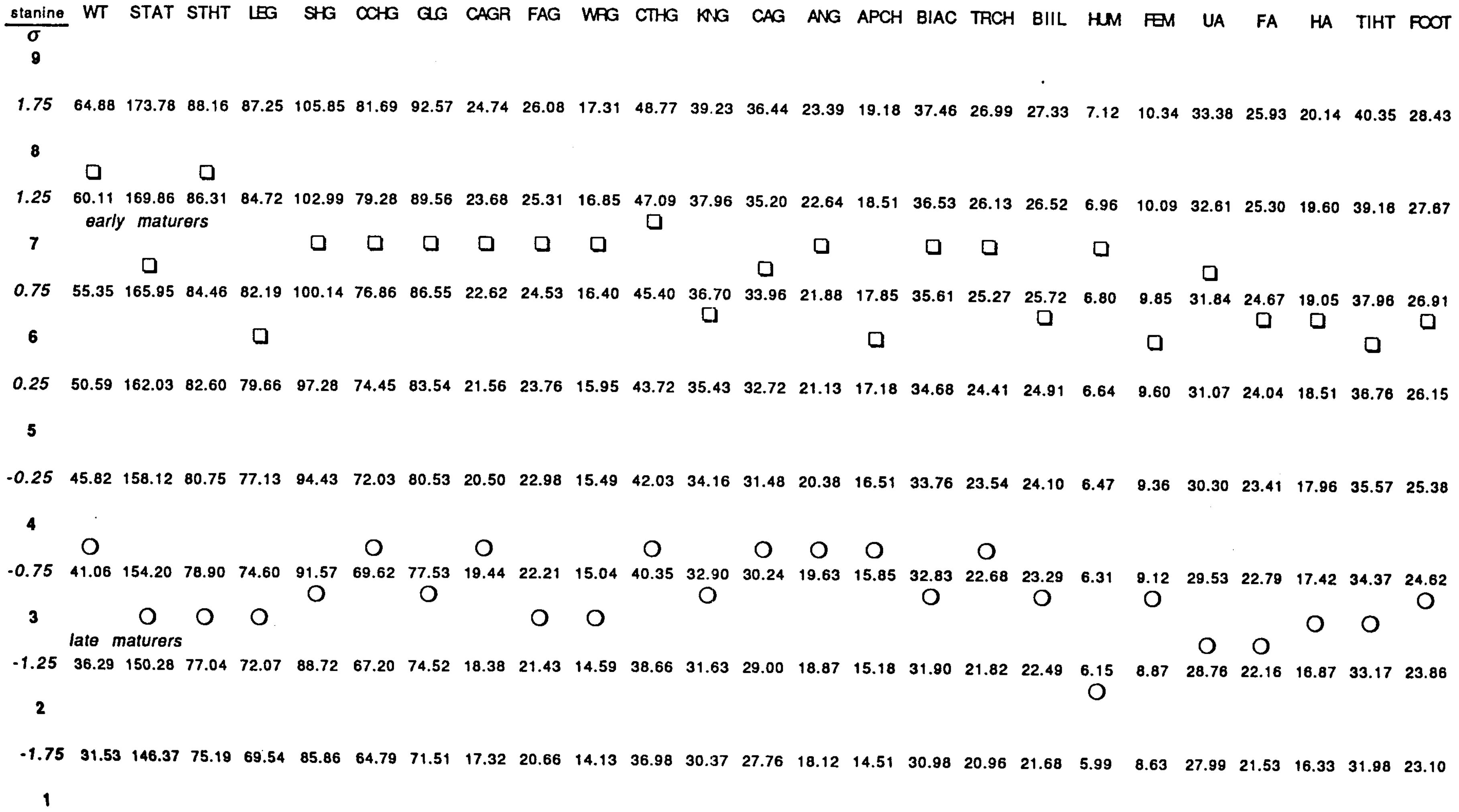
age 12	WT	STAT	SITHT	LEG	SHG	CCHG	GLG	CAGR	FAG	WRG	CTHG	KNG	CAG	ANG	APCH	BIAC	TRCH	BIIL	HUM	FEM	UA	FA	HA	TIHT	FOOT
		lengths			girths										breadths						segmental lengths				
mean	39.13	147.35	75.98	71.37	87.36	66.31	74.69	18.05	21.17	14.29	38.46	31.73	29.23	19.16	15.60	31.75	22.34	22.28	6.07	8.92	28.99	22.02	16.81	33.13	24.11
SD	7.41	6.92	2.98	4.70	5.56	3.53	5.84	1.64	1.41	0.81	3.29	2.29	2.29	1.48	1.09	1.61	1.27	1.24	0.31	0.45	1.25	1.24	0.94	2.19	1.40

Figure 9.6 Anthropometric maturity chart for chronological age 11.5 to 12.499



age	WT	STAT	SITHT	LEG	SHG	CCHG	GLG	CAGR	FAG	WRG	CTHG	KNG	CAG	ANG	APCH	BIAC	TRCH	BIIL	HUM	FEM	UA	FA	HA	TIHT	FOOT
13		lengths			girths										breadths						segmental lengths				
mean	42.60	152.67	78.26	74.40	91.20	68.80	77.49	19.39	22.04	14.81	40.45	33.04	30.43	19.73	16.07	32.66	22.86	23.06	6.27	9.10	29.74	22.67	17.36	34.41	24.77
SD	8.43	7.31	3.29	4.67	5.36	3.80	5.46	1.94	1.45	0.79	3.26	2.33	2.19	1.38	1.20	1.72	1.36	1.32	0.28	0.45	1.56	1.02	0.98	2.32	1.37

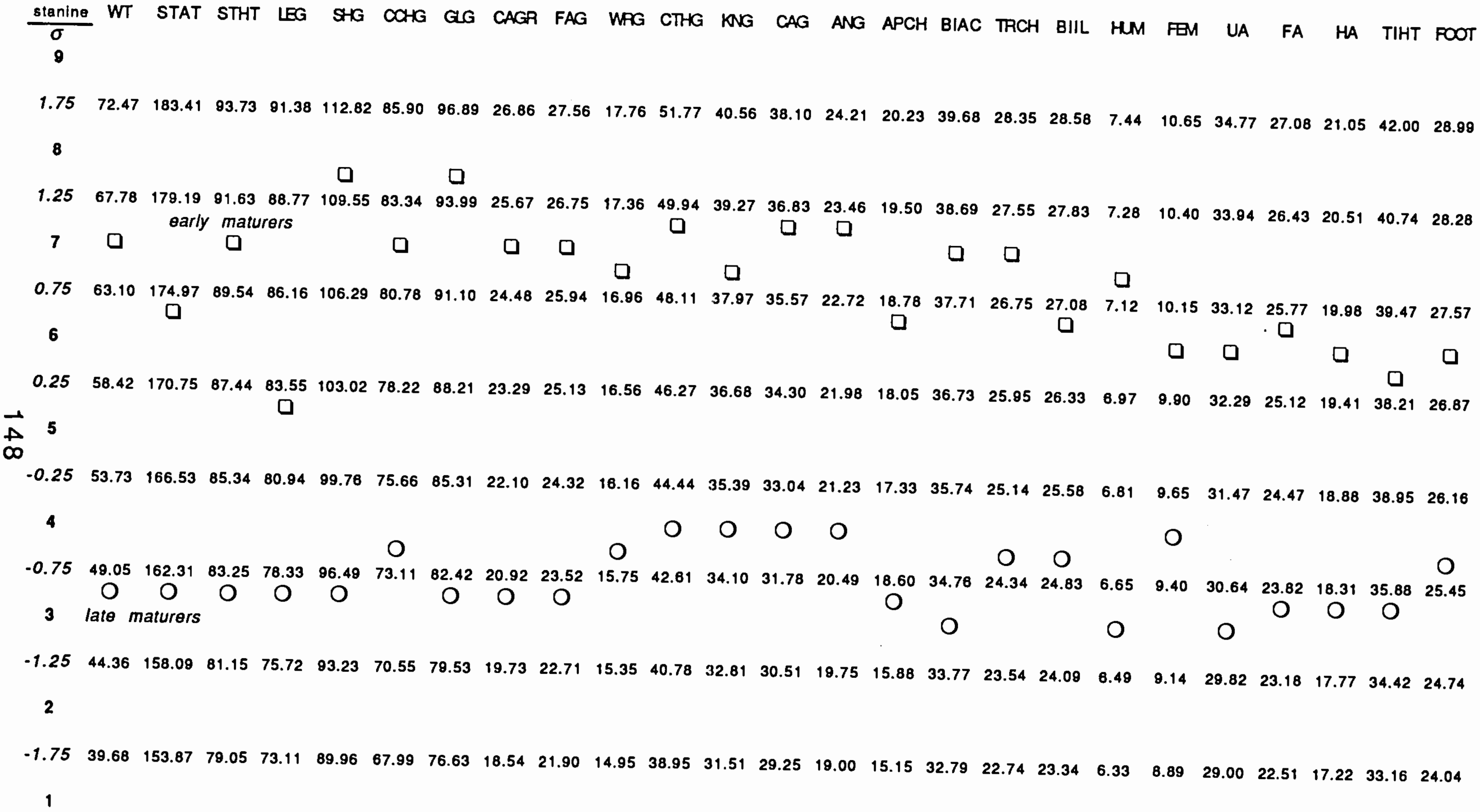
Figure 9.7 Anthropometric maturity chart for chronological age 12.5 to 13.499



stanine σ	WT	STAT	STHT	LEG	SHG	OCHG	GLG	CAGR	FAG	WRG	CTHG	KNG	CAG	ANG	APCH	BIAC	TRCH	BIIL	HUM	FEM	UA	FA	HA	TIHT	FOOT
9																									
1.75	64.88	173.78	88.16	87.25	105.85	81.69	92.57	24.74	26.08	17.31	48.77	39.23	36.44	23.39	19.18	37.46	26.99	27.33	7.12	10.34	33.38	25.93	20.14	40.35	28.43
8																									
1.25	60.11	169.86	86.31	84.72	102.99	79.28	89.56	23.68	25.31	16.85	47.09	37.96	35.20	22.64	18.51	36.53	26.13	26.52	6.96	10.09	32.61	25.30	19.60	39.16	27.67
7																									
0.75	55.35	165.95	84.46	82.19	100.14	76.86	86.55	22.62	24.53	16.40	45.40	36.70	33.96	21.88	17.85	35.61	25.27	25.72	6.80	9.85	31.84	24.67	19.05	37.96	26.91
6																									
0.25	50.59	162.03	82.60	79.66	97.28	74.45	83.54	21.56	23.76	15.95	43.72	35.43	32.72	21.13	17.18	34.68	24.41	24.91	6.64	9.60	31.07	24.04	18.51	36.76	26.15
5																									
-0.25	45.82	158.12	80.75	77.13	94.43	72.03	80.53	20.50	22.98	15.49	42.03	34.16	31.48	20.38	16.51	33.76	23.54	24.10	6.47	9.36	30.30	23.41	17.96	35.57	25.38
4																									
-0.75	41.06	154.20	78.90	74.60	91.57	69.62	77.53	19.44	22.21	15.04	40.35	32.90	30.24	19.63	15.85	32.83	22.68	23.29	6.31	9.12	29.53	22.79	17.42	34.37	24.62
3																									
-1.25	36.29	150.28	77.04	72.07	88.72	67.20	74.52	18.38	21.43	14.59	38.66	31.63	29.00	18.87	15.18	31.90	21.82	22.49	6.15	8.87	28.76	22.16	16.87	33.17	23.86
2																									
-1.75	31.53	146.37	75.19	69.54	85.86	64.79	71.51	17.32	20.66	14.13	36.98	30.37	27.76	18.12	14.51	30.98	20.96	21.68	5.99	8.63	27.99	21.53	16.33	31.98	23.10
1																									

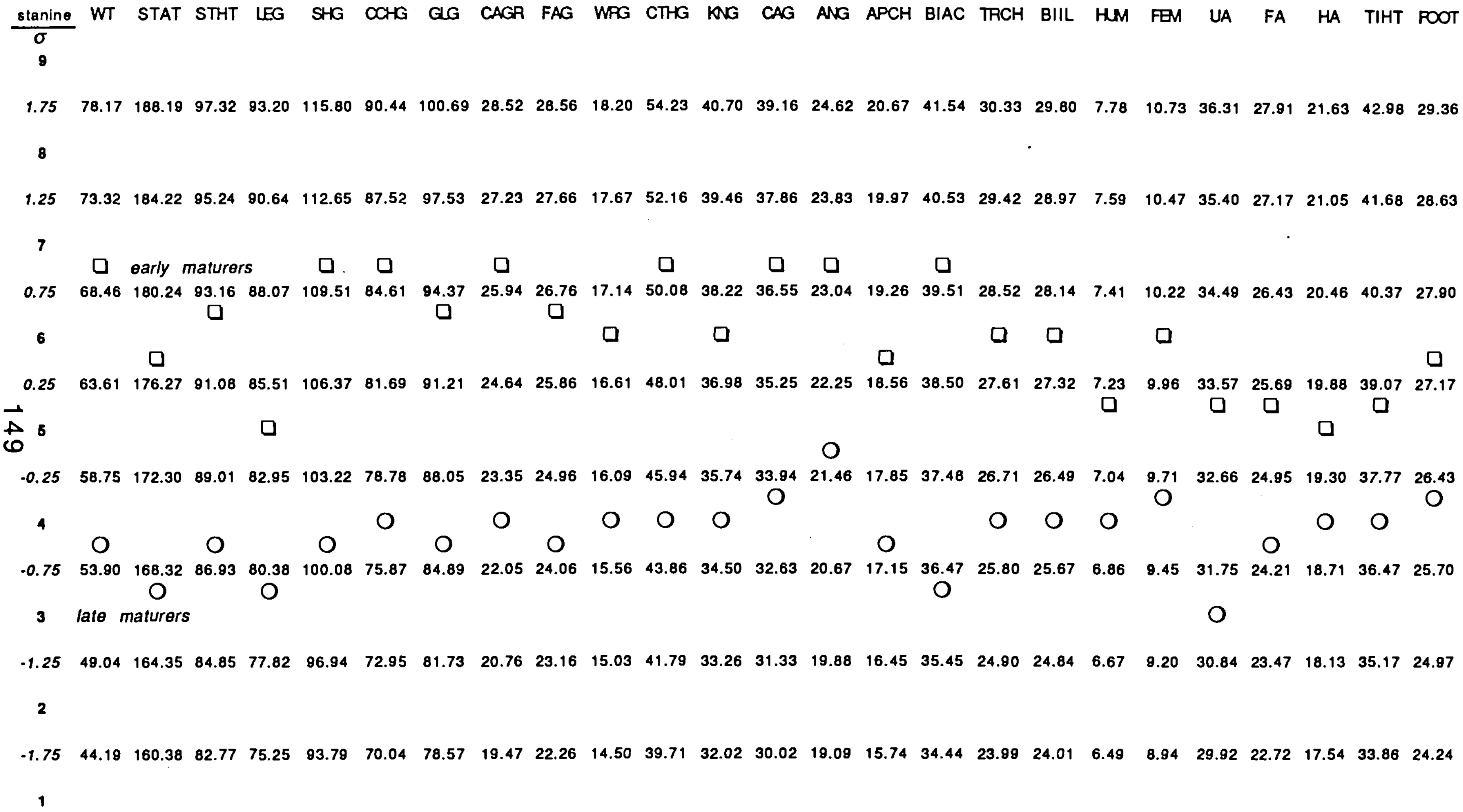
age	WT	STAT	STHT	LEG	SHG	OCHG	GLG	CAGR	FAG	WRG	CTHG	KNG	CAG	ANG	APCH	BIAC	TRCH	BIIL	HUM	FEM	UA	FA	HA	TIHT	FOOT
14		lengths			girths										breadths						segmental lengths				
mean	48.20	160.07	81.68	78.39	95.85	73.24	82.04	21.03	23.37	15.72	42.87	34.80	32.10	20.76	16.85	34.22	23.98	24.51	6.56	9.48	30.69	23.73	18.23	36.16	25.76
SD	9.53	7.83	3.71	5.06	5.71	4.83	6.02	2.12	1.55	0.91	3.37	2.53	2.48	1.51	1.33	1.85	1.73	1.62	0.32	0.49	1.54	1.26	1.09	2.39	1.52

Figure 9.8 Anthropometric maturity chart for chronological age 13.5 to 14.499



age 15	WT	STAT	SITHT	LEG	SHG	CCHG	GLG	CAGR	FAG	WRG	CTHG	KNG	CAG	ANG	APCH	BIAC	TRCH	BIIL	HUM	FEM	UA	FA	HA	TIHT	FOOT
		lengths			girths										breadths						segmental lengths				
mean	56.07	168.64	86.39	82.24	101.39	76.94	86.76	22.70	24.73	16.36	45.36	36.04	33.67	21.61	17.69	36.23	25.55	25.96	6.89	9.77	31.88	24.80	19.14	37.58	28.51
SD	9.37	8.44	4.19	5.22	6.53	5.12	5.79	2.38	1.62	0.80	3.66	2.58	2.53	1.49	1.45	1.97	1.60	1.50	0.32	0.50	1.65	1.31	1.10	2.53	1.42

Figure 9.9 Anthropometric maturity chart for chronological age 14.5 to 15.499



stanine σ	WT	STAT	STHT	LEG	SHG	CCHG	GLG	CAGR	FAG	WRG	CTHG	KNG	CAG	ANG	APCH	BIAC	TRCH	BIIL	HUM	FEM	UA	FA	HA	TIHT	FOOT
9																									
1.75	78.17	188.19	97.32	93.20	115.80	90.44	100.69	28.52	28.56	18.20	54.23	40.70	39.16	24.62	20.67	41.54	30.33	29.80	7.78	10.73	36.31	27.91	21.63	42.98	29.36
8																									
1.25	73.32	184.22	95.24	90.64	112.65	87.52	97.53	27.23	27.66	17.67	52.16	39.46	37.86	23.83	19.97	40.53	29.42	28.97	7.59	10.47	35.40	27.17	21.05	41.68	28.63
7																									
0.75	68.46	180.24	93.16	88.07	109.51	84.61	94.37	25.94	26.76	17.14	50.08	38.22	36.55	23.04	19.26	39.51	28.52	28.14	7.41	10.22	34.49	26.43	20.46	40.37	27.90
6																									
0.25	63.61	176.27	91.08	85.51	106.37	81.69	91.21	24.64	25.86	16.61	48.01	36.98	35.25	22.25	18.56	38.50	27.61	27.32	7.23	9.96	33.57	25.69	19.88	39.07	27.17
5																									
-0.25	58.75	172.30	89.01	82.95	103.22	78.78	88.05	23.35	24.96	16.09	45.94	35.74	33.94	21.46	17.85	37.48	26.71	26.49	7.04	9.71	32.66	24.95	19.30	37.77	26.43
4																									
-0.75	53.90	168.32	86.93	80.38	100.08	75.87	84.89	22.05	24.06	15.56	43.86	34.50	32.63	20.67	17.15	36.47	25.80	25.67	6.86	9.45	31.75	24.21	18.71	36.47	25.70
3																									
-1.25	49.04	164.35	84.85	77.82	96.94	72.95	81.73	20.76	23.16	15.03	41.79	33.26	31.33	19.88	16.45	35.45	24.90	24.84	6.67	9.20	30.84	23.47	18.13	35.17	24.97
2																									
-1.75	44.19	160.38	82.77	75.25	93.79	70.04	78.57	19.47	22.26	14.50	39.71	32.02	30.02	19.09	15.74	34.44	23.99	24.01	6.49	8.94	29.92	22.72	17.54	33.86	24.24
1																									

age	WT	STAT	SITHT	LEG	SHG	CCHG	GLG	CAGR	FAG	WRG	CTHG	KNG	CAG	ANG	APCH	BIAC	TRCH	BIIL	HUM	FEM	UA	FA	HA	TIHT	FOOT
16		lengths			girths										breadths						segmental lengths				
mean	61.18	174.28	90.05	84.23	104.80	80.24	89.63	23.99	25.41	16.35	46.97	36.36	34.59	21.86	18.21	37.99	27.16	26.91	7.13	9.84	33.12	25.32	19.59	38.42	26.80
SD	9.71	7.95	4.16	5.13	6.29	5.83	6.32	2.59	1.80	1.06	4.15	2.48	2.61	1.58	1.41	2.03	1.81	1.65	0.37	0.51	1.83	1.48	1.17	2.60	1.47

Figure 9.10 Anthropometric maturity chart for chronological age 15.5 to 16.5

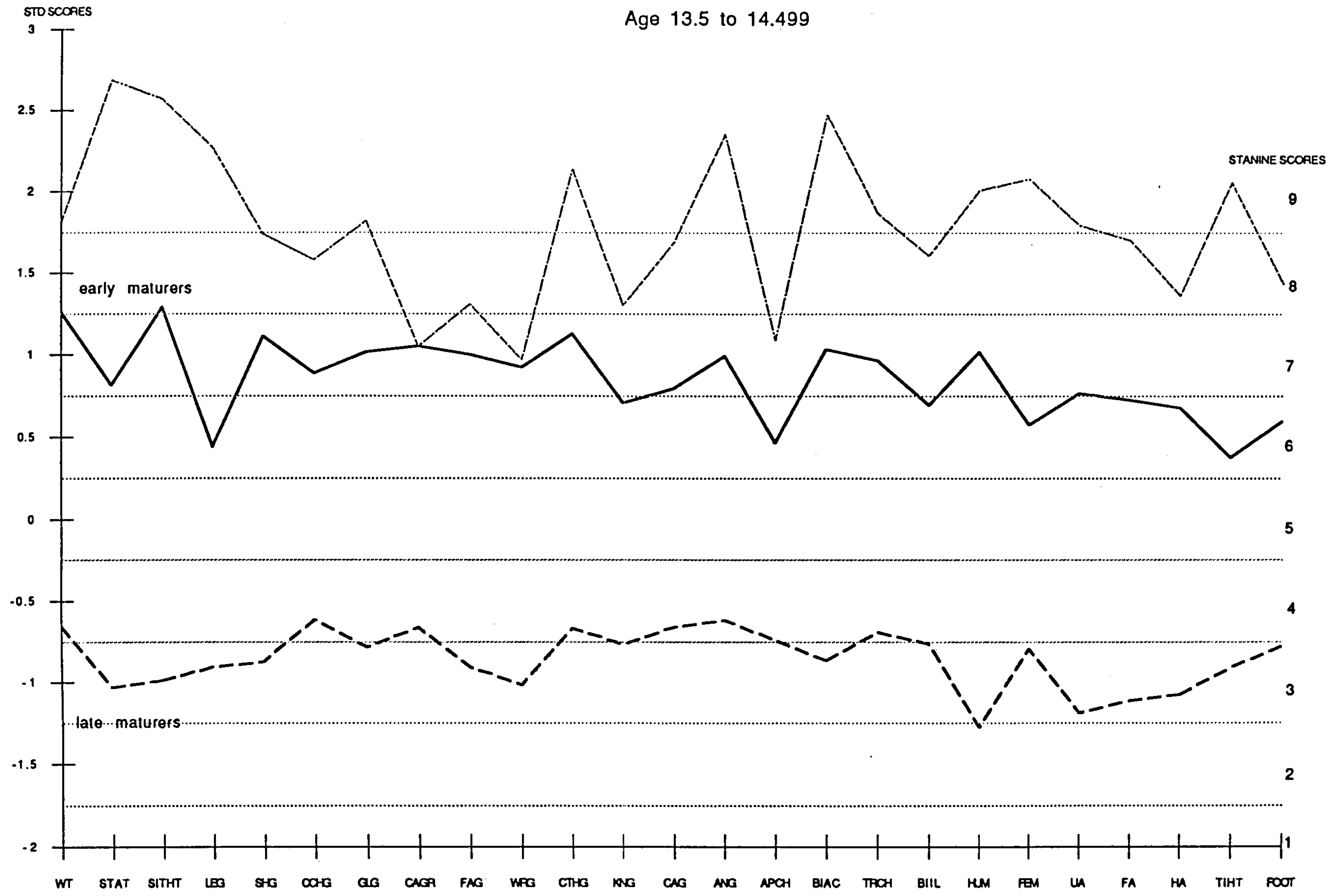


FIGURE 9.11 Early maturing boy (MI: 1.11) age 13.87, on chronological age 14 norms.

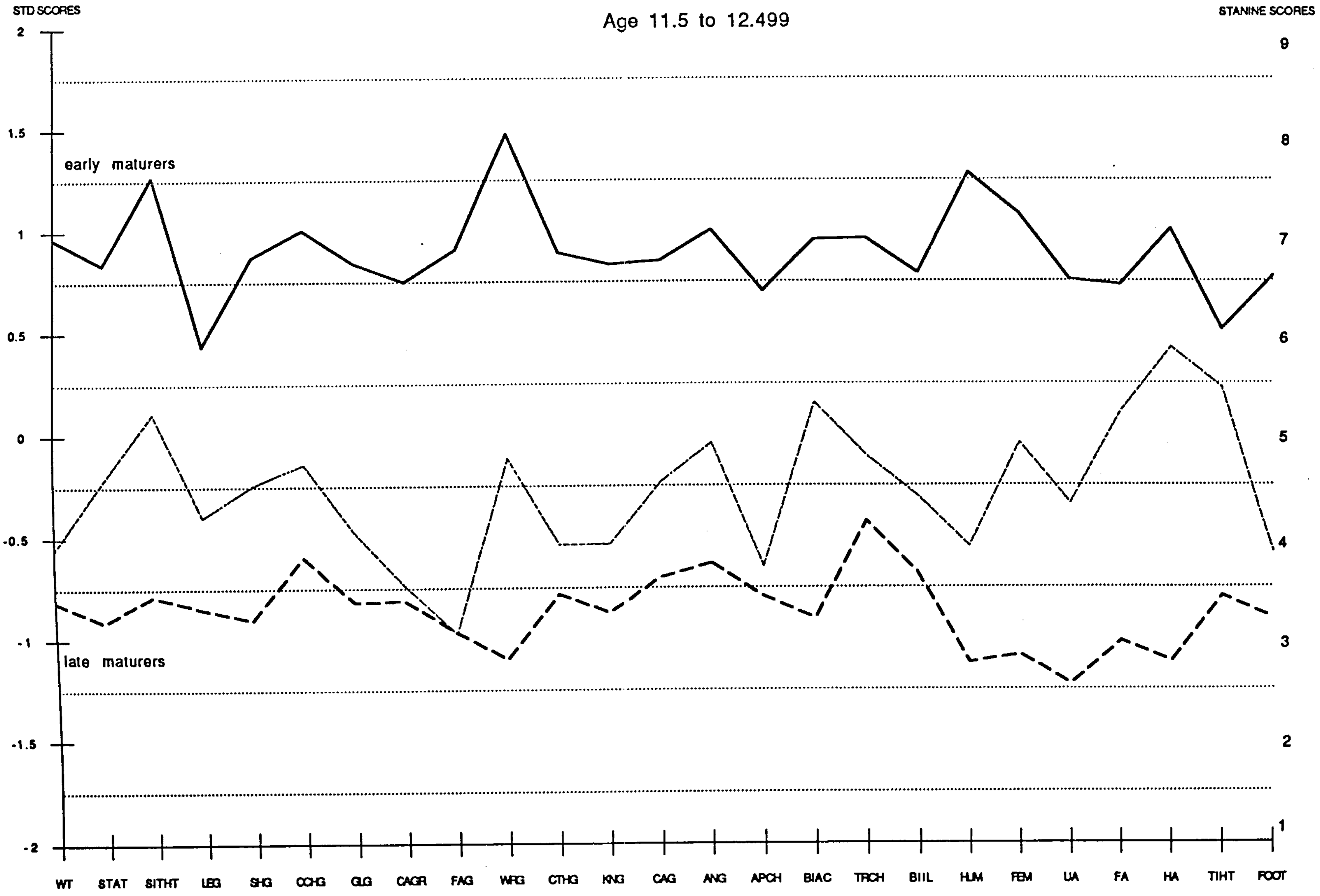


FIGURE 9.12 Average maturing boy (MI: 1.0) at age 11.72, on chronological age 12 norms.

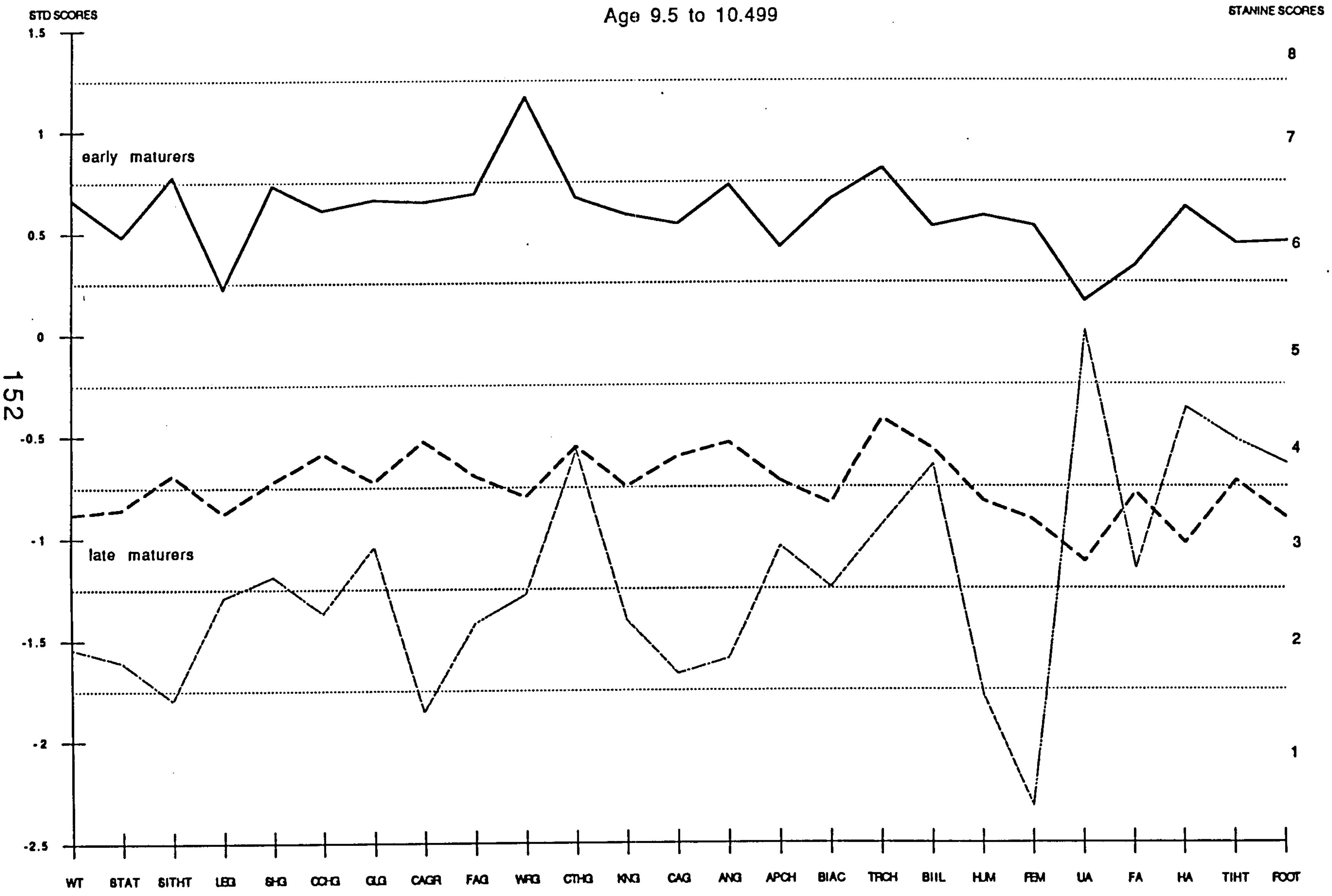


FIGURE 9.13 Late maturing boy (MI: 0.882) age 10.06, on chronological age 10 norms.

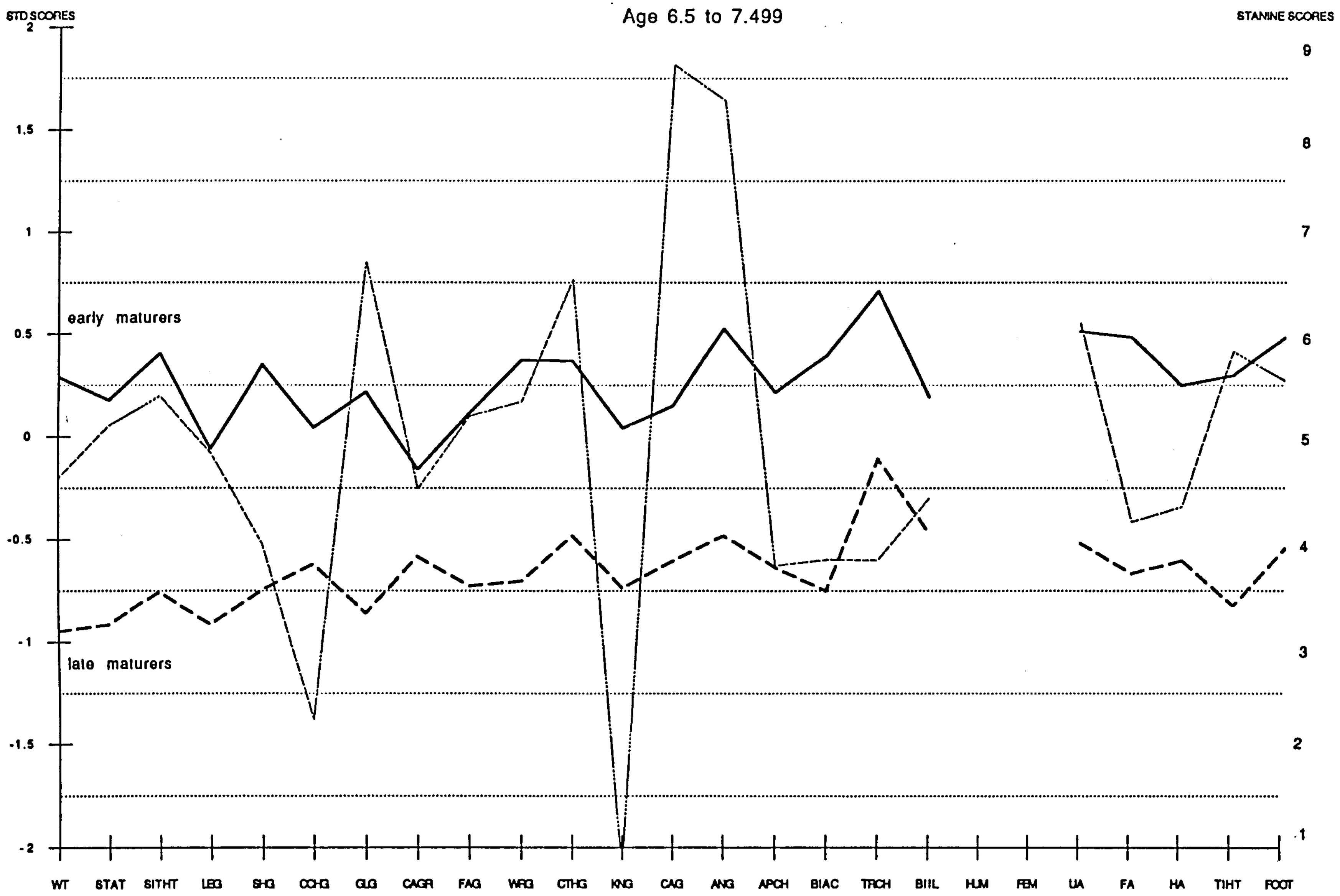


FIGURE 9.14 Average maturing boy (MI:1.03) age 7.016, on chronological age 7 norms.

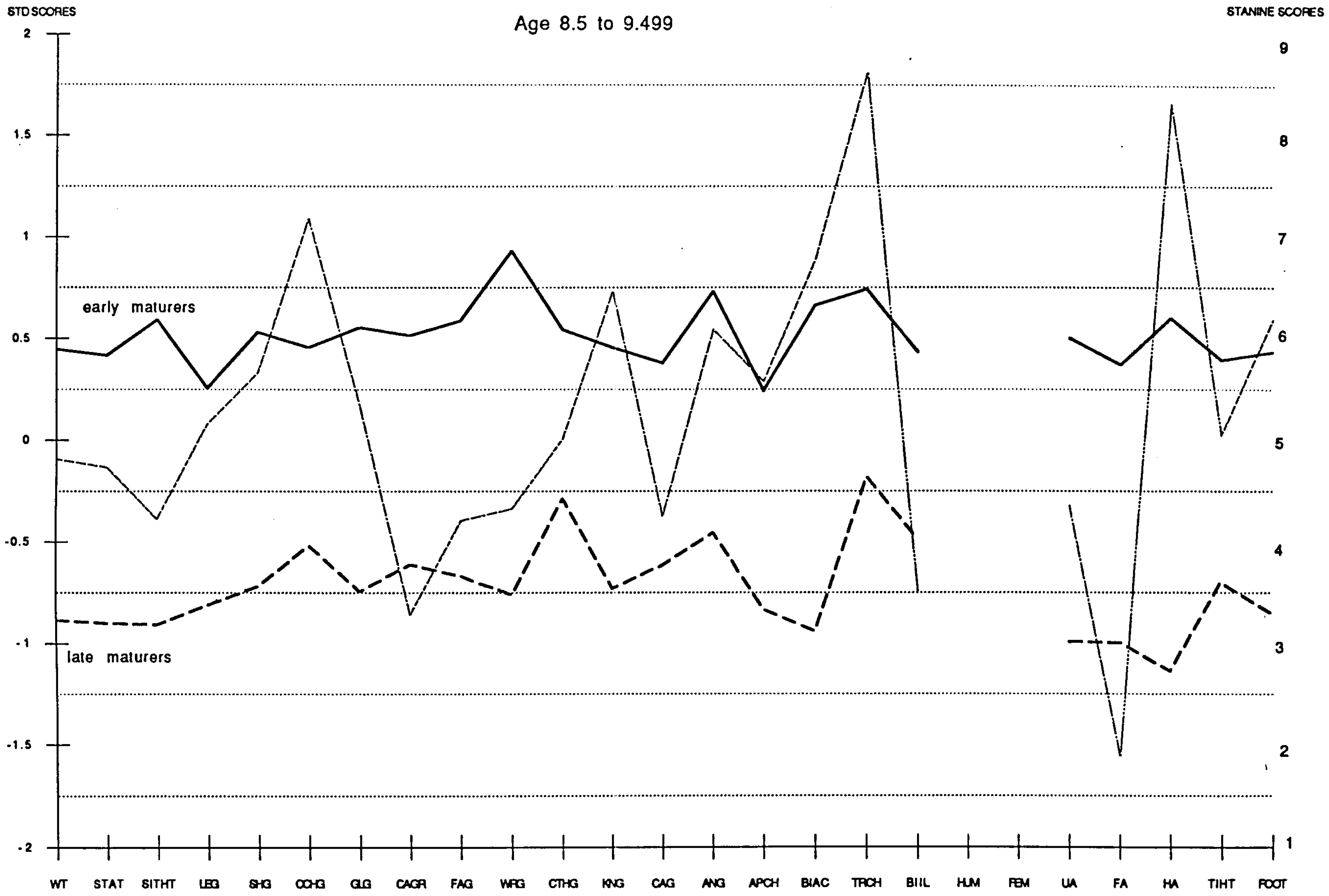


Figure 9.15 Average to late maturing boy (MI: 0.93) age 8.66, on chronological age 9 norms.

Chapter 10 SUMMARY AND CONCLUSIONS

The purpose of this thesis was to develop a system whereby the developmental status of a child could be assessed on the basis of his morphology. Auxologists have long recognized the shape and size changes which accrue throughout growth to be characteristic of different stages of development. However, these phenomena have not been formally applied to the appraisal of relative maturity. While other methods exist for this task, most involve complex or invasive procedures as to be of little use outside specialized clinical practice.

In order to develop a morphometric system of maturity appraisal, a number of investigations were required.

The physique characteristics of the different developmental stages had to first be identified. This involved assembling a comprehensive and complete anthropometric database from the Saskatchewan Growth and Development Study. These data were augmented by 20% through the measurement of limb segmental lengths from annual somatotype photographs. While not as accurate as conventional anthropometry, this photogrammetric procedure produced measurement errors within the ranges acceptable for use with grouped data.

As a benchmark of relative developmental status, age at peak height velocity was successfully identified for most subjects through curve-fitting of longitudinal stature data on the Preece-Baines1 model. Skeletal age assessed at age 11 provided a second, though more limited estimate of maturity.

No conclusions regarding anthropometric subsets which might best characterise developmental status could be drawn from principal components analysis of the full database. Using stature-scaled variables, anthropometric differences between early and late maturers at the same chronological age were readily identified. However, these proved to be only general guidelines in the eventual appraisal systems.

Both conventional statistical and novel non-parametric approaches were used in the development of the proposed developmental age systems. Although the data appeared to be multivariate normal and highly linear, no multiple regression equation could be found by which either the stature-scaled or raw data could adequately predict age at peak height velocity, or skeletal age. Of the non-parametric models constructed, those based on the premise of minimal distance from a developmental prototype were the most successful, in that they were moderately associated with skeletal maturity. While the relationships of the estimates provided by these models support their use for group assessment of maturity, individual assessment or substitution for radiographical procedures could not be recommended. However, the fact that these associations were based on a single measurement of skeletal maturity at age 11, suggests these models may show higher levels of accuracy given a more definitive validation source.

The modeling procedures disclosed a number of important points. It was apparent foremost, that size and shape bore little association with age at peak height velocity except within a very few years around that landmark. Skeletal maturity was more strongly related to physique at all ages.

It was also evident that size (analogous to stature) was a critical component of the morphological differences among developmental stages. Scaling for stature appeared to minimize much of the shape distinction seen at each stage. While maturity was generally shown to acccount for a modest component of stature variance, there was evidence to suggest that relative size was a more conclusive indicator of developmental progress among the late maturing cohort, than among average or early maturers. However, height alone was determined to be of limited use in the evaluation of maturity status.

On a more technical point, it was found that the commonly employed procedure of re-aligning growth data on age at peak height velocity to adjust for maturity variance, appeared to distort the data at all points except immediately surrounding the key. Maturity-adusted prototypes were therefore not recommended for this type of anthropometric investigation, and their use in other studies involving longitudinal growth data should be re-assessed. It is suggested that they be replaced with norms based on average-maturing individuals.

The most central discovery of this work was that individual physique variation is similar to that produced by developmental differences at any chronological age, to the extent that mathematical systems designed to differentiate the two are not highly successful. Among the evidence for this was the failure of discriminant analysis to organize the subjects into broadly generalized developmental groupings, granting statistical support to the notion that a large proportion of the anthropometric variance could not be attributable to maturity ranking.

The fact that no mathematical solutions to the anthropometric assessment of developmental age could be devised may suggest the concept itself is untenable. Biological age, which can be represented by differences in physique may be similar to the philosopher's stone, an idealized tool which cannot exist given current technology and understanding.

As an alternative to mathematical systems, a series of anthropometric maturity assessment charts offering a systematic display of individual physique differences on developmental norms was constructed. These included provisions for stanine ratings, sigma scores, and comparison with early and late maturing means for 25 variables at each chronological age from 7 to 16. For manual use, the raw values for each variable at the eight stanine divisions formed a template on which any of the anthropometric measures could be plotted. A second format provided chart construction as well as data transformation and plotting from a microcomputer spreadsheet. Both systems have the advantage of enabling one to generalize about maturity status with less influence from the element of variance in size and shape which confounded even the most generous mathematical functions. There are evidently many elements at work in the production of the size and shape of an individual child. Maturity itself is a highly variable phenomenon which is superimposed upon the physique characteristics designed by genetics, time, and environmental influence.

Future work in this area should include the following:

1. investigations into the relationships among body weight; total, and regional adiposity and the maturity status of boys.

2. parallel investigations regarding physique and maturity indicators in girls, including the creation of anthropometric maturity charts.

3. tri-dimensional analysis of categorical differences at each age to determine if a specific 'drive' toward a less diverse adult shape is evident.

4. with acquisition of longitudinal data sets including comprehensive skeletal age ratings:

   - the expansion and testing of minimal sums models and anthropometric assessment charts
   - examination of the 'difficult to assess' cases in context with both PHVage and skeletal age information, possibly leading to conclusions regarding the influence and timing of combined hormonal effects on physique.

5. more detailed investigation into the differential relationships of short and tall stature with maturity status; including analysis of these associations in other anthropometric variables.

6. examination of growth curves of segmental lengths in relation to those of other anthropometric variables; leading to assessment of order of growth among variables.

APPENDICES

APPENDIX A-1 Decimal age distribution of SFU sample.

ID	age	ID	age
27	6.226	23	11.261
42	6.927	9	11.472
25	7.266	17	11.540
26	7.565	1	11.907
43	7.841	30	12.372
45	7.841	21	12.422
44	8.060	31	12.433
13	8.183	8	12.501
41	8.241	39	12.936
15	8.246	38	13.057
20	8.370	5	13.164
11	8.851	40	13.552
24	9.043	2	13.634
14	9.561	4	13.739
12	9.979	37	13.971
22	10.338	36	14.179
19	10.355	29	14.724
18	10.587	28	15.135
6	10.694	32	15.179
10	10.809	33	15.606
7	10.817	35	15.696
16	11.105	3	15.765
		34	15.918

APPENDIX A-2 Plots of regressions predicting anthropometric segmental lengths

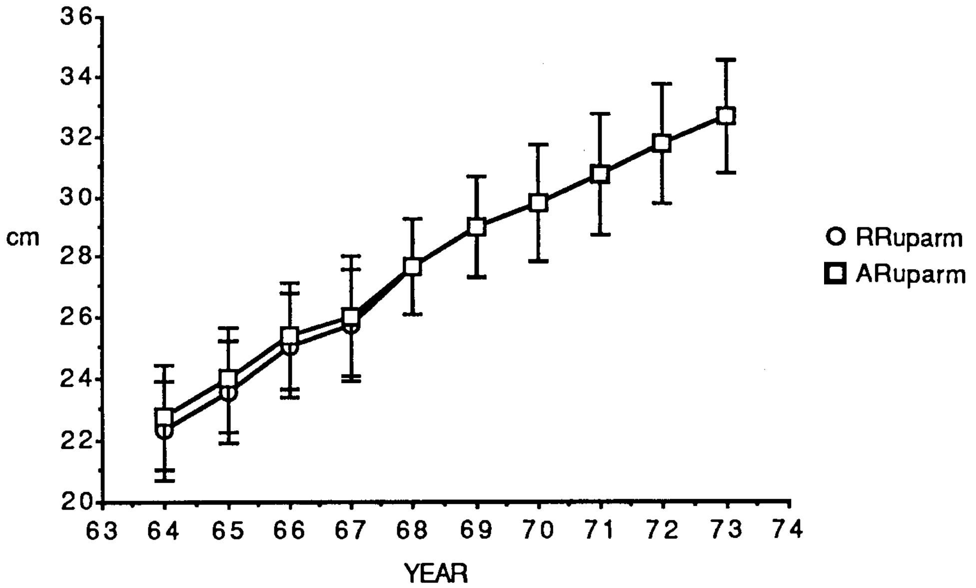


Figure A-2.1 Plots of the two regression routes to prediction of anthropometric upper arm length. RR= anatomical pose predicting standard pose (photogrammetry), predicting anthropometric equivalent. AR= anatomical pose directly predicting anthropometric equivalent.

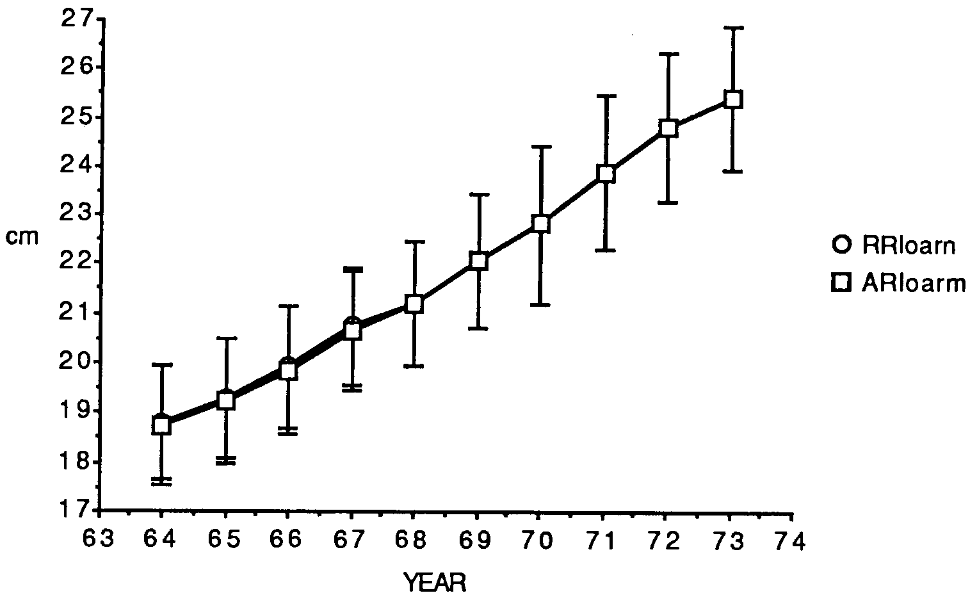


Figure A-2.2 Plots of the two regression routes to prediction of anthropometric lower arm length. RR= anatomical pose predicting standard pose (photogrammetry), predicting anthropometric equivalent. AR= anatomical pose directly predicting anthropometric equivalent.

APPENDIX A-2 Plots of regressions predicting anthropometric segmental lengths

.....continued

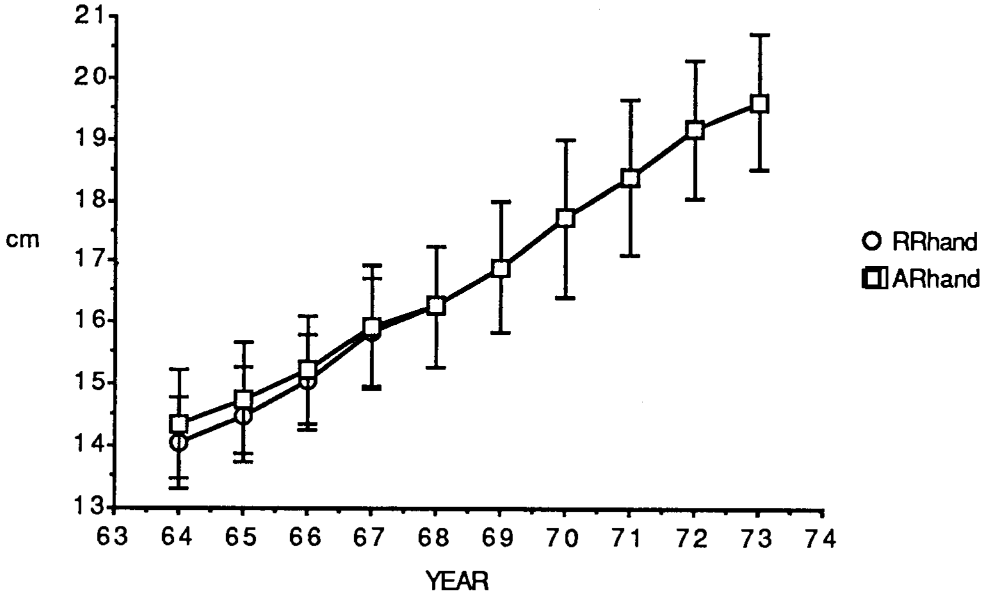


Figure A-2.3 Plots of the two regression routes to prediction of anthropometric hand length. RR= anatomical pose predicting standard pose (photogrammetry), predicting anthropometric equivalent. AR= anatomical pose directly predicting anthropometric equivalent.

APPENDIX B-1 Early and late maturers determined by PHVage

Early Maturers		Late Maturers	
ID	Age at PHV	ID	Age at PHV
99	11.56	153	15.65
57	11.80	166	15.84
91	11.83	86	16.15
223	12.41	101	16.16
143	12.45	74	16.18
128	12.46	180	16.32*
59	12.61	152	16.58*
132	12.67	53	16.86**
46	12.70	103	16.86*
126	12.70	202	17.08**
28	12.74	124	17.20**
75	12.78	72	17.32**
227	12.78	41	17.43**
141	12.83	62	17.95**
190	12.84	158	17.97**
218	12.84	16	18.08**
51	12.85	61	18.43**
39	12.91		
112	12.98	69	15.3^
207	12.98	194	15.34^
14	12.99	145	15.43^
188	13.07	197	15.44^
212	15.49^		

---

* subjects for whom PB-estimated PHVage exceeds age at which last data were collected.

** subjects for whom PB-estimated growth parameters suggest invalid estimation of PHVage.

^ subjects added to late-maturing cohort when potential outliers are removed.

APPENDIX B-2 Early and late maturers determined by maturity index of skeletal age

Early maturers		Late maturers	
ID	MI	ID	MI
77	1.077	197	0.664
116	1.079	113	0.711
60	1.081	146	0.748
59	1.086	69	0.757
225	1.090	130	0.765
66	1.091	147	0.767
96	1.095	70	0.772
207	1.095	202	0.774
28	1.099	21	0.784
39	1.100	36	0.789
208	1.102	170	0.804
227	1.109	139	0.809
29	1.113	141	0.817
90	1.117	166	0.818
57	1.124	119	0.821
223	1.134	158	0.824
128	1.138	22	0.824
195	1.142	196	0.839
181	1.142	176	0.846
75	1.145	81	0.848
99	1.164	161	0.850
91	1.182	222	0.850
		145	0.854
		220	0.860
		153	0.860

APPENDIX B-3 Ranked maturity according to PHVage and MI

ID	PHVage	ID	MI
99	11.56	91	1.182
57	11.8	99	1.164
91	11.83	75	1.145
223	12.41	181	1.142
143	12.45	195	1.142
128	12.46	128	1.138
59	12.62	223	1.134
132	12.67	57	1.124
46	12.7	90	1.117
126	12.7	29	1.113
28	12.74	227	1.109
75	12.78	208	1.102
227	12.78	39	1.100
141	12.83	28	1.099
190	12.84	96	1.095
51	12.85	207	1.095
39	12.91	66	1.091
112	12.98	225	1.090
207	12.98	59	1.086
14	12.99	60	1.081
188	13.07	116	1.079
60	13.14	77	1.077
89	13.18	184	1.075
167	13.18	97	1.063
181	13.21	51	1.058
225	13.21	152	1.057
29	13.31	46	1.050
20	13.32	143	1.050
125	13.32	13	1.050
50	13.34	16	1.047
67	13.38	212	1.044
96	13.38	132	1.044
172	13.38	50	1.043
97	13.43	101	1.042
170	13.45	100	1.041
95	13.49	98	1.038
109	13.5	20	1.034
38	13.54	43	1.029
3	13.66	3	1.029
129	13.66	160	1.029
116	13.76	174	1.028
209	13.76	131	1.026
211	13.79	117	1.023
196	13.87	109	1.022
176	13.88	198	1.021
70	13.9	93	1.021
208	13.92	38	1.021

Appendix B-3 continued......

ID	PHVage	ID	MI
139	14.01	180	1.019
37	14.04	172	1.015
43	14.09	14	1.014
184	14.12	56	1.012
44	14.14	44	1.010
119	14.19	86	1.000
161	14.19	124	0.998
163	14.22	120	0.993
48	14.24	167	0.991
228	14.26	118	0.991
182	14.28	188	0.991
174	14.31	194	0.990
186	14.34	215	0.984
130	14.35	89	0.978
215	14.35	226	0.976
148	14.37	41	0.971
33	14.38	217	0.971
195	14.4	209	0.970
66	14.41	25	0.970
131	14.42	34	0.967
98	14.47	206	0.965
226	14.51	125	0.965
77	14.52	95	0.963
25	14.53	129	0.962
220	14.53	154	0.953
81	14.55	186	0.948
102	14.59	103	0.944
117	14.59	53	0.937
160	14.62	112	0.935
222	14.62	62	0.932
34	14.64	61	0.930
198	14.65	37	0.926
204	14.68	126	0.926
120	14.7	163	0.919
5	14.71	40	0.917
90	14.73	148	0.915
93	14.75	33	0.907
100	14.77	211	0.902
154	14.8	190	0.900
206	14.86	228	0.896
56	14.91	102	0.890
21	14.93	72	0.887
118	14.93	204	0.884
113	14.94	5	0.883
147	14.96	67	0.880
146	15.01	182	0.873
22	15.03	48	0.871
36	15.07	153	0.860
13	15.09	220	0.860
40	15.19	145	0.854
217	15.25	222	0.850

Appendix B-3 continued..........

ID	PHVage	ID	MI
69	15.3	161	0.850
194	15.34	81	0.848
145	15.43	176	0.846
197	15.44	196	0.839
212	15.49	22	0.824
153	15.65	158	0.824
166	15.84	119	0.821
86	16.15	166	0.818
101	16.16	141	0.817
180	16.32	139	0.809
152	16.58	170	0.804
53	16.86	36	0.789
103	16.86	21	0.784
202	17.08	202	0.774
124	17.2	70	0.772
72	17.32	147	0.767
41	17.43	130	0.765
62	17.95	69	0.757
158	17.97	146	0.748
16	18.08	113	0.711
61	18.43	197	0.664

APPENDIX C-1 Anthropometric variables showing least absolute differences in mean z-scores between early and late maturers for ages 7 to 16.

AGE	HA	FT	FA	HUM	SIT	LEG	APC	WRG	SHG	KNG	CAL
7	0.005	0.054	0.074	0.096	0.117	0.13	0.182	0.204	0.215	0.227	0.235
AGE	BIB	BIA	SIT	LEG	CHG	FEM	HUM	THG	CAL	FT	SHG
8	0.017	0.032	0.053	0.06	0.077	0.099	0.106	0.11	0.167	0.193	0.205
AGE	CHG	SHG	UA	FEM	TCH	KNG	THG	FAG	FA	BIA	HUM
9	0.006	0.009	0.011	0.031	0.042	0.066	0.075	0.085	0.099	0.102	0.125
AGE	APC	BIA	THG	CHG	TCH	SIT	SHG	HUM	LEG	FT	BIB
10	0.011	0.025	0.055	0.063	0.072	0.082	0.082	0.096	0.108	0.164	0.173
AGE	APC	BIA	TCH	SIT	LEG	FEM	CAL	HUM	CHG	FT	KNG
11	0.005	0.011	0.026	0.061	0.077	0.099	0.102	0.106	0.14	0.162	0.185
AGE	FA	FEM	CAL	BIB	SIT	FT	BIA	LEG	SHG	TCH	HUM
12	0.021	0.031	0.047	0.074	0.078	0.086	0.09	0.094	0.108	0.117	0.125
AGE	APC	CAL	HUM	TCH	BIB	CHG	KNG	BIA	UA	SIT	FT
13	0.009	0.025	0.06	0.069	0.127	0.14	0.204	0.225	0.262	0.305	0.316
AGE	LEG	BIB	APC	ANG	WRG	HUM	SIT	TCH	CHG	GLG	HA
14	0.01	0.011	0.11	0.113	0.146	0.224	0.283	0.3	0.362	0.362	0.406
AGE	APC	KNG	BIB	FA	TCH	HUM	ANG	CFG	THG	HA	BIA
15	0.03	0.162	0.169	0.218	0.307	0.311	0.39	0.442	0.499	0.515	0.519
AGE	APC	UA	WRG	FA	ANG	KNG	BIB	HA	HUM	TCH	CHG
16	0.034	0.077	0.151	0.172	0.18	0.181	0.186	0.306	0.433	0.437	0.514

APPENDIX C-2 Anthropometric variables showing greatest absolute differences in mean z-scores between early and late maturers for ages 7 to 16.

AGE	THG	BIA	BIB	TCH	GLG	FEM	CAG	UA	CFG	FAG	ANG
7	.273	0.325	0.426	0.429	0.434	0.449	0.551	0.62	0.758	0.838	0.891
AGE	FA	UA	KNG	TCH	GLG	FAG	HA	ANG	CFG	WRG	CAG
8	0.251	0.253	0.275	0.359	0.459	0.469	0.48	0.567	0.63	0.654	0.723
AGE	LEG	ANG	FT	APC	WRG	CFG	BIB	GLG	HA	CAG	CAL
9	0.148	0.165	0.185	0.189	0.201	0.243	0.249	0.272	0.276	0.293	0.35
AGE	KNG	ANG	HA	FAG	WRG	FA	UA	GLG	FEM	CFG	CAG
10	0.213	0.217	0.254	0.285	0.298	0.313	0.348	0.368	0.449	0.48	0.621
AGE	UA	SHG	HA	THG	BIB	FAG	GLG	ANG	CFG	CAG	FA
11	0.199	0.206	0.257	0.258	0.332	0.406	0.421	0.506	0.531	0.596	0.654
AGE	APC	UA	CHG	ANG	GLG	FAG	THG	WRG	CFG	HA	CAG
12	0.19	0.217	0.234	0.288	0.293	0.388	0.401	0.424	0.564	0.572	0.669
AGE	GLG	SHG	ANG	THG	FEM	WRG	HA	FA	CFG	FAG	CAG
13	0.349	0.39	0.435	0.467	0.471	0.602	0.645	0.718	0.74	0.785	1.199
AGE	BIA	CFG	FA	SHG	FAG	CAL	UA	FEM	KNG	FT	CAG
14	0.429	0.456	0.491	0.549	0.576	0.576	0.612	0.927	1.048	1.058	1.129
AGE	CHG	FAG	SIT	LEG	SHG	WRG	UA	CAL	FEM	FT	CAG
15	0.595	0.624	0.635	0.657	0.674	0.715	0.824	0.879	0.955	1.237	1.565
AGE	FAG	FEM	CAL	CFG	GLG	SIT	FT	SHG	LEG	BIA	CAG
16	0.62	0.654	0.662	0.683	0.729	0.777	0.8	0.876	0.889	1.016	1.408

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