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VALIDATION AND APPLICATION OF A NONINVASIVE PREDICTION OF ADULT HEIGHT

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VALIDATION AND APPLICATION OF A
NONINVASIVE PREDICTION OF ADULT HEIGHT

By

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ABSTRACT

VALIDATION AND APPLICATION OF A
NONINVASIVE PREDICTION OF ADULT HEIGHT

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Traditionally, methods for predicting adult height have been used for clinical purposes in the diagnosis and treatment of growth pathologies. There has been an increase in the interest of predicting adult height of children in the field of kinesiology. Likewise, there is similar interest in noninvasive methods of predicting adult height, such as the Khamis-Roche [KR] (1994) method. The attractiveness of the KR method to predict height is its applicability as a biological maturity indicator. Percentage of [predicted] adult height, a somatic maturation indicator, has yielded favorable results in recent studies involving youth sports, albeit, without serial data. The purpose of this study is to validate the KR method of predicting adult height with a longitudinal data set of boys and girls. The KR method was also examined in terms of rate of maturation. The second purpose of this study was to examine the accuracy of the KR method in estimating biological maturity (predicted percentage of adult height). Samples of 205 boys and 227 girls had heights predicted semi-annually from ages 4.0 to 17.5 years of age. Accuracy of prediction was based on calculation of the median absolute deviation (MAD) at each chronological age. ANOVA of condensed means for boys and girls revealed statistically significant differences for average of 50% (MAD) and 90% error bounds. Averages of the MAD for boys and girls, however, were within acceptable range of errors. When boys and girls

were separated into early-, average-, and late-maturing groups, significant differences were reported for gender and maturation category. Average-maturing boys and girls reported lower MAD values than late- and early-maturing boys and girls. Predicted adult height was used to calculate predicted percentage of adult height (PPAH) with corresponding z-score (PZ). The PZ was used to assign boys and girls to early-, average-, and late-maturing categories. The frequencies of PZ were compared to frequencies generated from z-scores (AZ) calculated from the actual percentage of adult height (APAH). Chi Square analysis confirmed similar frequency distributions for most ages for boys and girls.

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CHAPTER I

INTRODUCTION

Prediction of Adult Height

The height of an individual is often an important variable in studies of kinesiology, but it is also an important concept in various practices of human performance. Parents, teachers, family members, and friends take an interest in a person's height. Height (recumbent length) is measured at birth and is frequently reported along with weight. Stature is often reported on sport team rosters and health records. Parents, as well as their children, are frequently curious as to how tall children will become. Thus, potential adult height is of great concern to parents, physicians, teachers, and coaches, especially in the pre-adolescent and adolescent periods (Sodhi, Malhotra, & Saini, 1982; Żarów, 1997). The interest in ascertaining adult stature of individuals, while they are yet in their childhood years, has been evident throughout human existence. The nature of investigating the prediction of adult height has revolved around a physician's need to know, as well as that of the kinesiology practitioner.

Prediction of adult height has largely been developed by examining variables linked to growth in stature and, subsequently, to skeletal maturation. Statistical procedures have identified skeletal maturation to be the most influential of these variables (Bayley, 1946; Bayley & Pinneau, 1952; Drayer, 1997; Onat, 1975, 1983; Shuttleworth, 1939; Tanner, Whitehouse, Marshall, & Carter, 1975; Tanner, Whitehouse, Marshall, Healy, & Goldstein, 1975), especially when used in conjunction with other variables (Mészáros, Szmodis, Mochácsi, & Szabó, 1984; Roche, Wainer, & Thissen, 1974). Furthermore, there are several methods to date that can be used to predict a child's height. Naturally, when conducting research, there is going to be concern for the amount of error associated with each method, because there are consequences to an erroneous prediction, whether the need for prediction is medical or motor performance related. The need for this study is centered on the validation, medical application, and motor performance utility of these prediction methods.

Need for the Study

Historically, three major studies are considered seminal pieces of literature on the prediction of adult height. These include the research of Bayley and Pinneau (1952); Roche, Wainer, and Thissen (1974); and Tanner and his colleagues (Tanner, Whitehouse, Marshall, Healy et al., 1975). Each of these research teams has validated its methods of predicting adult height with large samples, in addition to being validated with other data samples. This is considered good practice in that the establishment of any prediction method should always be followed up by validating it with other data sources (Roche, 1980). In fact, validation of any height prediction method for children against other groups of children, independent of the data set used to derive the prediction equations, is an absolute necessity (Hintz, 1996).

Prediction equations should be validated for both sexes and at each stage of growth and development (Zadik, Segal, & Limony, 1997). Some prediction methods that have been developed are limited by having longitudinal samples of only one sex, such as the Beunen-Malina method (Beunen et al., 1997).

Validation of prediction methods is generally performed with normal populations (i.e., those that are free of disease), however, validation of prediction methods with pathological populations also has utility. For this reason, Brämswig and colleagues (1990) sought to examine the accuracy of five different methods of predicting growth because the main prediction methods being used to treat clinical cases, such as constitutional delay of growth and puberty (CDGP), were developed with "normal" samples. Other concerns for validation come from Joss, Temperli, and Mullis (1992) who state that the criteria for a good prediction method are reasonable accuracy over a large age range, small prediction error, and, if possible, validity for tall, short, and normal children.

The medical community has forged the impetus for the prediction of adult height. The accurate prediction of adult height is important in assessing the need for pharmacological intervention on growth and in evaluating the outcome of any associated therapy (Zadik et al., 1996). Due to the impact, strength, and reputations of the three primary prediction methods (Bayley-Pinneau [BP], Roche-Wainer-Thissen [RWT], and Tanner-Whitehouse Mark II [TW2]), many clinical studies have utilized these methods. Unfortunately, only the BP method was tested on both normal and pathological populations. The ease of use of their tables and the validation of the BP method on different populations are probable reasons for most researchers to use the BP method.

Another strength of these three primary prediction methods was the inclusion of skeletal age as a variable in which hands and wrists were examined using Roentgenic (X-Ray) technology. Prediction of final height based on bone age assessments has become an important tool in the management of patients with growth disorders, although the limitations of these predictions and the normal variability in bone age progression need to be clearly understood (Drayer, 1997). While skeletal age is clearly a dominant factor in predicting adult height, there was a need to develop a method that does not introduce a child to radiation exposure. The Khamis and Roche method (1994) is the dominant study to date that addresses a noninvasive approach to predicting adult height.

While most of the applications of the adult height prediction methods have been utilized in the medical and endocrinology areas, there is a need for predicting adult height for kinesiology practitioners. One such example is that of talent selection. Because stature is one of the most important morphological characteristics in a majority of sport activities, Sodhi, Malhotra, and Saini (1982) studied the heights of Punjabi boys ages 12-17 years. They were compelled to undertake this study because they believed, that to select a potential athlete at a young age, it is desirable to predict the adult height from his stature during childhood so that he can be advised on the sport for which he is likely to be most suited. Thus, knowing a child's predicted height can allow a coach to gain an insight into the potential of an athlete based on how tall he/she might become.

Height is important in various positions on team sports and in the success of individuals in some individual sports. This concept was the impetus for the research conducted by Mészáros, Szmodis, Mochácsi, and Szabó (1984) in which they sought to develop a method to predict the adult height of Hungarian youth. Talent selection, however, should not discourage participation in an activity. That should never be a goal of height prediction. Nicoletti (1988) stated that the prediction of adult height "is useful in guiding choices about sport and perhaps the chances of success in sport" (p. 19).

Another area where practitioners can utilize height prediction also falls within the domain of youth sports. Because children grow and mature with considerable variation in rate, chronological age is not always the most appropriate way to group children in activities. Grouping youth by skeletal maturation, however, might create heterogeneous ability groups. A noninvasive method of predicting adult height would assist in grouping these children by a predicted percentage of adult height. Grouping strategies based on physical size or biological maturity status may foster continued skill development and deter attrition of skilled yet smaller, later maturing athletes, especially during adolescence (Malina, Cumming, Morano, Barron, & Miller, 2005).

Researchers in kinesiology can also benefit from predicting adult height. Georgopoulous and colleagues (2001) utilized two methods of height prediction to determine the validity of the relationship of physical training and growth stunting. The study provided a strong argument for the necessity of height prediction methods in research related to issues of youth sports.

> Height predictions, irrespective of the methods used for their estimation, have been criticized for their inherent inaccuracy. Although definite conclusions should not be made unless adult height will be attained, in the vast majority of examined athletes, the finding of an almost identical adult height to the initially predicted adult height in those athletes who fulfilled their skeletal development, argue against an overestimation of our predictions of adult height (p. 5159).

The Khamis-Roche (KR) method is unique in that it is a noninvasive method of predicting adult height. Because of the ease of use and acceptable range of error, this procedure has been utilized in recent research. Several studies (Battista, Cumming, & Malina, 2003; Dompier, 2005; Morano, 2003) have used the Khamis-Roche method of predicting adult height for establishing indicators of maturation within field studies of youth sports and human performance. With increased interest and usage of this method of height prediction, it is necessary to ascertain where the greatest source of error in prediction occurs. Furthermore, the KR method is being applied to methods of noninvasive maturation indicators without having additional longitudinal validation.

Finally, there is a need to study height because of the psychological considerations that come with height. A child's perception of predicted height can sometimes deter him/her from participating in a physical activity. As well, some children are encouraged to participate in activity because of the benefits of their current and/or predicted stature. More importantly, perceptions of height have been linked to self-esteem. Recently, there has been some consideration of psychosocial aspects regarding height. One study (Erling, Wiklund, & Wikland, 2002) focused on the psychological functioning of boys of short stature, as defined by growth hormone (GH) insufficiency. The investigators found that boys with growth hormone insufficiency had a more negative self-perception of their physical appearance than a normal height sample. Additionally, they found that the lower the levels of GH, the more inhibited the boys of short stature were perceived to be by both themselves in a self-rating and by their parents.

Hunt, Hazen, and Sandberg (2000) believe that short stature is associated with significant problems of psychosocial adaptation and that hormone-induced increases in growth and height will be associated with improvements in psychosocial functioning in both the short- and long-term. While improvements are linked to increased measured heights, Hunt and colleagues postulate that if perceived height is more closely related to psychosocial adaptation than is measured height, then a therapeutic approach concerned only with the outcome variables (i.e., measured height or growth hormone therapy) may result in unexpected and potential negative psychosocial outcomes. In their study, patients and parents generally over estimated their predicted heights. Perceptions of taller stature were associated with increased patient and parent satisfaction with the child's height. Furthermore, these short stature patients scored higher on physical appearance and global self-worth questionnaires when they perceived themselves to be taller. Finally, the overestimated height also yielded few behavior problems. The authors believe perceived height is more closely linked to psychosocial adaptation than is measured height.

Player grouping strategies of youth football players based upon physical size or biological maturity was addressed by Malina, Cumming, Morano, Barron, and Miller (2005). This study examined a noninvasive way to match players based on size rather than chronological age for reducing the risk of injury and fostering increased skill development of later maturing athletes. There were also psychosocial implications for conducting this study. For example, some youth athletes may not persist in an activity if they view participating with younger players as a negative judgment on their playing ability. Similarly, younger athletes that are advanced in skill may not be able to cope with older athletes on an emotional, social, and/or cognitive level.

There is a logical need for predicting adult height in studies of kinesiology as well as within the professions of teaching and coaching. A method with the smallest margin of error, ease of acquiring data, minimal expense, and no adverse effects on the participants will best suit research and application in the field. An increase in the application of height prediction in studies of human performance and kinesiology clearly indicate a need to develop a method suited for youth sports and physical education activity programs.

Purpose of the Study

While there has been widespread use of adult height prediction methods in auxology and clinical endocrinology, there is an increasing need for predicting adult height in kinesiology, particularly in laboratory research and certainly in field studies. Prediction methods have been developed and utilized with skeletal age as a key variable. The use of skeletal age, while proven effective in predicting adult height, has also proven to be expensive, dubious in the reliability of the rater, and invasive by exposing young participants to radiation. In recent years, a method has been developed that substitutes chronological age for skeletal age, thereby removing the harmful effects of the use radiation (Khamis & Roche, 1994; Roche, Tyleshevski, & Rogers, 1983). The KR method has been validated by the authors with longitudinal data and has been utilized by other investigators (Battista et al., 2003; Cumming, 2002; Dompier, 2005; Malina, Cumming, Morano, Barron, & Miller, 2005; Morano, 2003) in their own studies. Because of the interest in and potential use of this prediction method, it is the purpose of the current study to validate the KR method of predicting adult height with a sample of boys and girls. Validating a method with different populations is recommended (Roche, 1980; Hintz, 2001) when attempting to substantiate the effectiveness of a prediction method.

The validation of KR with the mid-Michigan sample will employ the same procedures used by the original authors. In this way, the accuracy of the KR method can be examined in terms of various periods of childhood and adolescence. Specifically, this study will examine how accurate the KR method is with respect to rate of maturation (early-, average-, and late-maturing) as revealed by serial data on height.

An additional purpose of this study is to validate the utility of noninvasive prediction of adult height as a variable in noninvasive somatic maturation indicators. Recent studies in youth sports have utilized the KR method to calculate a predicted percentage of adult height in order to assign a group of children to early-, average-, or late-maturing status. The accuracy of the predicted somatic maturation method can be validated by comparing it to the actual percentage of adult height collected from serial measurements of height.

Scope of the Study

The magnitude of this study is three fold. First, there is a need to validate the Khamis-Roche method of predicting adult height with a sample comprised of both boys and girls (Haubenstricker, Branta, & Seefeldt, 1999), a longitudinal Motor Performance Study (MPS) conducted at Michigan State University that investigated growth and motor performance. The purpose of this validation is to compare the results with those of the original sample, the Fels Longitudinal Study. Additionally, there is a concomitant purpose of investigating the magnitude of error based on biological maturation (percentage of adult height attained). In this way, the accuracy of the KR method can be determined for early-, average-, and late-maturing boys and girls at different chronological ages.

Finally, the intention of this study was to validate an application of predicted adult height data to provide a noninvasive estimate of maturity status. The predicted height for each participant will be used to calculate a (predicted) percentage of adult height attained.

With this data, the accuracy of the predicted percentage of adult height can be compared to actual final height in determining rate of maturation at each chronological age.

Research Questions

The current research and literature on predicting adult height, in conjunction with the need for predicting adult height, has given rise to the following research questions:

1. What is the validity of the Khamis-Roche method (or how accurate is the method) of predicting adult height as applied to a sample of boys?
2. What is the validity of the Khamis-Roche method (or how accurate is the method) of predicting adult height as applied to a sample of girls?
3. How accurate is the Khamis-Roche method when evaluating early-, average-, and late-maturing boys and girls.
4. Does the Khamis-Roche method accurately provide biological maturity estimation by separating early-, average-, and late-maturing boys with a predicted percentage of adult height when compared to actual percentage of adult height?
5. Does the Khamis-Roche method accurately provide biological maturity estimation by separating early-, average-, and late-maturing girls with a predicted percentage of adult height when compared to actual percentage of adult height?

Limitations

One of the limitations encountered in this study is inter-rater reliability. The Motor Performance Study at Michigan State University was initiated in the December 1967 by Dr. Vern Seefeldt. The growth measurements in the study were taken according to established protocols (see Appendix A). Although no formal intra- and inter-individual errors were calculated, growth measurements were taken under the supervision of the principal investigator (Seefeldt). Duplicate measurements were taken by trainees and the principal investigator until the trainees demonstrated consistency in measurement with that of the principal investigator. However, across the 37-year history of the study, most of the growth measurements were taken by three faculty investigators. While error in measurement is standard practice for anthropometric studies, the training, experience, and reputation of the investigators should offset the fact that there is no reported technical error of measurement values for the growth measurements.

Secular trend could be an issue in this study. Data collection began in December 1967 which means that a potential sample for this study could span nearly four decades with some participants of the MPS concluding their serial measurements as recently as 2004. The secular increase for height has been recorded in other countries, albeit, the phenomenon has been slowing and is reported primarily for developing nations (Hauspie, Vercauteren, & Susanne, 1997; Karlberg, 2002; Matsuoka, Sato, Sugihara, & Murata, 1999; Murata, 1997). Karlberg (2002) reported a global secular trend in adolescent growth and subsequent increased mean final adult height. He also reported a propensity for earlier puberty, but that it is not strongly connected to the increase in height. However, this is in contrast to other findings (Matsuoka et al., 1999; Murata, 1997). Matsuoka et al. (1999), for example, reported that secular trends towards taller stature and earlier maturation are linked to improvements in nutrition and health, as evident in an observed secular trend initiating in 1900 for all of Japan. Their 1997 study reported that bone maturation reflects their nation's secular trend in height. With a series of 1986 and

1996 X-ray samples, they found that these data parallel secular trends in height and change in bone maturation, citing a relationship between growth and bone maturation. Murata (1997) reported a plateau affect for Japanese increase in height in the mid-1980s.

The secular trend in height has not been as evident in North American populations as in Asian and European countries. Secular trends in growth for the United States have been reported by the National Center for Health Statistics, Centers for Disease Control and Prevention. Roche (1995) wrote, "For children and adolescents aged 6-17 years, the secular trends in stature from NHES II (National Health Examination Survey Cycle II ages 6-11 years, 1963-1965) and NHES III (National Health Examination Survey Cycle III, 12-17 years, 1966-1970) to NHANES I (National Health and Nutrition Examination Survey, 1971-1974) , II (1976-1980), and III (1988-1994) have been small or nonexistent, except for an increase of approximately 2.2 centimeters at the 85th percentile level for males between NHES and NHANES III" (p. 10).

The current study is also limited by ethnicity in that a preponderance of the sample population is white or Caucasian. The majority of children in this study are from a mid-Michigan populace approximately 119,128 with 65% being White, 22% African-American, 10% Hispanic, and 3% Asian ("AreaConnect," 2004). Over 95% of the participants in the study are Caucasian and represent 21 different school districts in this mid-Michigan area. Although human beings are considered to be more similar than dissimilar, it is clear that variations in genotypic and phenotypic characteristics exist among groups of people that claim a specific racial and/or ethnic background (Malina, Bouchard, & Bar-Or, 2004). This is particularly important in studies of growth and maturation. For example, Murata (1997) found that Japanese children tend to attain skeletal maturity 1 to 2 years before samples of British/UK, Belgian, and Chinese children. While the Murata (1997) study focuses on differences in Asian and European samples, the uniqueness of the United States, as a melting-pot society, tends to have increased racial and ethnic heterogeneity in samples from this population.

The data collected for this retrospective study were mid-parent statures (see definitions). A recall method was used to obtain the information. While a correction factor was employed (Epstein et al., 1995), it should be noted that there is error in the recall of adult stature. Recall is not as accurate as measured stature. Men tend to over estimate their height and women tend to underestimate their height (Himes & Roche, 1982; Malina et al., 2004). Giles and Hutchinson (1991) reported that while men as a whole will overpredict stature by a magnitude of 2.5 cm (1 in), women under estimate their height to a lesser magnitude (1 cm or three-eighths of an inch) and thus, report their heights more accurately than men.

Definitions

The following definitions will aid in understanding the terminology used in this document.

<u>APAH</u>: The acronym used to designate the actual percentage of adult height is APAH.

<u>Adolescence</u>: Due to the variation in the timing of the adolescent (circumpubertal) growth spurt in boys and girls, the corresponding chronological age associated with this period of growth is much more difficult to define. For this study, the definition of adolescence by Malina, Bouchard, and Bar-Or (2004) is used. The age of

occurrence of adolescence in girls ranges from 8- to 19-years and boys from 10- to 22-years.

Auxology: The study of growth and the principles of growth.

ASCA: The acronym ASCA defines a predicted adult height that substituted chronological age for skeletal age using the Beunen-Malina method (Beunen et al., 1997). The Beunen-Malina method of predicting adult height is a noninvasive method.

ASTW: This acronym stands for adult stature Tanner-Whitehouse and designates an adult height prediction using the Tanner-Whitehouse method. The ASTW was tested and compared against the Beunen-Malina method (Beunen, et al., 1997).

AZ: A z-score generated from actual adult height.

BA: The acronym BA defines bone age and is synonymously used with the acronym SA, or skeletal age. Bone or skeletal age indicates the progress towards a mature state of skeletal maturation, complete ossification of short bones, and the fissure of the epiphyseal regions of long bones.

BM Method (of Predicting Adult Height): A noninvasive method to predict adult height of adolescent boys (Beunen et al., 1997).

BMI: BMI stands for body mass index and is the most often used expression of the relationship between height and weight. Mathematically, BMI is weight divided by stature squared (BMI = weight $\div$ stature^2 or kg $\div$ m^2).

Biological Maturation: The term biological maturation is used interchangeably with maturation, the progress towards a mature state and adult morphology of a physiological system. It is important to understand maturity as a state and maturation as a process (Malina et al., 2004).

BP: The acronym BP stands for the method of adult height prediction derived by Bayley and Pinneau (1952).

CA: The acronym CA indicates chronological age or calendar age. It refers the time span from an individual's date of birth to a designated point in time.

Childhood: The period of childhood begins with the first birthday of a child and proceeds to the start of adolescence, in accordance with the definition of Malina, Bouchard, and Bar-Or (2004). This period is partitioned into periods of early and middle childhood.

Correlation: Basic statistics used in studies to explain a relationship amongst measures of motor performance typically employ zero-order and partial correlation coefficients (Malina, 1996; Malina et al., 2004). These relationships are interpreted using the protocols established by Malina (1996). A coefficient below 0.30 will be considered low, between 0.30 and 0.60 is moderate, between 0.60 and 0.85 is moderately high, and over 0.85 are high.

CTS: The acronym designating constitutional tall stature is CTS. It is also known as familial tall stature and is a typical overgrowth syndrome.

Early Childhood: The period of time following the first birth date to about 5-years of age marks the period of early childhood.

Final Height: Final height is defined as that height an individual will obtain as an adult, with full skeletal maturation. While there are many ways to designate the attainment of this phenomena, as studied by Kato, Ashizawa, and Satoh (1998), final height for the current study is obtained when three successive, 6-month measurements of height are within three (3) millimeters of each other. Measurements for growth and performance in the Motor Performance Study at Michigan State University occurred every six months. Utilizing two series of longitudinal data, Kato and colleagues (1998) found the definition of final stature as the greatest height of an individual measurement to be the most practical.

GP: The acronym GP stands for Greulich-Pyle (Gruelich & Pyle, 1959) and is designated as a method of assessing skeletal maturation. This method utilizes an atlas of hand-wrist X-rays for comparison on individual long and short bones of the hand and wrist.

Growth: Growth is defined as an increase in size of a tissue or physiological system. This study will focus primarily on the growth of osseous tissue and the skeletal system.

Height: Used synonymously with the term stature, height will indicate the tallness of an individual at a specified chronological age during growth or as an adult.

Height Prediction: The use of statistical procedures to estimate the final adult height or adult stature.

ICPP: The acronym designating idiopathic central precocious puberty is ICPP. Children diagnosed with ICPP tend to be growing at an unusually high rate. The concern for these children is abnormally short stature. An early, increased rate of growth can potentially lead to early cessation of growth.

KR: The acronym KR stands for Khamis-Roche (Khamis & Roche, 1994), a multiple regression method of predicting adult height which utilizes the variables of current height, current weight, and mid-parent height.

MAD. The acronym MAD stands for median absolute deviation. The MAD is the statistic used for accuracy in predicting adult height (Khamis & Roche, 1994; Wainer, Roche, & Bell, 1978). Mathematically, the MAD is $|y - \hat{y}|$, where y represents the true adult stature and $\hat{y}$ represents the predicted adult stature for an individual of a given age and gender. For the given age and gender, $P[|y - \hat{y}| < \text{MAD}] = 0.50$, by definition of a median. Then algebraically,

$$P[-\text{MAD} < y - \hat{y} < \text{MAD}] = 0.50$$
$$P[\hat{y} - \text{MAD} < y < \hat{y} + \text{MAD}] = 0.50$$

When the MAD is added to and subtracted from the predicted adult stature, an interval is obtained within which 50% of the actual adult statures lie -- effectively, this is a 50% confidence interval, and the MAD is referred to as the 50% error bound (Khamis, 2007a).

Maturation: The term maturation indicates progress towards a mature state in a biological system. This study will focus on the skeletal system and the progress towards a mature, fully ossified skeletal and adult morphology.

Middle Childhood: The time in which a child usually spends in elementary school marks the middle childhood period. This is typical of children aged 5-years to the beginning of adolescence.

Mid-parent Height (Mid-parent Stature): Taking the average of the height of the mother and the father will yield mid-parent height. This calculation is commonly used in formulae for target height and methods for predicting final adult height. Mid-parent height is frequently used in parent-child stature relationships because it can summarize genetic contributions of both parents and allow for appropriate statistical and genetic assumptions (Himes, Roche, Thissen, & Moore, 1985).

MPS: The Motor Performance Study (MPS) was a longitudinal study of growth and motor performance of mid-Michigan boys and girls (Haubenstricker, Branta, & Seefeldt, 1999).

Noninvasive Maturity Indicator: Identifying rates of maturation or stages of change within a specific biological system that does not cause physical or emotional harm to an individual will indicate a noninvasive measure or indicator. For example, assessment of secondary sex characteristics, a method typically used to indicate overall biological maturation, is considered invasive because of the cultural stigma assigned to nudity, personal space, and physical contact. For this study, skeletal maturation assessed by means of Roentgenic (X-ray) measures introduces radiation to a child and is considered a physical threat to his/her health. Examples of noninvasive indicators are percentage of adult height attained and predicted percentage of adult height.

Percentage of Adult Stature: A maturity indicator for the skeletal system, percentage of adult height allows one to know how close an individual is to adult stature. Serial measurements of height are necessary for this maturity indicator, and are only helpful when retrospective inquiry is needed. Thus, this skeletal maturity indicator will benefit researchers, but is not practical for professional practice in an immediate sense. A synonym for percentage of adult stature is percentage of mature height (PMH).

PB1 The acronym PB1 represents the Preece-Baines Model 1 method of calculating parameters of growth, namely peak height velocity, age at peak height velocity, take-off of peak height velocity, and termination of peak height velocity.

PHV. The acronym PHV stands for peak height velocity, the maximum rate of growth of a child during adolescence. PHV is typically used as a maturation marker for both boys and girls in studies involving biological maturation as a variable because it has been proven to correlate with the timing of other maturation indicators (i.e., secondary sex characteristics).

PPAH: The acronym designating predicted percentage of adult height is PPAH.

Prediction: The usage of the term prediction in this paper will borrow the definition used by Roche (1980) in which one or more variables noted at one age are used to foretell a value at an older age.

Puberty: Puberty is often closely associated with adolescence and the circumpubertal growth spurt. The choice of definition for the onset or timing of puberty, as pointed out by Karlberg (2002), is dependent upon systems in questions (e.g., secondary sex characteristics, age at peak height velocity). For this paper, the timing of the growth spurt and age at peak height velocity will be milestones for indicating puberty.

PZ: The acronym for a z-score generated from a predicted adult height rather than an actual adult height, is designed by PZ.

Regression: Using arrays of correlated variables, the statistical procedure used to predict one variable from one or more variables is called regression.

RUS: In the Tanner-Whitehouse method for skeletal age assessment, the RUS portion includes the radial-ulnar skeleton.

RWT: The acronym RWT stands for Roche-Wainer-Thissen (Roche et al., 1974) and designates the method of predicting the adult height of a child from data recorded during an isolated examination. The data collected and measured during this examination includes recumbent length, nude weight, mid-parent stature, and skeletal age as assessed by a hand-wrist X-ray and evaluated using the Gruelich-Pyle (Gruelich & Pyle, 1959) method of skeletal assessment.

SA: The acronym designating skeletal age is SA. Skeletal age is a value used to designate how close to adult morphology various selected bones are at the time of assessment. There are three primary assessment methods, each yielding a different skeletal age based on their own criteria (see Chapter 2 for a review of literature).

SSP: The acronym SSP designates the prediction of adult height method called the Simplified Skeletal Profile (Nicoletti, 1988).

Stature: The term used to designate tallness of an individual will be shared by both height and stature, as the two terms will be used interchangeably as synonyms.

TH (Target Height): Not to be confused with predicting final height, target height will be used to designate genetic potential for growth in stature based on the principle of mid-parent height. There are several methods for computing target height. These are outlined in the section entitled "Adult Height Prediction" in Chapter II.

TW1: The acronym TW1 stands for the Tanner-Whitehouse Mark I method of predicting adult height (Tanner, Whitehouse, Marshall, & Carter, 1975). This multiple regression model utilizes height, occurrence of menarche (for girls), mid-parent height, and bone age as assessed by Tanner-Whitehouse standards (Tanner, Whitehouse, Marshall, Healy et al., 1975).

TW2: The acronym TW2 is defined as the Tanner-Whitehouse Mark II method of predicting adult height (Tanner, Landt, Cameron, Carter, & Patel, 1983). This method was designed to improve and replace the TW1 method by including samples of both taller and shorter children as well as boys and girls with clinical growth disorders. The variable for mid-parent height was also removed from the prediction equation.

$\underline{Z}_1$: The first option of predicting adult height using the Żarów (1997) method is Z_1. This multiple regression method, used for boys aged 6.5 to 16 years, does not include a sexual maturation stage in the prediction equation.

$\underline{Z}_2$: The second option of predicting adult height using the Żarów (1997) method is Z_2. This option includes a secondary sex characteristic, stages of pubic hair growth, as a substitute for the traditionally used skeletal age variable.

CHAPTER II

REVIEW OF LITERATURE

This review of literature will highlight research in the areas of predicting adult height, biological maturation, and maturity estimation as related to growth in height. Additionally, the application of prediction of adult height and uses of this variable in somatic maturation will be reviewed.

In the area of predicting adult stature, much of the literature on validating various methods has been derived from clinical need. Clinical endocrinologists and pediatric practitioners, for example, would benefit from this line of research in their efforts to understand and/or treat pathologies related to growth in stature. While there is a need to understand the full potential of predicting adult stature in a clinical manner, this is beyond the scope of this paper. The investigator acknowledges the profound impact of this research and therefore, only the current uses of prediction models in clinical areas (i.e., treatments of growth hormone) will be highlighted.

Adult Height Prediction

Prediction of final adult stature has traditionally employed statistical procedures (i.e., regression analysis) utilizing various biological measures as input. Equations for predicting adult stature have been derived from serial data of a variety of sources where the variables, such as anthropometric measurements of children and parents, have been isolated with statistical procedures (i.e., principal component analysis). The utility of these statistical methods has been made available to practitioners in the form of charts, tables, and variables with corresponding coefficients for input into equations. This section on adult height prediction will include information on various methods of computing: charts and tables; regression equations; mid-parent height; noninvasive methods; and other methods.

Charts and Tables

Shuttleworth (1939) was among the first to publish tables for predicting the adult height of children. There are four tables, calculated from the Harvard Growth Study longitudinal records on stature, that are used to estimate mature stature according to sex and racial stock at each age from 6.5 to 17.5 years. Each table has a corresponding correlation and prediction estimate (of error). The tables are organized by predictions on half-year increments. To find a prediction of a child of 7.0 years, for example, an average must be made of the predictions for the same child at 6.5 and 7.5, respectively. The racial stock is only Northern European or Italian.

One of the first and accepted forms of adult height prediction methods was tables by Bayley (1946). The prediction tables utilized the skeletal atlas developed by T. Wingate Todd (Todd, 1937) which would later be revised by Gruelich and Pyle (Bayley & Pinneau, 1952). Subsequently, a second set of tables was developed to reflect the widely accepted standard of radiographic assessment of skeletal maturation, the Gruelich-Pyle method. The second set of tables is now aptly called the Bayley-Pinneau (BP) Method. Bayley (1946) based her tables on 192 participants in the University of California Institute of Child Welfare study in Berkeley, California. The tables were validated with a separate sample. The tables are easy to use. Matching skeletal age to present height provides a percentage of mature height (PMH).

There are separate sets of tables for boys and girls, and three levels for each sex. There is a table for percentage of estimated mature stature for boys at chronological ages of 7-12 years whose skeletal ages are within one year of their chronological age. There is a separate table for boys aged 13 years to mature height. Additional tables for boys who are early maturing are also provided. For accelerated boys at ages 7-11 years, a table was created for those that have estimated mature statures with skeletal ages one year or more advanced over their chronological age. Another table exists for accelerated boys 12-17 years. Similar to the tables for accelerated boys, there are tables of estimated mature heights for boys who have skeletal ages one or more years less than their chronological age. This table range was for boys 6-13 years. Bayley termed this group "retarded in skeletal maturation".

Tables were also derived for girls with average, accelerated, and retarded growth. The age ranges for each were 6-11 years and 12-18 years for average; 7-11 and 12-17 years for accelerated; and 6-11 and 12-17 years for girls with retarded growth.

Post and Richman (1981) compiled the data used in the formulation of the BP method and amalgamated all 11 tables into one, easy-to-use table. The table facilitates the calculation of a decimal fraction of adult height attained for average, delayed, or advanced skeletal age when compared to chronological age. Dividing a child's present height by the decimal fraction yields the predicted height.

There are other charts (Center for Disease Control and Prevention, 2001; Nicoletti, 1988; Tanner, 1976) in existence that serve the same function as the Bayley-

Pinneau tables and the adaptation by Post and Richman (1981). The Simplified Skeletal Profile (SSP), for example, is very similar to the BP tables (Nicoletti, 1988). There are only five bones to be rated for SA, however, and utilized the criteria of Tanner (1975). The bones to be chosen for evaluation are dependent on the age of the child to be rated. It is the tables in the SSP that indicate which bones should be rated per chronological age (Nicoletti, 1988). This method, published in Italian, has not been validated in other studies.

The Center for Disease Control and Prevention (CDC) offer several different charts not only for height, but also charts for weight, head circumference, and body mass index (BMI). These charts are made available to the medical practitioner and general public via the internet (Center for Disease Control and Prevention, 2001). Similar charts for plotting height and weight have also been published. Tanner (1976) provided a detailed explanation of several different charts for use in a clinical setting based on data collected in the United Kingdom. The utility of height charts, height velocity charts, and standards for height allowing for mid-parent height are explained with regard to predicting adult height.

Mid-parent Height and Target Height

There is a general consensus that genetics plays a rather significant role in final adult height (Himes et al., 1985; Karlberg & Luo, 2000; Katzmarzyk, Mahaney, Blangero, Quek, & Malina, 1999; Luo, Albertsson Wikland, & Karlberg, 1998; Luo, Low, & Karlberg, 1999; Nicoletti, 1988; Preece, 1996; Sorva, Tolppanen, Lankinen, & Perheentupa, 1989; Welon & Bielicki, 1971). The genetic potential for growth in stature is often referred to as target height (TH) and has mid-parent height as a computing variable. While the equations for determining genetic potential in stature are not considered to predict final height, they are used to improve detection of potential growth pathologies (Wright & Cheetham, 1999). Typically, the mid-parent height is defined simply as the average of the height of the mother and the father. Originally, mid-parental height was defined by Galton (1886) when studying the relationship of parental and child stature. With this work was borne the concept of regression towards the mean and quite possibly the foundation for later work on predicting adult height.

While there have been other studies cited that have examined mid-parental height (Clemons, 2000; Cole, 2000), it was the work of Tanner and associates (Tanner, Goldstein, & Whitehouse, 1970) that examined target height and mid-parental height as variables in the prediction of adult height. A major contribution of their study was a sex-corrected mean parent height. They reported the difference to be 13 cm. In calculating target height, 6.5 cm is added to the mean parent height for a boy and 6.5 cm is subtracted for a girl. This method, however, fails to consider that maternal height has a smaller variance than paternal height (Cole, 1996). In addition, the range on which Tanner (1970) formulated the sex differences on growth data decades ago might fail to account for a secular trend in growth in stature. Thus, later data reflected a greater range in the Tanner (1970) sex-corrected stature (Wright & Cheetham, 1999).

Since the introduction of Tanner's sex-corrected version, there has been considerable interest in target height. Sorva, Tolppanen, Lankinen, and Perheentupa (1989), for example, developed two equations for the evaluation of growth with parent and child specific growth standards. Evaluating height as standard deviation scores

(SDS), they developed equations for determining parent specific mean height SDS and parent and child specific expected height SDS. The equations were made into nomograms for ease of use by a practitioner or pediatrician in detecting growth disorders (if child's height SDS differs by more than 2.0 from parent specific mean scores or 1.5 from expected score). This study served to provide initial validation in the use of mid-parental height as a variable in target height. Thus, in determining a family's height potential, mid-parental height is the best measure (Cole, 1996).

Other studies concur with the conclusions of Sorva et al. (1989) that detection of growth disorders needed to follow the concepts of regression towards the mean in mid-parental height calculation (Karlberg & Luo, 2000; Luo et al., 1998; Wright & Cheetham, 1999). This was particularly demonstrated for a normal population, but Wright and Cheetham (1999) found that short children are much more variable. A similar study on a large sample of Swedish children confirmed their findings (Luo et al., 1998).

Regression Equations

The use of multiple regression analysis has yielded several methods of predicting adult height (Roche, Wainer, & Thissen, 1975; Tanner, Whitehouse, Marshall, & Carter, 1975; Tanner, Whitehouse, Marshall, Healy et al., 1975; Walker, 1974; Żarów, 1997). Each of these studies provides coefficients to be entered into equations for various ages of children in order to predict adult height.

Walker (1974) originally sought to estimate somatotype of children, but published subsequent data on predicting adult height. Equations used by Walker were determined in one of three ways: (1) height at age alone, (2) height at age plus growth rate, and (3) height at age plus growth rate plus pre/post PHV status. Participants measured by Walker from a New Haven, Connecticut sample were cross-validated with a sample from Berkeley, California. The average error was reported at 2 to 3 cm in boys aged 9-14 years and girls 8-12 years. Thereafter, the error rate improves with increasing age for both boys and girls. When cross validating with the Berkeley sample, the equations consistently over-predicted adult heights from earlier ages. The uniqueness of Walker's study is the provision of the growth rate and status of PHV, which reportedly correlated considerably higher than height at age alone and height and growth velocity.

A protocol that utilizes skeletal age as a major variable in predicting adult height was developed using a sample of children from the Harpenden Growth Study (Tanner, Whitehouse, Marshall, Healy et al., 1975). The other variables used by Tanner and associates included present height, chronological age, and radial-ulnar skeletal (RUS) component of their TW2 radiographic assessment method. The RUS score involves the radius, ulna, and finger bones of digits I, III, and V. The accuracy of the TW2 method is based on residual standard deviation. Their data show that prediction accuracy improves with age in both boys and girls. Tanner and his colleagues reported that 95% of predictions for boys were within ±7 cm of actual adult height up to age 12, ±6 cm for ages 13 to 14, ±5 cm at age 15, and ±4 cm at age 16. For girls, the trend was the same, but there were considerations for pre- and post-menarchial participants. Tables listing coefficients for subjects delayed in skeletal maturation were also provided. The accuracy of these tables, where coefficients were based on classification by year of RUS bone age, was reported to be as accurate as the other tables except at bone ages 13-14 for boys and 12-13 for girls.

One of the more prominent and valid methods of predicting final adult stature used today was developed by Roche, Wainer, and Thissen (1974), which has been aptly referred to as the RWT method. The participants on which the regression equations were developed were white boys and girls from middle-class families of southwestern Ohio who were part of the Fels Longitudinal Study. There were 80 pieces of data collected, 78 obtained serially and two other variables, maternal and paternal stature. Most of the variables collected were individual bone ages of the hand, wrist, foot, ankle, and knee. During the first year, data were collected at one, three, six, nine, and 12 months. Following the twelfth month, children were measured every six months. Through various statistical procedures, the data were reduced to the four strongest predictor variables: recumbent length, weight, mid-parent stature, and skeletal age. Skeletal age was assessed using protocol established by Gruelich and Pyle (1959) for the left hand and wrist. Bone ages, however, were also assessed for the foot and ankle, as well as for the knee.

The investigators of the Fels Longitudinal Study compared the RWT method against the BP method, the most prominently used method at the time. Utilizing three data sets, the Fels, Harvard Boys, and Denver girls, the RWT errors were generally less than the corresponding BP errors (Roche et al., 1975). These results are also consistent with Lenko's (1979) findings on her Finnish sample that the BP tables tended to overpredict for boys and underpredict for girls. When compared to other methods, RWT holds up favorably. Żarów (1997), for example, reported absolute prediction errors when comparing the RWT method with his proposed prediction equations. The RWT had the lowest median error for boys 7-10 years of age utilizing his Polish sample. For the most part, Żarów (1997) reported his errors as similar to those of RWT. Two equations were derived by Żarów, however. The second (Z_2) utilized a simplified pubic hair development scale as a variable representing secondary sex development. With this equation, Z_2 reported smaller errors. This makes sense as it has been reported that ratings of secondary sex characteristics provide more reliable predictions of adult stature than those based on present stature and skeletal age, at least when using the BP tables (Roche et al., 1974). Lenko (1979) also reported comparable results with the RWT method and the TW2 method.

A longitudinal assessment examining the RWT, TW2, and BP prediction methods was reported by Roemmich, Blizzard, Peddada, Malina, Roche, Tanner, and Rogol (1997). In comparing the three methods, 23 healthy boys were measured every four months from about 9 years of age to final adult height. Predictions, however, were made every eight months following each method's respective protocol. Roemmich et. al (1997) found the TW2 method to yield the most accurate results with a slight tendency to underpredict. The RWT method was found to be more accurate than the BP method, which tended to overpredict more than the RWT method. Preece (1988) found that the RWT and TW2 predictions to also be more accurate than the BP predictions for normal population samples, but the BP predictions appear to be more accurate for subjects that have growth that is delayed or advanced (Preece, 1988a).

A key element to each of the RWT, TW2, and BP methods is skeletal age. The RWT method appears to concur with other methods (Bayley & Pinneau, 1952; Tanner, Whitehouse, Marshall, Healy et al., 1975) that skeletal age is a powerful predictor variable in estimating final adult stature. Utilizing skeletal maturity, however, presents obstacles in its usefulness. Radiographic protocols, the standard for assessing skeletal age, are expensive procedures and introduce participants to radiation exposure. There are also differences in assessment protocols, a fact substantiated in comparing TW2 and Gruelich-Pyle methods (Lenko, 1979) where the two simply yield different bone ages (Malina & Bouchard, 1991). To increase clinical usage of final adult stature prediction, the mid-parent stature and/or skeletal age variables can be removed from the RWT method without serious loss of accuracy (Wainer et al., 1978). Wainer and colleagues (1978) explain that in missing a variable, the mean of the predicted statures is equal to the mean of the actual statures for the corresponding sex. The mean is used as a default option and additional information from the predictor variables leads to a prediction for the individual that differs from the mean (Wainer et al., 1978). This was one of the first studies that examined the accuracy of prediction for an individual without including skeletal age and/or the father's height. The predictive accuracy was reported to be modest at all ages.

Noninvasive Methods

Roche, Tyleshevski, and Rogers (1983) have proposed a method of assessing physical maturation by noninvasive means. In predicting final adult stature, the RWT method can be modified by substituting chronological age for skeletal age in the regression equations. This can only be done, however, for boys under the age of 14 years and girls under 12. They reported that this noninvasive method applies for boys between 5-15 years and 3-13 years in girls. Reference data would also be necessary to assess an individual or a group to infer maturity.

More methods have been developed in recent years (Beunen et al., 1997; Khamis & Roche, 1994) that address noninvasive techniques of assessment. The Beunen-Malina method [BM] (Beunen et al., 1997), for example, considers the prediction of adult stature in boys aged 13 – 16 years of age. For reasons similar to those of Roche et al. (1983), the BM method was devised on the premise that it could be used as a maturity indicator in field studies of physical performance in youth sports. Like the modified RWT method (Roche et al., 1983), the prediction equation was developed in the absence of skeletal age as a predictor variable. They used a sample (n=102) from the Leuven Longitudinal Growth Study of Belgian Boys that were measured serially up to 18 years and then followed up at ages 30 and 35 years. Their predictor variables were current stature, sitting height, triceps and subscapular skinfolds, and chronological age. The authors compared their results to the original Tanner-Whitehouse prediction method and reported their results as favorable when compared to it. The BM method from ages 12.5 to 16.5 years had correlation coefficients range from 0.70 to 0.87 and standard error of estimate (SEE) values from 4.2 cm to 3.0 cm, respectively. The correlations for the TW method using skeletal age (ASTW) were the highest. Substituting chronological age for skeletal age (ASCA) yielded the lowest correlation coefficients. The correlation coefficients for the BM method were in between the ASTW and the ASCA.

Khamis and Roche (1994) established a method of predicting final adult stature using noninvasive means as well. Their method is considered to be more useful in the sense that there are only three variables in the prediction equation: stature, weight, and mid-parent stature. These variables were produced following the same methods as the RWT method. Unlike the Beunen-Malina method, however, the Khamis-Roche method has prediction equations and corresponding coefficients for both boys and girls. Participants of the Fels Longitudinal Study were followed from 1 month to 18 years of age, the age which is the excepted standard for adult stature. However, it has been shown that both boys and girls can grow beyond these chronological ages (Malina & Bouchard, 1991). The authors report a slight deterioration in prediction accuracy when comparing it to the modified RWT method, especially during pubertal years. Żarów (1997) also made comparisons to the Khamis-Roche method with his two prediction equations (Z_1 and Z_2); the former reported higher values of error in prediction than the latter. The comparison, applied to a Polish sample, is questionable due to the fact that Żarów (1997) used skeletal age as a predictor variable (Z_1) and an estimator of secondary sex development (Z_2).

Biological Maturation

Simply stated, maturation is biological system-specific progression towards an adult state of function within an individual. Similarly, maturity is the end result of the progression or the adult state of a biological system. Timing and sequence of these maturational events are typically used as landmarks in tracking and studying these phenomena for auxological or human performance purposes. The systems typically used are skeletal, sexual, and somatic. To a lesser extent, dental maturation can be used. The maturation indicators are studied with respects to a sample of children, but it is important to point out the individual variation that is common to maturation. Just like biological systems are independent in their progress towards a mature state, individual children are also independent in their progress towards becoming a mature adult. Boys and girls of the same chronological age do not necessarily have the same biological age. There are children that do indeed proceed in concert with norms for their chronological age, just as there are some that proceed in advance or behind norms for their chronological age.

This review will focus on the skeletal and somatic maturation of children as they pertain most to the methods of prediction of adult height and estimations of maturity. This section will also focus on the most prevalent somatic maturation indicator, peak height velocity, as well as the classification of early-, average-, and late-maturing individuals.

Skeletal Maturation

Skeletal maturation is the progress from an immature form of osseous tissue (cartilage) to a mature, fully ossified state including full morphological characteristics of specific bones. The uniqueness of utilizing the skeletal system for maturation indicators is that the beginning and end points of the process are known and, because of this, it has an advantage over other systems. The rate of skeletal maturation varies from bone to bone as well as between individuals. The characteristics of this progress from the cartilage to initial bone formation, to the shape of the bone, and eventual adult morphology are unveiled by various methods and do not yield the same result (Malina, Bouchard, & Bar-Or, 2004). The result, or skeletal age, is derived from methods of interpreting an X-Ray of the left hand and wrist. Other areas of the skeleton can be used to obtain a skeletal age (i.e., the knee), but the hand and wrist is the most common because it is reasonably typical of the skeleton as a whole (Malina, Bouchard, & Bar-Or, 2004).

Methods of Skeletal Maturation

There are three primary methods for estimating the maturity of the skeletal system utilized in both clinical settings and human performance studies. These methods are the Gruelich-Pyle (GP) Method (Gruelich & Pyle, 1959), Tanner-Whitehouse (TW) Methods (Tanner, Healy, Goldstein, & Cameron, 2001; Tanner, Whitehouse, Marshall, Healy et al., 1975; Tanner, Whitehouse, & Healy, 1962), and the Fels method (Roche, Chumlea, & Thissen, 1988). What is important about these different methods, for the purpose of this review of literature, is the individuality of each method. The similarities are in the use of a hand/wrist radiograph of a child and matching characteristics to an atlas, photo, and/or written description. The scores yielded by each, the respective SA, however, are not the same between methods of assessment. Thus, when interpreting the SA of a child, the method used for assessment is a necessary aspect of the SA to know.

The exact methodology for each skeletal maturation assessment method is beyond the scope of this paper. For a detailed description of each method, the reader is deferred to the respective reference.

Somatic Maturation

When serial growth measurements for a child are available and respective growth curves are plotted, then parameters of the growth curve can be used as maturation indicators. Examples include age at which the growth spurt occurs, maximum rate of growth during the growth spurt (PHV), and age at PHV. Therefore, somatic maturation is traditionally a longitudinal, retrospective analysis of maturation based on size attained at various ages or intervals. The more salient aspect of serial measurements is the change in velocity, or rate of growth that mark the entry into adolescence. Thus, the most common somatic maturation indicator is peak height velocity, or more importantly, the age at which peak height velocity occurs. Serial measurements can also provide a percentage of adult height attained but only if a final height is known.

Peak Height Velocity

A plot of serial height measurements against time (years) increments yields a distance growth curve and provides information about how much a child has grown from interval to interval. A velocity curve, however, yields the rate at which a child attains his/her height, revealed simply by the difference between two successive measurements/intervals. The velocity curve provides two important parameters: initiation of the growth spurt (take-off) and maximum rate of growth during the spurt (PHV). The age, rate, and size attained for both take-off and PHV are also provided. The benefit to knowing these parameters is in making comparisons to other maturation indicators (i.e., secondary sex characteristics), growth of other body dimensions, and human performance scores.

Initiation of the growth spurt tends to occur around the ages of 9-10 years for girls and 10-11 years of age for boys. The average age for peak velocity for girls and boys is 12 and 16 years, respectively. Finally, termination of the growth spurt or circumpubertal period for girls tends to fall at 16 years and 18 years of age for boys (Malina, Bouchard, & Bar-O4, 2004).

In order for the velocity curve to reveal the salient parameters, however, the curve requires interpolation. There are several methods used to calculate the parameters of the adolescent growth spurt. The most basic method is simply an analysis of changes between two observation periods. The obvious disadvantage is that simply connecting the increments with a straight line overlooks the continuity of the growth process. Individual longitudinal data must be smoothed by some procedure to remove measuring error, the effects of seasonal variation, and variations that may arise due to other causes (Tanner, Whitehouse, & Takaishi, 1966b). Graphic, mathematical-fitting, and smoothing-polynomial approaches provide a good description of the human growth curve for stature during adolescence and of the main parameters of the curve (Malina, Bouchard, & Beunen, 1988).

Graphic. Tanner, Whitehouse, and Takaishi (1966b) developed a method of calculating growth velocity from data obtained from the Harpenden Growth Study by three cycles of smoothing. The first cycle involves plotting a distance graph of a child's height at each age. A line of best fit is drawn to represent the growth pattern, not by connecting the dots, but between dots to represent a path of growth. They called this a fitted growth curve. The second cycle called for the increments of the fitted curve to be read off at three-month intervals, converted to cm/yr units and plotted. A velocity curve is then drawn by fitting the dots of the three-month increments. Finally, the actual increments given by the individual's measurements are then plotted. The fitted increments and the measured increments are compared and an adjusted velocity curve is drawn if deemed necessary.

The graphical method can also be fitted to longitudinal growth of other body dimensions. The pattern of growth in stature is followed by several commonly measured anthropometric measurements (Marubini, 1978). An example is provided by Bielicki and Welon's (1973) examination of growth velocities of 250 Polish girls, ages 8-17 years. In determining PHV of eight different somatic measurements, there were three different schemata used to graphically interpolate the peak. The schemata utilized a fitted (French) curve and the location of the two increments immediately adjacent to the peak. A schema was chosen based on the location of two points adjacent to the peak and position of the peak relative to the positions of the two adjacent increments.

Graphical interpolation is clearly only an approximate method (Tanner et al., 1966b) and can be criticized for not only the crudeness but that it implies too high a degree of accuracy in locating a true peak (Bielicki & Welon, 1973). The graphical method can also be considered biased and can only be reproducible by skilled hands (Largo, Gasser, Prader, Stuetzle, & Huber, 1978). While it is recognized as a crude measure, the results can yield parameters of the adolescent growth spurt and provide a good description of the human growth curve to stature and other bodily dimensions (Malina et al., 1988).

Mathematical. The use of mathematical formulae to fit the serial measurements of an individual has been utilized in a variety of models. Fitting of individual growth curves via mathematical model is also called a structural approach. Espousing the structural approach over non-structural approach (i.e., smoothing), Bock and Thissen (1984) state the purpose best:

> "In the structural approach, the objective is to find a mathematical model, usually expressed as a family of functions relating observable quantities in terms of unobservable parameters. The parameters are then estimated by those values that best fit the function to the particular record. If the model is found to fit sufficiently well and the number of parameters is small relative to the number of observations, the statistical estimation of the parameters is tantamount both to summarizing and to smoothing the record." p 266

Logistic functions (i.e., Gompertz) were first used to describe the adolescent growth spurt and were followed by single, double, and triple logistic models as well as modified logistic models (Malina et al., 1988). Logistic curves provide a good fit to growth in stature during puberty (Healy, 1978), but suffer from large numbers of parameters with no clear meanings and render them problematic (Preece & Baines, 1978). Regression equations have also been used to fit growth curves. The least squares method has typically been employed (Hoang & Parsons, 1984). The use of nonlinear least squares methods, however, have been cautioned and generalized least squares method preferred (Hoang & Parsons, 1984).

The complexity of mathematical modeling is obvious in the computation, which has been made more manageable with the advancement of microcomputers. Another challenge appears to be in deriving biologically meaningful information from the selected mathematical model, from which there are many to choose. The selection of the model should be one that best characterizes the growth process.

Due to the equal complexity of the human growth process, it has been suggested to divide the curve into cycles and fit each of them separately (Karlberg, 1984; Marubini, 1978). The growth period has been separated into three phases (Karlberg, 1984) and into two broad phases (Deming, 1957). Separating the curves into different areas allows for a more biologically meaningful interpretation.

The mathematical model that has received a lot of attention in recent years is that of Preece and Baines (1978), specifically, the Preece-Baines Model I (PB1). These authors created a family of mathematical models that could describe the whole growth curve. Four different models were created, but it is the first model that received the most satisfactory results. They contend that their model provides a better fit to the growth curve as well as a reduction in the number of parameters for each individual. Variables that can be calculated using PB1 are: age at take-off; height at take-off; velocity at take-off; age at PHV; height at PHV; PHV; height increase or take-off to PHV; velocity increase or take-off to PHV; percentage adult height at take-off; and, percentage adult height at PHV.

Another important consideration of the mathematical model that requires addressing is that the model should be fitted to individual growth curves. Bock and Thissen (1984) state that the structural model-fitting approach to longitudinal data analysis is more productive of applications and articulates better with physical or biological theory than does the non-structural (i.e., smoothing polynomials). Similar to high-order polynomials, smoothing spline functions suffer from too many parameters that have no clear meaning (Preece & Baines, 1978).

Smoothing Polynomials. The smoothing spline technique is a rather well-known approach for curve fitting and interpolation of growth curves (Oosting & Negelkerke, 1984). Smoothing splines seek to unveil parameters that summarize the important properties of the human growth process. The common way to do this has been to fit a parametric family of curves and ascertain the parameter values for each individual by the least squares method (Largo et al., 1978). Spline methods, however are non-parametric and no fixed parametric functions needs to be postulated for modeling growth (Gasser et al., 1984). Human growth is highly variable before, during, and after puberty and this difference presents a problem to finding a parametric family of curves to fit all individual series of measurements without systematic errors as well as summarize the property of curves needed for analysis (Largo et al., 1978).

Smoothing polynomials can provide a good fit to data and estimate parameters of human growth (Malina et al., 1988). However, using polynomials can be problematic and underestimate parameters (Largo et al., 1978). Marubini (1978) illustrated that polynomial equations are shown to not fit data as well as generalized logistic and logistic Gompertz functions and should be avoided.

Maturity Estimation

The maturity status of youth has been well documented as well as matuirty associated variations with respect to sex, chronological age, and even motor performance (Malina, Bouchard, & Bar-Or, 2004) . In recent years, there have been a number of research articles that address maturity estimation, particularly in the area of youth sports and injury prevention. This section will address percentage of adult height as a maturation indicator, application of percentage of adult height utilizing prediction of adult height, and other maturity estimation studies.

Percentage of Adult Height Attained

When the final height of a child accompanies serial growth measurements, a percentage of their adult height can be obtained. This is helpful when comparing children of the same chronological age. A child closer to his/her adult height, thus, yielding a higher percentage than another child, is more advanced in skeletal maturity.

The disadvantage to using percentage of adult height as a maturation indicator is the necessity of a final height measurement. The development of prediction methods for adult height, however, increases the utility of percentage of adult height maturation indicators.

Boys and girls will usually reach 91.3% of their adult height at their age of PHV. At the end of their growth spurt, boys will have achieved 97.5% of their adult height and girls will have achieved 96.5% of their adult height (Largo et al., 1978).

Noninvasive Methods for Maturation Indicators

The utility of percentage of adult height as a maturity indicator needs further validation (Malina et al., 2004). Several studies to date have explored this issue with relative success or utilized this procedure in an effort to assign youth to a maturation level (Battista et al., 2003; Cumming, 2002; Dompier, 2005; Malina, Cumming et al., 2005; Malina, Koziel, & Bielicki, 1999; Malina, Morano, Barron, Miller, & Cumming, 2005; Morano, 2003). While a few of these studies had mixed-longitudinal data (Malina, Cumming et al., 2005; Malina, Morano et al., 2005), none of the studies had longitudinal data and corresponding final adult height measurements. Dompier (2005), however, did have skeletal ages for participants which allowed for comparison of maturation indicators (predicted percentage of adult height and SA).

As mentioned in the previous section, several studies have been conducted in recent years that have utilized a noninvasive method of assigning youth to a maturational indicator. The somatic indicator is a predicted percentage of adult height. The somatic maturation indicator of percentage of adult height requires a final height. Because of this,

this method has been used in retrospective examinations involving longitudinal data that provided a final height measurement. In order to use this somatic maturation indicator in studies where the research participants have not concluded their statural growth, several studies (Battista et al., 2003; Cumming, 2002; Dompier, 2005; Malina, Cumming et al., 2005; Malina et al., 1999; Malina, Morano et al., 2005; Malina, Morano et al., 2006; Morano, 2003) have used a method to predict their final adult height. Each of these studies utilized the Khamis-Roche method of adult height prediction, a noninvasive method that substitutes chronological age for skeletal age.

Each of these studies reflects the need to assign maturational indicators in studies of youth in sports. Cumming (2002) examined biological maturity as a factor in gender and program differences for perceived physical and soccer confidence of recreational and travel team soccer players. Similarly, Battista et al. (2003) examined sex and program related differences in heights, weights, and biological maturity status of youth recreational and travel team soccer players. They found that male and female soccer players approximated the reference values for height, but were above the median weights reference values. This study concluded that the noninvasive estimate of biological maturity status was consistent with results for youth soccer players based on skeletal age and sexual maturity.

Estimation of biological maturity status was also employed in several studies utilizing youth (American) football players and incidences of injury (Dompier, 2005; Malina, Cumming et al., 2005; Malina et al., 1999; Malina, Morano et al., 2005; Malina, Morano et al., 2006; Morano, 2003). Malina, Cumming, Morano, Barron, and Miller (2005) utilized the KR method to assign youth football players to a maturational status.

The advantage to using this method is that percentage of mature height attained at a given age has been found to be positively related to skeletal maturity during childhood and sexual, skeletal, and somatic maturing during adolescence (Malina et al., 2005). The current height of a football player was expressed as a percentage of his predicted mature height to provide his maturity status. A z-score was computed for the predicted percentage of mature height. A z-score between -1.0 and +1.0 was deemed average or on time. A z-score greater than +1.0 indicated an early or advanced maturity status and a z-score below -1.0 indicated a late or delayed maturity status (Malina, Cumming et al., 2005). The z-score also allowed for comparison with longitudinal studies, the Fels (Roche et al., 1983) and Guidance Study (Bayer & Bayley, 1959) samples. The two different samples were needed because Fels data provided only reference data on the whole year interval (within two months of birthdate) and the Guidance Study provided reference data on half-year intervals.

Initial research involving the noninvasive method for assessing biological maturity has demonstrated that this method is applicable in boys between 5 and 15 years of age, and females between 3 and 13 years of age (Roche et al., 1983). More recent research (Khamis & Roche, 1994), however, suggests that this method of assessing biological maturity is applicable for males and females between the ages of four and seventeen years. Morano (2003), for example, applied the KR method in order to estimate biological maturity status and examine its relationship as a predictor of injury in youth football. He also examined other variables, such as height, weight, and body mass index as predictors of injury.

Like the aforementioned studies utilizing KR in predicting percentage of adult height, Dompier (2005) investigated the validity of this method in youth football players. Additionally, he examined maturity as a risk factor for injury in the same population. The study design was not longitudinal, but utilized skeletal age to validate the predicted percentage of adult height. He concluded that the noninvasive KR method of predicted adult stature is a valid estimate of maturity when current stature is expressed as a percentage of predicted adult stature.

The value in the research on youth football is significant because it revealed several findings about youth football. In youth football, the players were characterized as taller, heavier boys when compared to American reference values (Malina, Morano et al., 2005; Malina, Morano et al., 2006) and they tend to be early maturing. Addressing injury in youth sports, particularly in youth American football, is another salient issue. Malina, Morano, Barron, Miller, Cumming, and Kontos (2006) reported injured fourth through fifth grade participants were significantly lighter in weight with lower BMI than older players. Additionally, injured and noninjured players did not differ in predicted adult height and estimated maturity status was not a significant predictor of injury.

Other Methods of Estimating Maturity

While most studies that use noninvasive methods of maturation have utilized a prediction of adult height method, one other study (Mirwald, Baxter-Jones, Bailey, & Beunen, 2002) developed a maturation indicator by predicting age at peak height velocity. Mirwald et al. (2002) developed a simple, noninvasive method to assess maturity status in children in years from peak height velocity by using anthropometric variables. By using age of PHV as the maturational benchmark, each of their anthropometric measurement occasions were described as years from PHV. This was done by subtracting age of PHV from the chronological age at each measurement occasion. The difference, therefore, indicated what they termed a value of maturity offset. The variable used to predict maturational status was leg length to sitting height ratio. As a single measurement on two occasions, approximately one year apart, it provides a broad categorization of maturity. If the ratio is increasing, the individual is pre-PHV and if the ratio is decreasing, the individual is post-PHV (Mirwald et al., 2002, p. 691). Predictive equations for both boys and girls were established and cross-validated from two prominent longitudinal studies. They conclude that the equations can be used within acceptable statistical standards and reported their proposed maturity offset be estimated within an error of ± 1 year 95% of the time, sufficient for adolescence to be assigned a maturational classification.

Clinical Use of Height Prediction

Utility of height prediction methods are more widely used by clinical endocrinologists and pediatric physicians than researchers and/or practitioners in kinesiology. There have been a myriad of studies published regarding conditions of excessively tall stature (i.e., familial or constitutional tall stature) and the excessively short stature (i.e., idiopathic growth hormone deficiency). It is important, however, to know each method's tendency to overestimate or underestimate adult height, and to be aware of the errors of estimate whether a child is receiving or is not receiving treatment (Brämswig et al., 1990). This research, however, is beyond the scope of this paper. This portion of the review will highlight areas of height prediction as they pertain to the validity of the three most commonly used methods: BP, RWT, and TW2.

Clinical Studies of Excessively Tall Stature

Excessively tall stature is often termed overgrowth, which connotatively can offer a broad range of conditions including, but not limited to: endocrine hormone disorders, normal variant conditions, syndromes with known genetic mutations, and those with unknown mechanisms (Ambler, 2002). A typical overgrowth syndrome is constitutional or familial tall stature (CTS) and is assigned to a child that has a height more than two standard deviations (+2 SD) above the mean for categories of age, sex, and racial group when no other pathological conditions associated with tall stature are recognizable (Ambler, 2002). Prediction of adult height is an important tool in the management of tall children (de Waal, Stijnen et al., 1996). These children are often treated with hormones (such as diethylstilbestrol in girls and fluoxymesterone in boys) to decrease the velocity of growth and ultimately return a child to a median percentile for height acceptable to the child, parents, and physician (Gardner, 1975). Other characteristics of CTS are mean birth length at the 75th centile (+0.7 SD), a +2.5 SD at 4 years of age, and a +2.75 SD during the years between 4 and 9 years (Ambler, 2002).

Bayley-Pinneau. Several studies have used the BP method to assist in the diagnosis of growth disorders and certainly in evaluating treatment of growth disorders. This is probably due in part that Bayley and Pinneau (1952) included tables for children with bone ages within one year of CA, tables for at least one year in advance of CA, and tables for one year of delay in CA. It is also the simplest method to use with a single table design for the physician to calculate the predicted mature height according to bone age (Preece, 1988b). There is a tendency for the BP method to greatly overestimate boys, especially before the age of 12 years where there is slight improvement thereafter (Joss et al., 1992). Joss et al. (1992) reported an overestimation of girls between 9-12 years but show improvement with increasing age.

The BP method is typically used to monitor treatment of tall children. For example, Decker, Partch and Sippell (2002) evaluated their use of a combination therapies for tall boys. While recognizing that other studies found the BP method to overestimate boys by +2 cm (de Waal, Stijnen et al., 1996; Joss et al., 1992), they found a decrease in predicted adult height after six months of treatment from the initial prediction.

In the case of girls, there is a general consensus that the BP method tends to underestimate. For example, de Waal, Stijnen, Lucas, van Gurp, de Muinck Keizer-Schrama, and Drop (1996) compared their proposed adult height prediction method to other methods. When the BP method was used on their sample of 16 tall girls, it underestimated by –0.2 cm (±3.1) and an absolute error range of –6.4 to 5.4 cm was reported. In a larger study, de Waal, Greyn-Fokker, Stijnen, van Gurp, de Muinck Keizer-Schrama, and Aarsen (1996), reported an overestimation for girls (+0.5±2.7) in terms of mean error.

Tanner-Whitehouse. As previously reported, the BP method is easier to use and that ease of use is probably why it used so often. The accuracy of the TW2 method for predicting adult height has also been evaluated (de Waal, Greyn-Fokker et al., 1996; de Waal, Stijnen et al., 1996; van Teunenbroek et al., 1996). Joss, Temperli, and Mullis

(1992) found that TW2 provided a good estimation of final height when bone ages reach 13 years with a 1 cm overestimation. With increasing age, there is an increase in overestimation, especially in boys +3SD scores. Other studies (de Waal, Greyn-Fokker et al., 1996; de Waal, Stijnen et al., 1996) have found that the TW method systematically underestimate final height while the BP method overestimate (Ambler, 2002).

The TW method was transformed into a computer-aided scoring system for skeletal age in an effort to reduce the error of interpretation of maturity stages. This is significant for improving the accuracy of predicting adult height when protocols utilizing SA are necessary. To evaluate the reliability of the computer-aided skeletal age scoring system (CASAS), van Teunenbroek, de Waal, Roks, Chinafo, Fokker, Mulder, de Muinck Keizer-Schrama, and Drop (1996) compared results with normal, healthy children (81 boys, 70 girls) as well as children with growth pathologies. Eighty-seven girls with Turners Syndrome and 362 children with CTS (115 boys, 247 girls) made up the growth pathology groups, respectively. The TW method of estimating bone age employed both a 13-bone and 6-bone protocol. Results were favorable for all populations of boys and girls.

Clinical Studies of Excessively Short Stature

There are more studies that deal with short stature than there are with excessively tall children. Just as parents of tall children, as well as the child himself/herself, is concerned with being too tall, seek an intervention to slow growth the same is generally true for children diagnosed with idiopathic central precocious puberty (ICPP). The general concern is that these children when untreated will be short adults because of early maturation of the bones (Bar, Linder, Sobel, Saenger, & DiMartino-Nardi, 1995). The general cause of accelerated somatic and pubertal growth result from increased production of sex steroids (Kirkland, Gibbs, Kirkland, & Clayton, 1981).

Most of the prediction methods were created and evaluated with normal children, or those children that do not present growth pathology (Hintz, 1996). Recognizing this fact, there have been an increasing number of studies that examine the accuracy of height prediction methods with populations of short children (Brämswig et al., 1990; Cara, Kreiter, & Rosenfield, 1992; Maes et al., 1997; Südfeld, Kiese, Heinecke, & Brämswig, 2000; Zachmann, Sobradillo, Frank, Frisch, & Prader, 1978). These studies range from diagnosis to monitoring treatment.

Height Prediction and Diagnosis. The accuracy of five different methods of predicting adult heights on untreated boys and girls of short stature was examined by Brämswig, Fasse, Holthoff, von Legerke, von Petrykowski, and Schellong (1990). The methods tested were the BP, RWT, target height, TW1 and TW2. Utilizing 37 boys and 32 girls of short stature, height predictions were made for total group and children that had parents and siblings of normal height. The predictions gave similar results for girls when examining absolute error, with no method superior to the others. The BP, TW1, and TW2 methods elucidated underestimation while the RWT method overestimated. In addition, the short statured girl in the familial short stature sample obtained better prediction results except when using the RWT method. The RWT method, however, provided the best results for boys for all groupings of boys. The BP method overestimated boys by 3.1 cm, yielding similar results to other studies (Lenko, 1979). Both TW1 and TW2 underestimated adult height.

Bar, Linder, Sobel, Saenger, and DiMartino-Nardi (1995) examined the accuracy of the BP method on girls and found the method to be useful in identifying those girls with ICPP at risk for short stature. Although the sample was small (n=20), 75% of the girls achieved a final height within 6.3 cm of their original height prediction which was promising because 99% of normal children grow to within 6.3 cm of their initial height prediction (Bar et al., 1995). Kirkland, Gibbs, Kirkland, and Clayton (1981) also performed a retrospective study, but arrived at a different opinion of the BP method. They found that the BP method produced both overestimation and underestimation with no clear trend for either. The uniqueness of their study, however, illustrated that the predictions for short girls tended to improve as the child approached adult stature. One can then assume that early detection of ICPP, to which early diagnosis is essential, that the BP method would not be useful.

Roche and Wettenhall (1977) examined the accuracy errors in the RWT and BP methods of predicting adult heights on untreated short boys. The accuracy was determined from the differences between the height prediction and final adult height with absolute and relative errors being reported (Roche & Wettenhall, 1977). In the case of the 28 short, Australian boys, the RWT method tended to overpredict and BP method to underpredict. This sample of short boys had a slightly more accurate prediction of adult height than normal boys of the same age. Finally, the RWT method was slightly superior to the BP method.

Monitoring Treatment with Height Prediction. The above studies examined accuracy of adult height prediction methods with untreated boys and/or girls. Other studies have examined the effectiveness of a treatment by utilizing adult height prediction methods (Hochberg, Leiberman, Landau, Koren, & Zadik, 1994). Hochberg, Leiberman, Landau, Koren, and Zadik (1994) examined the impact of age on predicted adult height, and subsequent bone maturation on 65 boys being treated with human growth hormone. Prediction methods examined were the BP, RWT, and TW2. They found that the RWT predictions were significantly higher than those of TW2 and BP, which tended to give more indistinguishable results. However, factoring in the added or lost height in predictions due to treatment, each method was statistically similar (Hochberg et al., 1994). Similar to previous studies (Kirkland et al., 1981; Zachmann et al., 1978), they also reported that younger ages provided greater errors on prediction and that advancing CA increases predictive accuracy.

Summary

There is a clear and present need for assigning youth to a maturational indicator for use in teaching physical activity and coaching youth sports as well as in research involving young athletes. Providing practitioners and researchers with a tool that facilities assignment of maturational indicators that do not violate or perpetuate insecurities of youth participants is in the best interest of all involved. Clearly, the Khamis-Roche method of predicting adult height has proven to be a valuable tool in conducting research on youth within the field. Furthermore, several studies mentioned in this review of literature have reported favorable results supporting somatic maturational indicator based on predicting adult height in order to obtain a percentage of adult height. If the Khamis-Roche method can be validated against another longitudinal sample, further support will be provided for such findings.

CHAPTER III

RESEARCH METHODS

The specific aims of this investigation are: (a) to determine if the Khamis-Roche method of predicting adult height is valid when applied to a sample of mid-Michigan children and; (b) to estimate biological maturity status based on a predicted percentage of adult height.

This chapter is divided into two major sections. Because this study includes data collected in the Motor Performance Study (MPS) at Michigan State University, the first section provides a brief history of the MPS, its participants and the data collection procedures pertinent to the current study. The second section contains information regarding the procedures to be followed in implementing the current study.

Motor Performance Study

Background Information

Some of data for the current study are derived from the Motor Performance Study (MPS), a 37 year longitudinal study conducted in the Department of Kinesiology at Michigan State University. The MPS was initiated in 1967 to investigate the physical growth and motor performance of children and youth. Haubenstricker, Branta, and Seefeldt (1999) state that the purposes of the study were to determine:

1. the changes over time that occur in the physical growth, biological maturity, and motor skill acquisition of children and youth;
2. the processes involved in the attainment of basic and complex motor skills; and

3. the influence of changes in the learners' environments on the rates of motor skill acquisition (p. 105).

While the original aims of the study included motor skill acquisition, the thrust of the current study involves the first purpose of the MPS. Implications for the second and third purposes, however, will be generated based on the results of this study.

Variables collected for physical growth and motor performance are listed in Table 3-1. Not included in the list of variables is skeletal maturation. Hand and wrist Roentenograms were collected annually during the summer season from 1968 to 1975, but the practice was discontinued for practical, perceived safety and financial reasons.

Table 3-1. Physical growth (anthropometry) and motor performance variables collected semi-annually in the Motor Performance Study.

Anthropometry	Motor Performance
Weight	Flexed-Arm Hang
Standing Height	Jump-and-Reach
Sitting Height	Thirty-yard Dash*
Biacromial Width	Sit-and-Reach
Bicristal Width	Agility Shuttle Run
Acrom-radiale Length	Standing Long Jump
Radio-stylion Length	400-foot Shuttle Run
Arm Girth	Balance Beam Walk**
Thigh Girth	
Calf Girth	
Triceps Skinfold	
Subscapular Skinfold	
Umbilical Skinfold	

* running start

** part of original data, but discontinued

MPS Participants

Original procurement of research participants for the MPS utilized an application procedure in which mid-Michigan residents learned of the study in the area newspaper. Subsequent annual additions to the study were made from a waiting list. During the course of its 37-year history, 1,220 children and youth (647 boys and 573 girls) participated in the MPS. Approximately 97% of the participants are Caucasian. The current study will use data from a sub-sample of the 1,220 participants, specifically those who attained adult stature while active in the study.

MPS Data Collection Procedures

Physical growth and motor performance data were collected semi-annually during the months of June-July and December-January. Arrangements for data collection were made by telephone and participant files were arranged in the order of scheduled appointments. Forms utilized for this purpose are located in Appendix D. Chronological age in months was calculated for each subject and entered on the subject's longitudinal record. Upon arrival, current grade in school and date of measurement were entered on the record. Once these data were recorded, anthropometric measurements were taken and recorded.

The instruments used to collect the anthropometric (growth) data included a standard, free-standing anthropometer (GPM Anthropological Instruments; Zurich, Switzerland) with sliding beams, bow caliper, stainless-steel measuring tape, Lange skinfold caliper (Beta Technology Inc.; Cambridge, Maryland), platform scale, and 30 cm and 60 cm wooden benches.

The physical growth measurements were taken by three primary investigators and trained graduate students. Participants were requested to wear appropriate attire, boys in trunks and girls in a two-piece swim outfit or shorts and a tank top. Thirteen measures of somatic growth included weight, height measurements (standing and sitting), breadth measurements (biacromial and bicristal), limb length measurements (acrom-radiale and radio-stylion), girth measurements (arm, thigh and calf), and skinfolds of subcutaneous fat (triceps, subscapula, and umbilicus).

Measurements were recorded to the nearest millimeter on all variables except the skinfolds (0.5 mm) and weight (nearest pound). Limb length, girth, and skinfold measurements were taken on the left side of the body. The specific protocols for all anthropometric measurements are provided in Appendix A.

Procedures for the Current Study

The procedures used for the current study are presented in this section. They include identification of the research participants, informed consent procedures, new data collection, statistical design, and data analysis. Statistical design and data analysis will be organized according to the two specific aims to this study: (a) to validate the Khamis-Roche method of predicting adult height, and (b) to estimate biological maturity status based on a predicted percentage of adult height.

Participants

Two groups of participants were identified for this study: (a) MPS participants with recorded final heights; and (b) the parents of these participants. In order to ascertain which MPS participants had final adult heights recorded, a list of all the participants was printed. The list contained information regarding the status of each participant, including whether or not the participant had completed his or her growth in height. Those participants who had completed their growth in height were potential participants for the current study. Individuals who had three consecutive measurements within 3 mm of each other were defined as having completed their growth in height. The list yielded

568 individuals (269 males and 299 females), who had completed their growth in stature. Inclusion of these participants in the current study was contingent on the availability of information from their parents.

The current study required information about the stature of the parents of the MPS participants; however, the original MPS data did not include this information. To obtain the names and addresses of parents, the original file folders of participants stored in filing cabinets in a secure room were examined. The file folders contained contact information, including the work and residential telephone numbers and the mailing addresses of the parents. Since some of this information is dated, each mailing address and telephone number was verified using a current, local telephone directory. If no current listing was found, additional sources were consulted including a current MSU Faculty/Staff Directory, Internet search engines (i.e., Google and Yahoo), and Internet directory (i.e., Yahoo People finder, http://people.yahoo.com). In some instances, MPS participants (now adults) were contacted in order to locate their parents.

Informed Consent

The extant data on the MPS participants were collected under informed procedures prevailing at the time that they were collected and will not be discussed further here. However, informed consent was required of the parents who decided to participate in the current study. Human subjects approval was granted by the Institutional Review Board (IRB). The IRB approval documentation is provided in Appendix C. The investigator of the current study and the principal investigator of the MPS prepared a letter that served both as informed consent and as a means of data collection. The letter identified the specific aims of the current study in addition to requesting their adult height. A copy of the letter is placed in Appendix D. Included in the mailing was a coded form on which the parents were to record their name and self-reported adult height. The letter and form, written on official letterhead of the Department of Kinesiology, included a self-addressed, stamped envelope in which the parents were to return the completed form to the investigator. In some instances, the parents were contacted by telephone as a follow-up or as an alternate form of collecting their reported heights. The script for the telephone conversation is also included in Appendix D.

All participants were assured of anonymity in treatment of their data with confidentiality. Likewise, they were provided contact information for further inquiry into the study and were also assured that they were able to withdraw from the study at anytime without prejudice.

Data Collection

Letters and forms were mailed to parents of those MPS participants who had completed their growth in stature. Parents were requested to complete the enclosed form by providing their name and maximum height (in feet and inches) if they consented to participate in the study. If they did not wish to participate, they were requested to return the form containing only their name to avoid follow-up correspondence. Self-reported maximum height was requested because many of the parents today are senior citizens and no longer are as tall as they were in their 20s and 30s. In those instances where a parent is deceased, the surviving spouse was asked to provide the maximum height of the deceased parent.

If a response was not received within two weeks after the initial mailing, a follow-up mailing or telephone call was made. Only those MPS participants for whom the height of both parents was received were included in the current study.

Khamis-Roche Method

The first objective of this study was to determine if the Khamis-Roche method of predicting adult height is valid when applied to a sample of mid-Michigan children. This section will describe procedures used in calculating predicted adult height as established by Khamis and Roche (1994).

Predicting Adult Height Using the KR Method. The variables necessary for the KR method are current height, current weight, and mid-parent height. The regression equation used to predict adult height follows:

$$PAH = \beta_0 + (\text{stature} \times \beta_1) + (\text{weight} \times \beta_2) + (\text{mid-parent stature} \times \beta_3)$$

where PAH = predicted adult height, β_0 = intercept, β_1 = coefficient for child's stature in centimeters, β_2 = coefficient child's weight in kilograms, and β_3 = coefficient for mid-parent stature in centimeters. A table of coefficients was published separately for boys and girls at half-year increments starting at age 4.0 to 17.5 years.

Calculating Median Absolute Deviation. At each chronological age (4.0 to 17.5 years), the median absolute deviation (MAD) was calculated and used as the determinant for accuracy of prediction. In Khamis and Roche's study (1994), the MAD represented the median of the absolute values of the differences between the actual 18-year statures and the predicted 18-year statures. When the MAD for the matching age and gender is added to and subtracted from a predicted adult stature, a range of values is obtained within which 50% of actual statues lie for the given chronological age and gender (Khamis & Roche, 1994).

At each measurement, the child had his or her predicted adult height subtracted from his or her final adult height measurement. This was done for all participants at the same chronological age. The average of the differences was calculated and an absolute value taken. This step was repeated for each age category 4.0 to 17.5, respectively. An average of the MAD values across the chronological ages was also calculated. The average of the MAD values (with corresponding standard deviation) for all ages combined is a measure of the accuracy of the predicted procedure for the given range of chronological ages (Khamis & Roche, 1994). The reported average MAD for a sample of boys and girls from the Fels Longitudinal Study was 0.851 inches (±0.218) for boys and 0.657 inches (±0.254) for girls, respectively.

Similarly, 90% error bounds were also calculated so that at a given age, a range is provided within which 90% of the actual adult statures lie for a group of children. The reported average 90% error bounds across age categories for boys was reported at 2.101 inches (±0.545). The average 90% error bound for girls was 1.675 inches (±0.646). The reported (Khamis & Roche, 1994) average of the MAD and average 90% error bounds and standard deviation values are summarized in Table 3-2 for both boys and girls.

Table 3-2. Reported average error bounds at 50% (MAD) and 90% for predictions of adult height from ages 4.0 to 17.5 years (Khamis & Roche, 1994).

	50% Error Bounds (in)		90% Error Bounds (in)	
	Mean	SD	Mean	SD
Boys	0.851	0.218	2.101	0.545
Girls	0.657	0.254	1.675	0.646

Validating the Khamis-Roche Method

> Research Question 1: *What is the validity of the Khamis-Roche method (or how accurate is the method) of predicting adult height as applied to a mid-Michigan sample of boys?*
>
> Research Question 2: *What is the validity of the Khamis-Roche method (or how accurate is the method) of predicting adult height as applied to a mid-Michigan sample of girls?*

This section describes how the KR method was applied to the MPS data to predict adult height. The steps for calculating the prediction of adult height were followed according to the protocol described previously with the exception of mid-parent height. The investigators of the Fels Longitudinal Study, from which the KR method was derived, measured the parents of their participants. As mentioned previously, original MPS data did not include parental heights. Therefore, these data had to be collected separately. This section will include how the mid-parent height was calculated, as well as the statistical procedures for validating the KR method with the MPS sample.

Calculating Mid-parent Height. Because self-reported heights tend to be biased, the self-reported adult heights, in feet and inches, were adjusted using a protocol established by Epstein et al. (1995). The equations for adjusting height for both men and women are identified below:

$$\text{adjusted height for women} = 2.803 + (0.953 \times \text{height of mother})$$

$$\text{adjusted height for men} = 2.316 + (0.987 \times \text{height of father})$$

The adjusted parental heights were converted from feet and inches to centimeters by multiplying total height in inches by 2.54. The equation for calculating the mid-parent height in centimeters is identified below:

$$\text{Mid-parent Stature} = \frac{\text{adjusted height of mother} + \text{adjusted height of father}}{2}$$

After the parental heights were adjusted and converted to centimeters, the mid-parent statures were calculated. These variables were added to the data files of the appropriate MPS participants.

Height and Weight. For each MPS participant, height and weight values were obtained during each semi-annual measurement cycle. The exact age of the child for each measurement was calculated by converting the date of birth and each date of measurement into a decimal format utilizing the conversion tables established by Tanner, Whitehouse, and Takaishi (1966a). The date of birth was subtracted from the testing date thus providing the decimal age, or the exact chronological age of the child when he or she was measured. Once decimal ages were calculated, they were rounded to half-year increments. Increments of 0.25 to 0.74 were rounded to 0.50 while 0.75 to 0.24 were rounded to whole units in years (i.e., 1.0 years).

Predicting Adult Height Using KR Method. Intercept and regression coefficients were obtained from a table of coefficients (Khamis & Roche, 1995b) for each participant at each half-year increment from 4.0 years to 17.5 years, respectively. The tables were published separately for boys and girls. Predicted adult height, therefore, was calculated from the following formula:

$$PAH = \beta_0 + (\text{stature} \times \beta_1) + (\text{weight} \times \beta_2) + (\text{mid-parent stature} \times \beta_3)$$

Calculating MAD. The 50% error bounds or (MAD) was calculated for each participant. The absolute value of the difference between actual adult height and predicted adult height was computed for each participant. The equation used is reported below:

$$|y - \hat{y}|,$$

where y represents actual adult stature and $\hat{y}$ represents the predicted adult stature for an individual of a given age and gender. To calculate the 50% error bound, therefore, the following formulae were used:

$$P\,[-\text{MAD} < y - \hat{y} < \text{MAD}] = 0.50$$

$$P\,[\hat{y} - \text{MAD} < y < \hat{y} + \text{MAD}] = 0.50$$

A 90% error bounds was also calculated for each participant. The same procedure used to obtain the 50% error bounds was done in order to get the 90% error bounds. The MAD or 50th percentile of $|y - \hat{y}|$ above, was replaced by the 90th percentile of $|y - \hat{y}|$. The formulae for 90% error bounds are represented below:

$$P\,[-\text{MAD} < y - \hat{y} < \text{MAD}] = 0.90$$

$$P\,[\hat{y} - \text{MAD} < y < \hat{y} + \text{MAD}] = 0.90$$

Khamis and Roche (1994) used the 18-year stature measurements as their adult or final height. In calculating the 50% and 90% error bounds, the predicted height was subtracted from the final height at 18-years of age. In the current study, final height was determined by 3 successive measurements within 3 mm. Thus, calculating 50% and 90% error bounds on MPS participants, the predicted final height was subtracted from the final height regardless of the age at which it was attained.

Design and Analysis. The KR procedures were applied to the MPS data to calculate the average of the MADs, the measure of the accuracy of the procedure.

In order to verify if the MPS and Fels samples were significantly different statistically, an analysis of variance (ANOVA) for condensed means was run for boys' 50% error bounds. The same protocol was applied to means for MPS and Fels girls.

A condensed means protocol was chosen due to a lack of information regarding the Fels sample where only the means, standard deviations, and sample size were known. The following formula was obtained on the Internet with corresponding Java Script to execute the analysis (http://home.ubalt.edu/ntsbarsh/Business-stat/otherapplets/SeveralMeans.htm):

$$y_n = n \cdot X - (n-1)y_1$$

with the following assumption:

$$y_i = \overline{X} + \sqrt{\frac{s^2}{n}}$$

for all i when $i = 1, 2, \ldots, n$-1.

An additional analysis was applied to the means for 90% error bounds. The ANOVA for condensed means was applied for both samples of MPS and Fels boys and girls.

Rate of Maturation

Research Questions 3. *How accurate is the Khamis-Roche method when comparing early-, average-, and late-maturing boys and girls.*

In order to address the accuracy of the KR method when rate of maturation is a consideration, the MPS sample of boys and girls were separated into early-, average- and late-maturing groups based on the age at which final adult height was attained. The mean age at which boys in the sample attained adult height was calculated along with the standard deviation. A z-score was used to establish the maturation groups. The formula for calculating z-score is as follows:

$$z = \frac{X - \overline{X}}{s}$$

The *X* represents age of final adult height, *X*-bar indicates the mean age for attaining adult height of all boys (or girls) in the sample, and *s* indicates the standard deviation. Determination of maturity status followed the protocols of other studies (Malina, Cumming et al., 2005). Average or an on time maturity status utilized a z-score between -1.0 and +1.0, while a z-score greater than +1.0 indicated an early or an advanced maturity status and a z-score less than -1.0 indicated a late or a delayed maturity status.

The median average deviation (MAD) was calculated for each maturity group following the same procedures as described previously. Likewise, 90% error bounds were also calculated for each maturity group.

A 2×3 design for ANOVA employed two levels of gender and three levels of maturity: early-maturing MPS participants (MPS-E), average-maturing MPS participants (MPS-A), and late-maturing MPS participants (MPS-L). Post hoc analyses (i.e., Tukey's HSD) were conducted when significant group main effects were found.

<u>Application of the Khamis-Roche Method</u>

> Research Question 4: *Does the Khamis-Roche method accurately provide biological maturity estimation by separating early-, average-, and late-maturing boys with a predicted percentage of adult height when compared to actual percentage of adult height?*
>
> Research Question 5: *Does the Khamis-Roche method accurately provide biological maturity estimation by separating early-, average-, and late-maturing girls with a predicted percentage of adult height when compared to actual percentage?*

The final objective of this study was to apply the KR method of predicting adult height to estimate maturity status. The predicted adult height was used to calculate a predicted percentage of adult height (PPAH). The PPAH can be used as an indicator of maturity when compared to children of the same chronological age. In general, taller children at a given age tend to be more mature than shorter children at the same age.

A child's measured height at a given chronological age category can be divided by the predicted adult height and multiplied by 100 to determine the predicted percentage adult height (PPAH). The actual percentage of adult height (APAH) was also calculated in the same manner as PPAH, however, substituting the predicted adult height with the actual adult height.

Maturity Status Expressed as a z-score. Statistical z-scores were used to divide the boys and girls into early-, average-, and late-maturity groups at each age category using the following formula:

$$z = \frac{X - \overline{X}}{s} = PZ = \frac{\%PAH - M\%PAH}{SD_{M\%PAH}},$$

where *%PAH* indicates percentage of predicted adult height, *M%PAH* indicates mean percentage of predicted adult height, and $SD_{M\%PAH}$ indicates the standard deviation of *M%PAH*. The acronym PZ will indicate a z-score that was calculated from the predicted percentage of adult height. An additional z-score was calculated using the actual percentage of adult height (APAH) with corresponding mean and standard deviation. This z-score is designated as AZ.

Determination of maturity status followed the protocols of other studies (Cumming, 2002; Cumming, Battista, Standage, Ewing, & Malina, 2006; Dompier, 2005;

Malina, Cumming et al., 2005; Morano, 2003). Average or on time maturity status utilized a z-score between -1.0 and +1.0 while a z-score greater than +1.0 indicated an early or advanced maturity status and a z-score below -1.0 indicated a late or delayed maturity status.

Design and Analysis. At each age category, each participant has an actual percentage of adult height (APAH) based on his or her actual final adult height as well as a predicted percentage of adult height (PPAH) based on the KR formula. The frequencies of early-, average-, and late-maturing boys and girls were computed from the PZ and AZ.

In order to test the validity of the predicted percentage of adult height as a biological maturity estimate, a non-parametric analysis was run on the frequency distributions of early-, average-, and late-maturing categories derived from PZ and AZ. The Chi Square analysis employed a goodness of fit protocol was applied to the PZ and AZ scores. A 2×3 factorial design was used with PZ designated as the observed frequencies and the AZ as the expected frequencies and with three levels of maturation (early, average, and late).

Chi Square does not indicate the strength of a relationship. Therefore, a Cramér's V statistic was calculated with the following formula (http://planetmath.org/encyclopedia/CramersV.html):

$$V = V(X,Y) = \sqrt{\frac{\chi^2}{n \min(M-1, N-1)}}$$

where X represents PZ and Y represents AZ. The variable M represents the number of categorical variables for X or PZ, or in this case early, average, and late. The variable N, therefore, establishes the number of categorical variables for Y or AZ.

CHAPTER IV

RESULTS

The specific aims of this study were: (a) to determine if the Khamis-Roche method of predicting adult height is valid when applying it to a sample of boys and girls denizen to mid-Michigan and; (b) to estimate biological maturity status based on a predicted percentage of adult height.

In this chapter, the research questions will be addressed individually. In addition to the research questions, information on participant demographics will be provided.

Participant Demographics

This study utilized longitudinal data procured as an ancillary project of the Motor Performance Study. From 1967 through 2003, data on 13 anthropometric measurements and eight measurements of motor performance (see Table 3-1) were collected on children and youths. However, no anthropometric data were collected on the parents. Thus, participant demographics will include information on the extant measures previously collected as part of the longitudinal portion of the MPS as well as information collected retrospectively on parental heights.

MPS Participants

The total number of participants enrolled into the MPS since its inception in 1967 is 1,220. This included 647 boys and 573 girls, respectively. Approximately 97% of this population was Caucasian. Of the 1,220 that participated, 568 individuals had completed their growth measurements in height and weight. This included 269 boys and 299 girls, respectively.

The potential number of MPS participants was 568. The total number of eligible participants generated from parental response was 432 (205 boys and 227 girls). Of the 136 participants that could not be used for predicting adult height, 108 were excluded because their parents could not be located, 13 were excluded because they were adopted (9 boys and 4 girls), and 15 participants were excluded because either their parents declined to participate (3 boys and 6 girls) or only one parent provided his or her height (2 boys and 4 girls).

In rare occasions, a spouse reported the final adult height of a deceased mate. Nine fathers had their heights reported by their surviving wife. The Epstein et al. (1995) procedure was applied to the correct gender of the spouse even if it was reported by a surviving spouse.

MPS Parent Participants

Parents of the MPS participants were contacted in order to obtain a self-reported measurement of height. With this information, a mid-parent height variable could be calculated and used in the Khamis-Roche method of predicting adult height.

This study was limited by the number of parents that could be successfully contacted for self-reporting their adult height. A majority of these data were collected via a letter sent through the US Postal system that included a reporting form. The form was returned in a self-addressed, stamped envelope. Attempts were made to contact those parents from whom responses were not received within 3-4 weeks of the mailing.

There were a total of 284 families that made up the 568 children with completed growth measures. Of these, 279 families were initially contacted by mail. Five families did not have an address to which a letter could be sent. The number of families that returned a completed card was 180 (65%). This total included those that agreed to participate, declined to participate, or reported adoptive status. In two instances, families returned a card following the telephone conversation. The number of families contacted via telephone that reported their heights was 39 (14%). A total of 199 sets of parents (76%) were available from which a mid-parent height value could be calculated. The remaining 85 families were either unable to be contacted or they did not return their reporting card. The demographic data for parents are summarized in Table 4-1.

Table 4-1. Mean and standard deviation values for self-reported heights of fathers and mothers. These reported values were corrected following the Epstein et al. (1995) protocol.

	Paternal Height (cm)	Maternal Height (cm)
Mean	179.8	164.5
Standard Deviation	7.4	6.2
n	199	199

The average number of children per family was 2.11 ± 1.00 (n = 199). Fifty percent of the families had two children, about 22% of the families had one child, and about 20% of the families had three. The family with the largest amount of children was 8 (n=1). The next largest family had 5 children (n=5). Figure 4-1 provides a frequency distribution of the number of children per family.

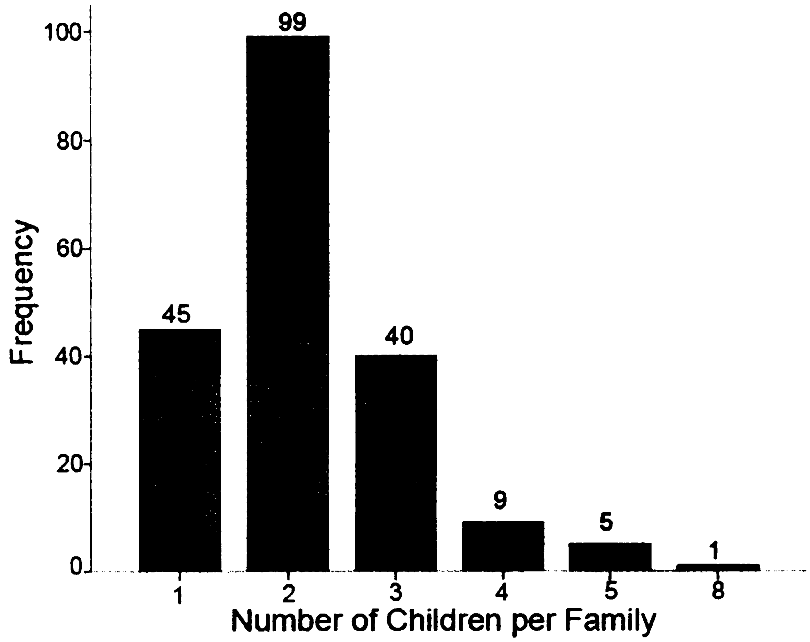

Figure 4-1. Frequency distribution for the number of children represented in a family unit.

Validating the Khamis-Roche Method

The first two research questions addressed the validity of the Khamis-Roche method for predicting adult height. The protocol established by Khamis and Roche (1994) was used to predict the height of 432 boys and girls from the mid-Michigan sample. The variables needed were height, weight, and mid-parent height. Descriptive statistics for mid-parent height for both boys and girls are provided in Table 4-2.

Table 4-2. Mean and standard deviation values for mid-parent height (cm) for boys and girls.

	MPH Values for Boys (cm)	MPH Values for Girls (cm)
Mean	171.1	170.9
Standard Deviation	5.2	5.1
n	205	227

Khamis and Roche (1994) used the median of absolute deviations (MAD) as the measure of accuracy for the KR prediction method. Similarly, the mean values for 50% error bounds and 90% error bounds were calculated for the MPS sample (see Table 4-3).

Table 4-3. Mean and standard deviation values for boys' and girls' average of the MAD (50% error bounds) and 90% error bounds for MPS and Fels samples.

		Fels (cm)	MPS (cm)
Boys	50% Error Bounds	2.16 (0.55)	2.32 (0.62)
	90% Error Bounds	5.34 (1.38)	6.73 (1.49)
Girls	50% Error Bounds	1.67 (0.65)	2.06 (0.69)
	90% Error Bounds	4.25 (1.64)	4.77 (1.85)

Research Question 1: *What is the validity of the Khamis-Roche method (or how accurate is the method) of predicting adult height as applied to a mid-Michigan sample of boys?*

The variables necessary for the prediction of adult height utilizing the KR method are height, weight, and mid-parent height at half-year intervals from ages 4.0 to 17.5 years. Descriptive statistics for the predictor variables of height (cm) and weight (kg) at each chronological age category for boys are reported in Table 4-4.

Table 4-4. Mean, standard deviation, and median values for height (cm) and weight (kg) for boys at each age of measurement.

Age (yr)	Height for Boys (cm) n	Mean	SD	Median	Weight for Boys (kg) n	Mean	SD	Median
4.0	91	103.11	4.78	103.30	91	14.57	1.71	14.17
4.5	101	106.80	4.63	106.90	101	15.33	1.90	15.35
5.0	117	110.35	4.65	110.30	117	16.27	2.34	16.14
5.5	128	113.95	4.79	114.30	128	17.48	2.09	17.32
6.0	135	117.25	4.85	117.50	134	18.53	2.29	18.50
6.5	143	120.57	5.07	120.80	142	19.65	2.61	19.69
7.0	155	123.54	5.33	123.60	154	20.70	2.94	20.47
7.5	165	126.82	5.50	127.00	165	21.96	3.08	21.65
8.0	169	129.70	5.40	130.00	169	23.31	3.24	23.23
8.5	176	132.65	5.84	132.70	176	24.70	3.54	24.41
9.0	183	135.44	5.94	135.70	183	26.13	3.98	25.98
9.5	187	138.23	6.07	138.20	187	27.54	4.29	27.17
10.0	189	140.93	6.15	141.00	189	29.08	4.87	28.74
10.5	197	143.51	6.32	143.70	197	30.64	5.19	30.31
11.0	196	146.15	6.52	146.15	196	32.16	5.34	31.89
11.5	197	148.88	6.81	148.70	197	33.84	5.73	33.46
12.0	199	151.75	6.96	152.00	199	35.59	6.03	35.04
12.5	202	155.08	7.48	155.35	202	38.08	6.92	37.20
13.0	202	158.88	7.89	159.50	201	40.67	7.60	39.76
13.5	201	162.66	8.18	163.10	201	43.40	8.19	42.91
14.0	203	166.47	8.22	167.30	201	46.31	8.61	46.46
14.5	203	169.93	7.95	170.70	201	49.71	8.24	50.00
15.0	201	172.82	7.65	172.70	199	52.43	8.24	51.97
15.5	197	174.79	7.42	174.40	195	54.42	7.63	54.33
16.0	196	176.59	7.19	176.00	193	56.50	8.19	55.51
16.5	193	177.57	7.28	177.20	192	58.29	8.53	57.09
17.0	178	178.76	7.30	178.05	178	59.32	8.78	57.87
17.5	157	179.31	7.32	179.40	157	60.29	8.93	58.27

The 50% error bounds or median absolute deviation (MAD) was calculated for each age category as well as the 90% error bounds (see Table 4-5). The original data with corresponding MAD values for each chronological age category were not published by Khamis and Roche (1994). Therefore, the data were adapted from Khamis and Roche's (1994) graph that was originally reported in inch units. Those values, interpreted from the graph, were converted to centimeters.

Table 4-5. 50% and 90% error bounds for MPS and Fels boys. The data for the Fels sample was adapted from Khamis & Roche (1994).

	MPS		Fels	
Age (yr)	50%	90%	50%	90%
4.0	2.82	8.39	2.29	5.72
4.5	2.95	8.42	2.41	5.66
5.0	2.59	7.73	2.54	5.97
5.5	2.50	8.08	2.41	5.97
6.0	2.37	7.36	2.29	5.59
6.5	2.36	7.51	2.24	5.54
7.0	2.31	7.03	2.11	5.33
7.5	2.32	6.54	2.03	5.33
8.0	2.20	6.55	2.03	5.33
8.5	2.22	6.52	2.03	5.33
9.0	2.14	6.96	2.03	5.33
9.5	2.16	6.80	2.11	5.28
10.0	2.12	6.86	2.16	5.21
10.5	1.88	7.00	2.29	5.46
11.0	1.87	6.67	2.36	5.54
11.5	2.17	7.21	2.36	5.79
12.0	2.55	7.06	2.41	6.22
12.5	2.82	7.82	2.54	6.73
13.0	3.09	7.96	2.67	7.11
13.5	3.37	8.04	2.79	7.24
14.0	3.37	7.98	2.79	7.11
14.5	3.12	7.17	2.74	6.73
15.0	2.69	7.12	2.29	5.84
15.5	2.11	5.88	1.91	4.70
16.0	1.73	4.68	1.40	3.81
16.5	1.20	3.45	0.89	2.54
17.0	0.74	2.77	0.76	1.91
17.5	1.23	2.98	0.94	1.98

The average of the MAD represents the 50% error bounds. The 50% and 90% error bounds were calculated for the Fels population by Khamis and Roche (1994). The 90% error bounds represent the 90^{th} percentile for absolute deviation at each chronological age. The mean for 50% and 90% error bounds for the MPS sample (MPS50 and MPS90, respectively) and for the Fels boys (KR50 and KR90, respectively) at each chronological age are graphically represented in Figure 4-2.

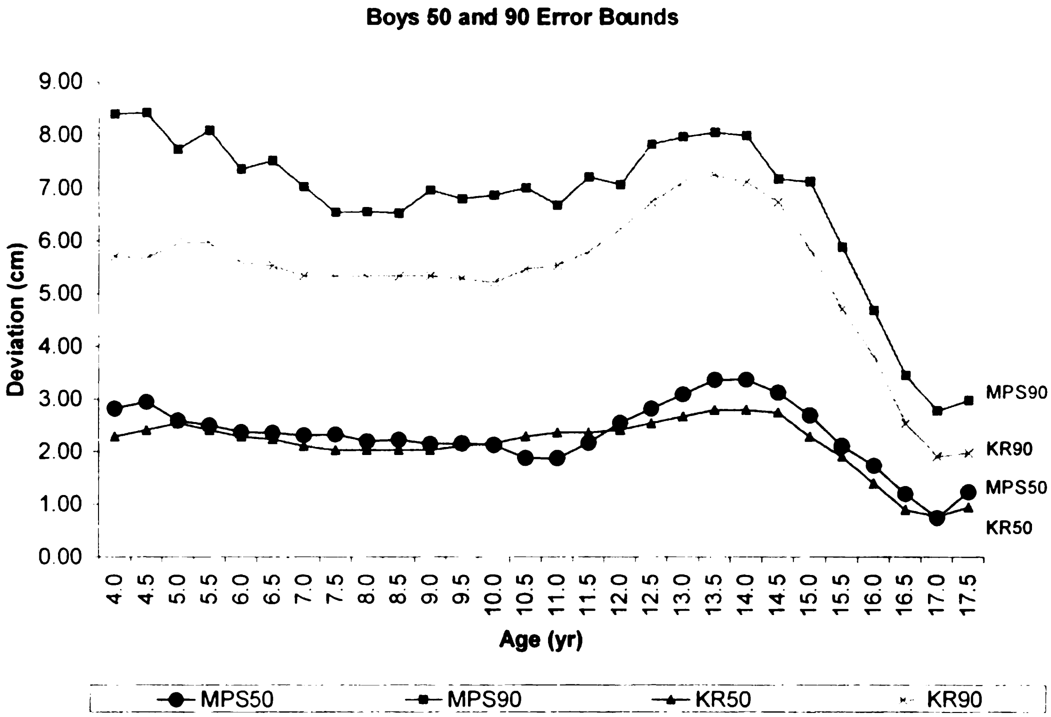

Figure 4-2. The 50% (MAD) and 90% error bounds for MPS and Fels boys for 4.0 to 17.5 years. The data for Fels boys were adapted from Khamis & Roche (1994).

The mean and spread for the MPS boys are greater than what was reported by Khamis and Roche (1994), but the shapes and pattern of the curves are relatively similar. The MAD for MPS and Fels boys are similar during the childhood period. Fels boys report lower MAD values at most ages except 5.0 and 5.5 years where the two are about the same. MPS boys, are more accurate than Fels boys at 10.5, 11.0, and 17.0 years. The greatest difference occurs during the pubertal growth spurt. The disparity in the spread between the two samples is most evident during the adolescent growth period where there is a substantial disparity between Fels and MPS boys. There is greater disparity, or greater differences exist between 90% error bounds for MPS and Fels boys. The MPS boys reveal higher values at all ages. The pattern of errors for MPS boys is similar at all ages when compared to Fels boys except at 4.0-5.5 years where the MPS boys report much higher values.

In order to verify if the two samples were significantly different statistically, an analysis of variance (ANOVA) for condensed means was run for boys 50% error bounds. A condensed means protocol was chosen due to a lack of information regarding the Fels sample where only the means, standard deviations, and sample size were known. The following formula was obtained on the Internet with corresponding Java Script to execute the analysis (http://home.ubalt.edu/ntsbarsh/Business-stat/otherapplets/SeveralMeans.htm):

$$y_n = n \cdot X - (n-1)y_1$$

with the following assumption:

$$y_i = \overline{X} + \sqrt{\frac{s^2}{n}}$$

for all i when $i = 1, 2, \ldots, n-1$.

The ANOVA revealed a statistically significant difference, reporting a value less than the alpha level of 0.05 for Fels and MPS sample means. The variation between means was 2.734, the variation within means was 0.584, and $F_{(1, 223)} = 4.686$, p = 0.003. This was evidence to suggest that one sample mean differed significantly from the other. The KR method for predicting adult height is more accurate for the Fels boys than for the MPS boys.

A similar ANOVA was run on the means for the 90% error bounds. The variation between means was 206.369, the variation within means was 1.432, and $F_{(1, 223)} =$ 144.044, p = 0.001. This evidence also suggested that one population mean differed significantly from the other. Again, the KR method is less accurate with the MPS boys than with the Fels boys.

Research Question 2: *What is the validity of the Khamis-Roche method (or how accurate is the method) of predicting adult height as applied to a mid-Michigan sample of girls?*

The KR method to predict height was applied separately to the data for girls. Descriptive statistics for the predictor variables of height (cm) and weight (kg) at each chronological age category for girls are reported in Table 4-6. The median absolute deviation (MAD) was also calculated for each age category. See Table 4-7 for median absolute deviation at each age category for MPS with corresponding data for Fels girls adapted from Khamis and Roche (1994). The 90% error bounds were also calculated.

The MAD values for MPS girls were higher than those reported for Fels girls at all age categories, except for 17.5 years. The MAD values for MPS girls were relatively stable until about 13.5 years of age at which the values started to decrease and improve in accuracy. The MAD values for Fels girls, however, were relatively stable to age 9.5 years and then improved in accuracy with steadily decreasing values to 17.0 years of age.

The average of the MAD across all ages for girls was computed. The average of the MAD for MPS girls and Fels girls was 2.06 (±0.69) and 1.67 (±0.65), respectively. The mean for 50% and 90% error bounds for the MPS girls sample are graphically represented in Figure 4-3. The mean and spread are greater than what was reported by Khamis and Roche (1994), which was a similar finding to the MPS boys. The spread for 50% and 90% error bounds is less for the MPS girls, however, than what was found for MPS boys.

Table 4-6. Mean, standard deviation, and median values for height (cm) and weight (kg) for girls at each age of measurement.

Age (yr)	Height for Girls (cm) n	Mean	SD	Median	Weight for Girls (kg) n	Mean	SD	Median
4.0	125	101.63	4.58	101.30	125	13.77	1.71	13.39
4.5	137	105.47	4.97	105.50	137	14.77	1.90	14.57
5.0	145	109.03	5.05	108.70	145	15.83	2.15	15.35
5.5	154	112.56	5.17	112.30	154	16.84	2.35	16.54
6.0	164	115.89	5.31	115.30	164	17.83	2.50	17.32
6.5	172	119.16	5.44	118.65	172	19.00	2.81	18.50
7.0	176	122.27	5.56	121.60	175	20.05	2.94	19.69
7.5	158	125.29	5.68	124.50	157	21.34	3.33	20.87
8.0	192	128.12	5.71	127.45	192	22.66	3.35	22.05
8.5	197	130.97	5.96	130.40	197	24.00	3.87	23.62
9.0	208	133.92	5.99	133.80	207	25.40	4.19	24.80
9.5	212	136.65	6.10	136.40	211	26.82	4.53	25.98
10.0	219	139.44	6.49	138.90	218	28.38	5.02	27.56
10.5	220	142.52	6.69	142.35	220	30.35	5.70	29.13
11.0	224	145.71	7.04	145.35	224	32.26	6.37	31.10
11.5	222	149.18	7.27	148.60	222	34.36	6.90	33.07
12.0	226	152.68	7.32	152.20	226	36.79	7.64	35.43
12.5	226	155.92	7.23	155.65	226	39.15	7.67	38.19
13.0	225	158.52	6.93	158.30	225	41.54	8.02	40.55
13.5	225	160.82	6.73	160.40	225	43.31	7.96	42.52
14.0	225	98.01	1.62	98.32	224	45.17	7.86	44.09
14.5	224	163.57	6.46	163.40	223	46.43	7.66	44.88
15.0	217	164.26	6.34	164.60	214	47.01	7.36	45.67
15.5	204	165.02	6.36	165.15	202	47.74	6.73	46.46
16.0	181	165.69	6.10	165.30	180	48.02	5.94	46.85
16.5	148	166.13	6.08	165.70	146	48.31	5.88	47.64
17.0	106	166.54	5.86	166.10	104	48.84	5.23	48.03
17.5	66	167.00	5.80	166.30	65	49.18	6.23	48.82

An analysis of variance (ANOVA) for condensed data sets was also computed for the girls 50% error bounds in the same manner in which it was computed for boys. The ANOVA revealed a statistically significant difference ($p < 0.05$) between the means for KR and MPS girls samples. The variation between means was 16.591, the variation within means was 0.671, and $F_{(1, 227)} = 24.735$. This result suggested that the population means for MPS and Fels girls differed significantly from each other. The average of the MAD was slightly higher for MPS girls than what was reported for Fels girls.

Table 4-7. 50% and 90% error bounds for MPS and Fels girls. The data for the Fels sample was adapted from Khamis & Roche (1994).

Age	MPS		Fels	
(yr)	50%	90%	50%	90%
4.0	2.94	6.27	2.29	5.46
4.5	2.88	6.41	2.16	5.66
5.0	2.55	6.33	2.41	5.46
5.5	2.45	6.07	2.29	5.41
6.0	2.63	6.11	2.16	5.16
6.5	2.51	5.70	2.03	4.95
7.0	2.48	5.85	1.98	4.83
7.5	2.30	5.91	1.96	4.83
8.0	2.42	5.64	1.96	4.95
8.5	2.23	5.19	1.96	5.03
9.0	2.41	5.29	1.91	5.13
9.5	2.38	5.76	1.78	5.28
10.0	2.36	5.63	1.85	5.41
10.5	2.54	5.87	1.91	5.59
11.0	2.51	6.23	1.96	5.72
11.5	2.60	6.09	1.98	5.72
12.0	2.72	6.01	2.03	5.59
12.5	2.38	6.16	2.03	5.33
13.0	2.06	5.68	1.91	4.75
13.5	1.81	4.80	1.60	4.14
14.0	1.56	4.06	1.27	3.30
14.5	1.27	3.14	0.94	2.54
15.0	1.17	2.14	0.64	1.96
15.5	1.07	1.94	0.51	1.60
16.0	1.05	1.62	0.58	1.45
16.5	1.06	1.35	0.61	1.27
17.0	0.85	1.16	0.58	1.22
17.5	0.49	1.16	0.64	1.27

When the ANOVA was applied to the means for the 90% error bounds, a similar result was found. The ANOVA revealed that the two sample means were not similar

($F_{1,227}$= 29.496, p= .001). The KR method is significantly more accurate in predicting the adult height of the Fels children than that of the MPS children.

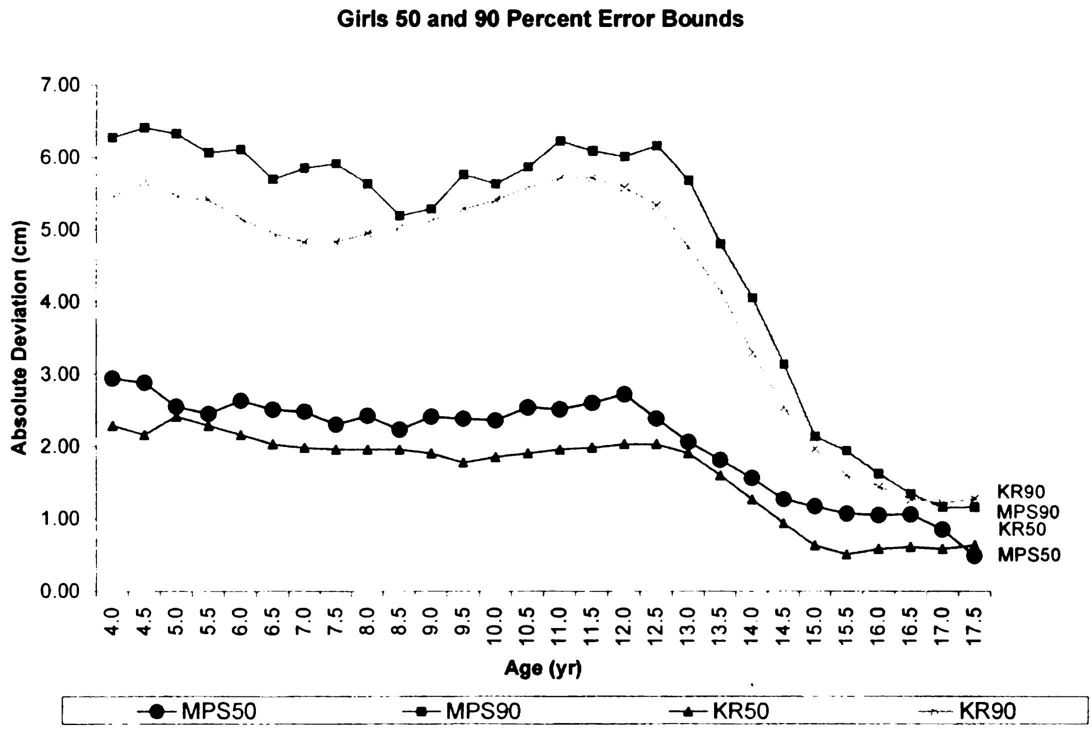

Figure 4-3. The 50% (MAD) and 90% error bounds for MPS and Fels girls for 4.0 to 17.5 years. Data for Fels girls were adapted from Khamis & Roche (1994).

While the two sample means were significantly different statistically, the girls from both samples had lower average MAD values than did the boys from both samples. The KR method for predicting adult height was more accurate for the Fels girls than for the MPS girls, but less accurate for boys, in general. The average of the MAD values for MPS boys and girls and Fels boys and girls were summarized in Table 4-3.

Rate of Maturation

Research Question 3. *How accurate is the Khamis-Roche method when comparing early-, average-, and late-maturing boys and girls?*

Both boys and girls were separated into maturation categories based on the age at which final adult height was attained. A z-score was used to establish the maturation groups of early-, average-, and late-maturing. The z-score less than -1.00 indicated an early maturing boy/girl and a z-score greater than +1.00 indicated a late-maturing boy/girl. All other z-scores between -1.00 and +1.00 were average-maturing boys/girls. An absolute deviation, or the absolute value of the difference between actual adult height and predicted adult height, was calculated for each participant at each chronological age category.

The mean, standard deviation, and median values of the absolute deviations were calculated for all boys and girls individually for each maturity group. These data are provided in Table 4-8. The average of the MAD across all age categories and per maturation group was also calculated. These data were calculated so that the means for each maturation category could be compared to the MPS population sample for boys and girls. Table 4-9 lists the mean and standard deviation values for average of the MAD for all age categories.

When boys and girls are separated into maturation categories, the average-maturing boy or girl had the lowest MAD values, on average. The early-maturing boy and early-maturing girl reported higher MAD values than average-, and late-maturing boys and girls, respectively. It appears for both sexes, that the KR method for predicting adult height is most accurate for average-maturing girls and boys, followed by late maturing-girls and boys. The least accurate predictions occurred for early-maturing boys and girls. Figures 4-4 and 4-5 illustrate the spread for the mean of the MAD data by maturation group for boys and girls, respectively.

Table 4-8. Mean, standard deviation, and median values for boys' and girls' individual average MAD per maturation category.

		Early	Average	Late
Boys	Mean	4.14	2.65	3.50
	SD	3.23	2.11	2.34
	Median	3.04	1.91	2.76
	n	32	139	34
Girls	Mean	3.36	2.10	2.88
	SD	1.72	1.50	2.29
	Median	3.35	1.73	1.98
	n	32	165	30

Table 4-9. Average of the MAD values for boys and girls with standard deviation.

		MPS Maturity Groups			MPS
		Early	Average	Late	Sample
Boys	Mean	3.20	2.10	2.89	2.32
	SD	1.01	0.65	0.83	0.62
	n	32	139	34	205
Girls	Mean	3.05	1.87	2.61	2.06
	SD	0.71	0.58	1.42	0.69
	n	32	165	30	227

The average maturing boys and girls have the most similar shape. Average-maturing boys have the lowest MAD at all ages over early-maturing boys except 4.0 years, and most ages of late-maturing boys except 4.0, 5.0, 5.5, 6.0, 11.5 and 12.5 years. The average-maturing boys are much more stable in predictive error than the other two groups to age 11.0 years. All groups show an increase in MAD values around the onset of puberty and then decrease sharply around 14.0 or 14.5 years. Early-maturing boys and average-maturing boys have their lower MAD at 17.0 years while late-maturing boys have their lowest MAD values during early childhood.

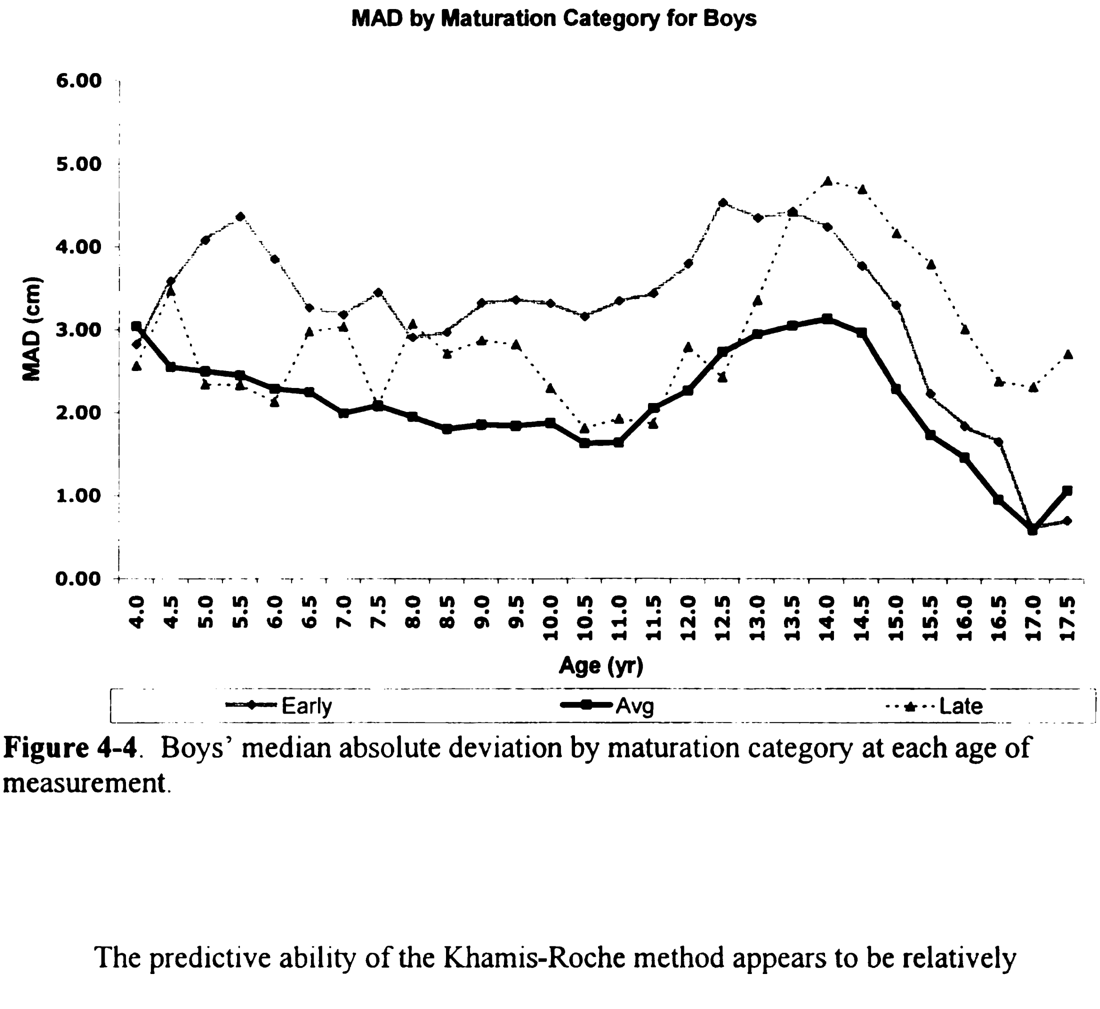

Figure 4-4. Boys' median absolute deviation by maturation category at each age of measurement.

The predictive ability of the Khamis-Roche method appears to be relatively constant for early- and average-maturing girls until age 12.0 or 12.5 years. After that, it increases in accuracy for all their maturity groups. Early-maturing girls show the same trend for accuracy as the average-maturing girls but with higher values at all ages. The late-maturing girls have significantly higher MAD values from 5.5 years to 8.0 years. At 8.5 years, there is a sharp decrease in MAD values and they approximate the same values for average-maturing girls until 12.0 years. At that age, MAD values of the late-maturing girls increased slightly while those of the average-maturing girls decreased steadily. By age 15.0 years, the late-maturing girls have the lowest values for MAD and show greater predictive accuracy over the average-, and early-maturing girls until age 17.5 years.

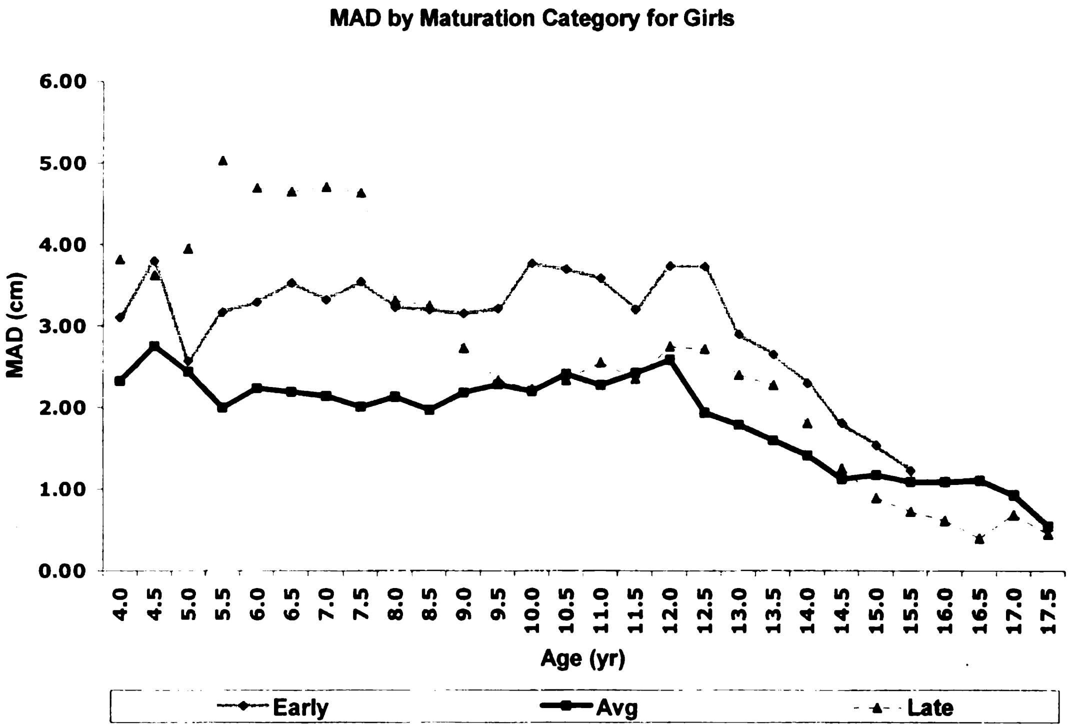

Figure 4-5. Girls' median absolute deviation by maturation category at each age of measurement.

An ANOVA was run on the data to compare differences between the means values for MAD per maturation group and sex. Statistically significant differences were found among the three maturation groups ($F_{2,432}$=14.818, $p < 0.05$) and between the two sexes ($F_{1,432}$=6.875, $p = 0.009$).

Post hoc analyses (Tukey's HSD) revealed that the MAD values for early-maturing and average-maturing children to be significantly different from each other ($p < .05$). Similarly, MAD values for average-maturing and late-maturing children were significantly different from each other (p=0.006). The early-maturing and late-maturing groups were found to be the most similar, but significantly different from each other.

When boys and girls were separated, post hoc analyses (Tukey's HSD) revealed that differences between the means of early-maturing and average-maturing boys were statistically significant (p=0.004) as well as the means of the early- and average-maturing girls ($p < .05$). Tukey's HSD also revealed a difference between the means for late-maturing and average-maturing girls (p=0.051) which modestly exceeds the alpha level of 0.05. Figures 4-6 and 4-7 illustrates residual box plot for boys and girls, respectively.

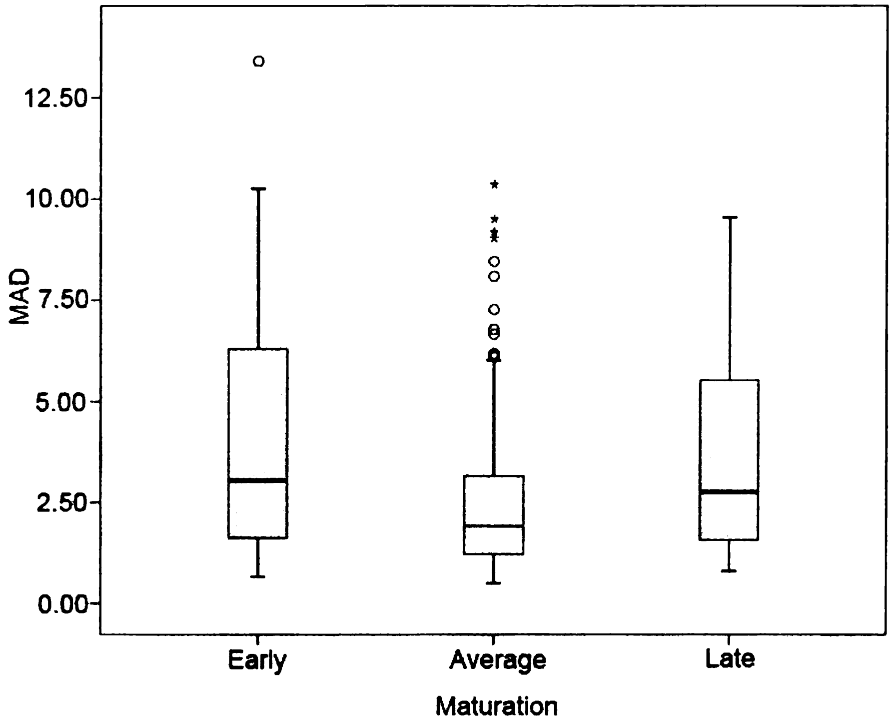

Figure 4-6. Residual plot for individual MAD values by maturation category for boys.

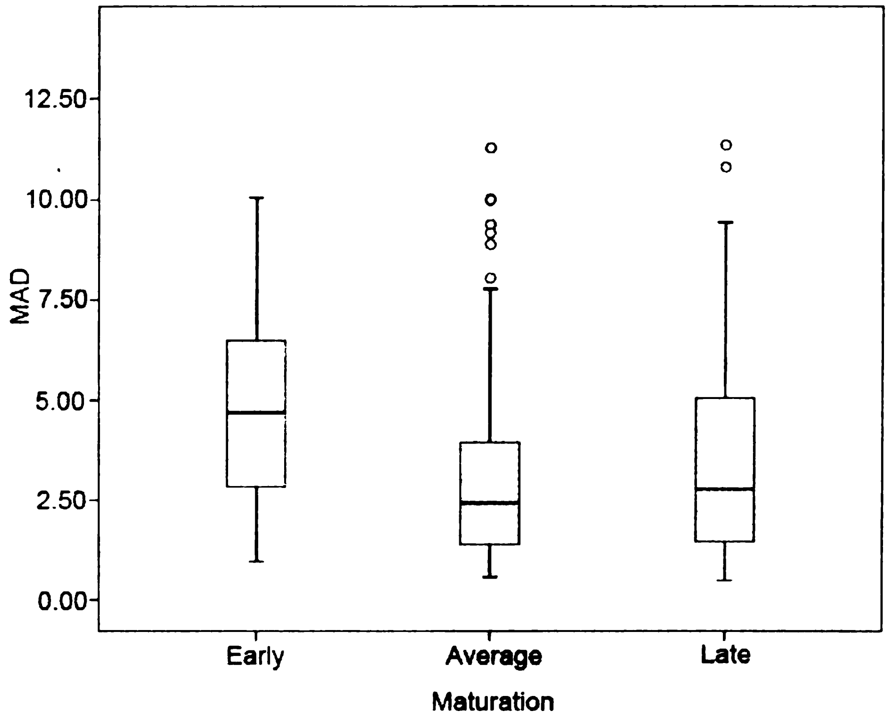

Figure 4-7. Residual plot for individual MAD values by maturation category for girls.

Application of the Khamis-Roche Method

The second aim of this study was to apply the KR method of predicting adult height to estimate maturity status. One of the more pervasive methods to estimate biological maturity in studies of youth sports in recent years has been to utilize a predicted percentage of adult height (PPAH). The KR method is used to predict the height of boys and girls in order to obtain a predicted percentage of adult height. The PPAH is then converted to a z-score and assigned a maturation category based on that score.

Research questions four and five of this study compared PPAH and corresponding z-scores and maturation categories for boys and girls separately. For each MPS participant, a PPAH was computed as well as the actual percentage of adult height (APAH). A corresponding z-score, PZ that utilized predicted adult height and descriptive statistics to create a standardized score and AZ that utilized actual adult height with corresponding descriptive statistics, was calculated for each participant.

Research Question 4: *Does the Khamis-Roche method accurately provide biological maturity estimation by separating early-, average-, and late-maturing boys with a predicted percentage of adult height when compared to actual percentage of adult height.*

The KR method was used to predict adult height for boys at each chronological age. Descriptive statistics for predicted adult height (PAH) is provided in Table 4-10. The PAH was used to calculate a predicted percentage of adult height (PPAH). At each chronological age category, the height of measurement was divided by PAH and was then multiplied by 100 in order to obtain the percentage. Each value was rounded to two decimal places. The actual percentage of adult height (APAH) was also calculated in the same way as the PPAH except substituting actual adult height for the predicted. Descriptive statistics for PPAH and APAH are listed in Table 4-11.

A z-score (PZ) was calculated from the mean PPAH and corresponding standard deviation for each age category utilizing the mean and standard deviation values for PPAH at the corresponding age. Additionally, a z-score was calculated from the mean of the APAH and corresponding standard deviation at each age category from the MPS sample (AZ).

Table 4-10. Mean, standard deviation, and median values for predicted adult height (PAH) on boys at each age of measurement.

Age (yr)	PAH for Boys (cm) N	Mean	SD	Median
4.0	90	179.74	7.61	180.06
4.5	100	179.85	7.48	179.87
5.0	115	179.67	7.05	179.73
5.5	125	179.54	7.05	179.85
6.0	132	179.56	7.23	179.92
6.5	140	179.76	7.17	180.35
7.0	151	179.53	7.14	179.90
7.5	158	179.72	7.33	179.99
8.0	162	179.11	9.05	179.90
8.5	169	179.17	9.04	179.68
9.0	174	179.20	8.91	179.59
9.5	178	179.39	8.90	180.42
10.0	180	179.58	9.10	179.91
10.5	186	179.52	9.15	179.86
11.0	185	179.25	9.49	179.90
11.5	186	179.11	9.77	179.65
12.0	188	178.96	9.73	179.60
12.5	191	179.02	9.71	179.62
13.0	190	179.24	9.62	179.90
13.5	190	179.28	9.48	179.59
14.0	192	179.21	9.14	179.40
14.5	193	179.19	8.84	179.79
15.0	191	179.12	8.46	179.10
15.5	186	178.93	8.12	179.00
16.0	185	179.47	6.48	179.21
16.5	182	179.18	6.80	179.15
17.0	168	179.29	7.22	178.87
17.5	149	178.51	7.69	178.64

Both sets of z-scores were used to assign each individual to a maturation category of early-, average-, or late-maturing. The two sets of values were used to create contingency tables for a Chi Square analysis. The goodness of fit protocol for Chi Square was followed. Table 4-12 provides a breakdown of the frequencies used to create the contingency tables.

Table 4-11. Mean, standard deviation, and median values for predicted percentage of adult height (PPAH) and actual percentage of adult height (APAH) for boys at each age of measurement.

	PPAH for Boys (cm)				APAH for Boys (cm)			
Age (yr)	n	Mean	SD	Median	n	Mean	SD	Median
4.0	89	57.39	1.17	57.43	91	57.00	1.99	57.19
4.5	99	59.41	1.22	59.46	101	59.23	1.95	59.37
5.0	114	61.42	1.21	61.50	117	61.29	1.82	61.38
5.5	125	63.42	1.16	63.46	128	63.16	1.93	63.16
6.0	132	65.26	1.19	65.35	135	65.05	1.92	65.16
6.5	139	67.02	1.15	67.06	142	66.88	1.94	66.91
7.0	151	68.79	1.15	68.79	154	68.64	1.95	68.71
7.5	158	70.53	1.17	70.61	164	70.48	1.96	70.48
8.0	162	72.21	1.18	72.27	168	72.10	1.95	72.11
8.5	169	73.84	1.11	73.81	175	73.73	2.11	73.74
9.0	174	75.40	1.17	75.36	181	75.33	2.10	75.50
9.5	178	76.85	1.19	76.77	185	76.83	2.15	76.87
10.0	180	78.28	1.34	78.16	187	78.39	2.23	78.50
10.5	186	79.72	1.48	79.73	195	79.85	2.27	79.94
11.0	185	81.27	1.57	81.22	194	81.34	2.31	81.43
11.5	185	82.84	1.74	82.92	194	82.85	2.65	82.84
12.0	188	84.49	1.91	84.60	197	84.52	2.86	84.27
12.5	191	86.29	2.20	86.29	200	86.36	3.49	86.07
13.0	189	88.28	2.40	88.28	199	88.44	3.76	88.13
13.5	190	90.37	2.45	90.36	199	90.58	3.92	90.71
14.0	192	92.55	2.40	92.71	201	92.74	3.84	93.59
14.5	192	94.53	2.13	94.79	201	94.68	3.38	95.73
15.0	190	96.19	1.78	96.36	199	96.22	2.87	97.06
15.5	186	97.39	1.38	97.49	195	97.41	2.27	98.15
16.0	186	98.34	1.04	98.36	194	98.27	1.73	98.72
16.5	181	99.01	0.68	99.02	189	98.86	1.27	99.18
17.0	169	99.67	0.31	99.65	175	99.27	0.90	99.55
17.5	149	100.42	0.22	100.41	156	99.54	0.63	99.83

The Chi Square (χ^2) analysis was applied to the frequencies in order to determine if there was a statistically significant difference between predicted maturation categories and actual maturation categories for each age. A 3×2 factorial design was used with three levels of maturation (early, average, and late) and with PZ designated as the observed frequencies and the AZ as the expected frequencies.

Table 4-12. Frequency of maturation categories for boys as assigned by the PPAH z-scores (PZ) and the APAH z-scores (AZ).

Age	Predicted MPS Maturation Categories from PZ			Actual Maturation Categories from AZ		
(yr)	Early	Average	Late	Early	Average	Late
4.0	5	79	7	13	65	13
4.5	12	82	7	16	72	13
5.0	11	92	14	17	84	16
5.5	15	95	18	17	90	21
6.0	14	105	15	18	96	20
6.5	15	108	18	22	97	22
7.0	19	115	20	21	108	25
7.5	19	128	18	26	114	25
8.0	19	125	25	24	118	27
8.5	21	133	22	24	128	24
9.0	22	139	22	28	128	27
9.5	23	136	28	28	131	28
10.0	23	141	25	25	138	26
10.5	22	147	28	23	143	31
11.0	26	140	30	23	147	26
11.5	28	138	30	27	144	25
12.0	31	135	33	23	145	31
12.5	30	141	31	33	143	26
13.0	34	132	34	36	131	33
13.5	32	132	37	44	116	41
14.0	31	133	37	40	113	48
14.5	34	128	39	36	118	47
15.0	31	137	31	24	144	31
15.5	35	131	29	18	152	25
16.0	30	133	30	21	149	23
16.5	31	128	33	23	167	2
17.0	27	127	24	3	152	23
17.5	25	108	24	21	133	3

Chi Square does not indicate the strength of a relationship. Therefore, a Cramér's V statistic was calculated with the following formula (http://planetmath.org/encyclopedia/CramersV.html):

$$V = V(X,Y) = \sqrt{\frac{\chi^2}{n\min(M-1,N-1)}}$$

where X represents PZ and Y represents AZ. The variable M represents the number of categorical variables for X or PZ, or in this case early, average, and late. The variable N, therefore, establishes the number of categorical variables for Y or AZ. Table 4-13 reports the results of the Chi Square and Cramér's V analyses.

Table 4-13. Results of the boys' Chi Square Analysis on frequencies of maturation categories computed from PZ and AZ. The Cramér's V statistic is also provided.

Pairings	n	*df*	χ^2	Cramér's *V*	*P*
PZ4.0 - AZ4.0	91	2	6.720	0.192	0.035
PZ4.5- AZ4.5	101	2	3.020	0.122	0.221
PZ5.0 - AZ5.0	117	2	1.780	0.087	0.411
PZ5.5 - AZ5.5	128	2	0.490	0.044	0.783
PZ6.0 - AZ6.0	134	2	1.620	0.078	0.445
PZ6.5 - AZ6.5	141	2	2.310	0.091	0.315
PZ7.0 - AZ7.0	154	2	0.880	0.054	0.644
PZ7.5 - AZ7.5	165	2	3.040	0.096	0.219
PZ8.0 - AZ8.0	169	2	0.860	0.050	0.651
PZ8.5 - AZ8.5	176	2	0.380	0.033	0.827
PZ9.0 - AZ9.0	183	2	1.680	0.068	0.432
PZ9.5 - AZ9.5	187	2	0.580	0.039	0.748
PZ10.0 - AZ10.0	189	2	0.140	0.019	0.932
PZ10.5 - AZ10.5	197	2	0.230	0.024	0.891
PZ11.0 - AZ11.0	196	2	0.640	0.040	0.726
PZ11.5 - AZ11.5	196	2	0.600	0.039	0.741
PZ12.0 - AZ12.0	199	2	1.600	0.063	0.449
PZ12.5 - AZ12.5	202	2	0.600	0.039	0.741
PZ13.0 - AZ13.0	200	2	0.080	0.014	0.961
PZ13.5 – AZ13.5	201	2	3.130	0.088	0.209
PZ14.0 – AZ14.0	201	2	4.190	0.102	0.123
PZ14.5 - AZ14.5	201	2	1.210	0.055	0.546
PZ15.0 - AZ15.0	199	2	1.070	0.052	0.586
PZ15.5 - AZ15.5	195	2	7.310	0.137	0.026
PZ16.0 - AZ16.0	193	2	3.420	0.094	0.181
PZ16.5 - AZ16.5	192	2	33.800	0.297	<.0001
PZ17.0 - AZ17.0	178	2	21.460	0.246	<.0001
PZ17.5 - AZ17.5	157	2	19.270	0.248	<.0001

The Chi Square analysis revealed that observed frequencies (ascertained from PZ) and expected frequencies (from AZ) had similar distributions at most ages. The distributions of frequencies at ages 4.0, 15.5 and 16.5-17.5 years were not similar. The strength of the relationship was determined by the V statistic where a value closer to 0 indicated a weaker association between predicted and actual maturation category. Conversely, a V value closer to 1 indicated a stronger relationship (http://planetmath.org/encyclopedia/CramersV.html). There was a relatively weak association between PZ and AZ at all ages. The highest associations were at the earliest and oldest ages, age 4.0 years in childhood and 16.5-17.5 years in adolescence, respectively. The similarities of the distribution suggest that PZ can assign boys to early-average-, or late-maturing categories similarly to the AZ for ages 5.0 to 15.0 years. However, the low association, as indicated by the V statistic, suggest interpreting these results with caution.

Research Question 5: *Does the Khamis-Roche method accurately provide biological maturity estimation by separating early-, average-, and late-maturing girls with a predicted percentage of adult height when compared to actual percentage of adult height.*

The KR method was used to predict adult height for girls at each chronological age. Descriptive statistics for girls predicted adult height (PAH) is provided in Table 4-14. The PAH was used to calculate a PPAH for girls in the same way that it was calculated for boys. The actual percentage of adult height (APAH) was also calculated. The mean, standard deviation, and median values for PPAH and APAH are listed in Table 4-15.

Both sets of z-scores (PZ and AZ) were used to assign each individual to a maturation category (early-, average-, or late-maturing). Those data are represented as a tabulated frequency distribution (see Table 4-16). The two distributions for the three categories of maturation appear to be similar at all ages up to 15.0 years. The AZ did not assign many girls to the early-maturing category after this age.

Table 4-14 Mean, standard deviation, and median values for predicted adult height (PAH) on boys and girls at each age of measurement.

	PAH for Girls (cm)			
Age (yr)	n	Mean	SD	Median
4.0	125	165.40	5.78	165.24
4.5	137	165.55	6.05	164.97
5.0	145	165.69	5.78	165.36
5.5	154	166.14	5.81	165.42
6.0	164	166.12	5.89	165.50
6.5	172	166.07	5.72	165.80
7.0	175	166.22	5.76	166.00
7.5	178	166.19	5.54	165.75
8.0	192	166.22	5.68	165.76
8.5	197	166.08	5.52	165.51
9.0	207	165.91	5.43	165.53
9.5	211	166.08	5.29	165.81
10.0	218	166.52	5.25	166.00
10.5	220	166.21	4.95	165.85
11.0	224	165.85	4.84	165.53
11.5	222	166.32	4.74	165.79
12.0	226	166.56	4.83	166.24
12.5	226	166.39	4.95	166.19
13.0	225	166.11	5.15	165.84
13.5	225	166.24	5.40	165.88
14.0	224	166.28	5.68	165.99
14.5	223	166.37	5.99	166.27
15.0	214	166.28	6.19	166.46
15.5	202	166.54	6.44	166.55
16.0	180	166.95	6.28	166.76
16.5	146	167.16	6.16	166.79
17.0	104	167.33	5.71	167.04
17.5	65	167.53	5.47	166.83

Table 4-15. Mean, standard deviation, and median values for predicted percentage of adult height (PPAH) and actual percentage of adult height (APAH) at each age of measurement for girls.

	PPAH for Girls (cm)				APAH for Girls (cm)			
Age (yr)	n	Mean	SD	Median	n	Mean	SD	Median
4.0	125	61.42	1.11	61.38	125	61.37	1.90	61.58
4.5	137	63.70	1.19	63.71	137	63.58	1.94	63.73
5.0	145	65.78	1.27	65.79	145	65.59	2.02	65.80
5.5	154	67.74	1.46	67.61	154	67.73	2.04	67.79
6.0	164	69.74	1.38	69.59	164	69.76	2.04	69.74
6.5	172	71.74	1.51	71.71	172	71.73	2.08	71.64
7.0	175	73.54	1.50	73.50	176	73.60	2.04	73.55
7.5	178	75.37	1.47	75.27	178	75.46	2.10	75.36
8.0	192	77.07	1.55	77.04	192	77.24	2.14	77.04
8.5	197	78.84	1.58	78.79	197	79.01	2.20	78.75
9.0	207	80.70	1.67	80.61	208	80.76	2.27	80.54
9.5	211	82.27	1.83	82.17	212	82.41	2.46	82.23
10.0	218	83.72	2.00	83.69	219	84.11	2.59	83.81
10.5	220	85.72	2.32	85.60	220	86.01	2.86	85.72
11.0	224	87.83	2.60	87.50	224	87.95	3.09	87.57
11.5	222	89.67	2.72	89.46	222	90.01	3.19	89.67
12.0	226	91.64	2.65	91.49	226	92.16	3.22	92.28
12.5	226	93.67	2.33	93.61	226	94.22	3.33	94.47
13.0	225	95.43	1.95	95.36	225	95.72	2.61	96.27
13.5	225	96.72	1.50	96.62	225	97.06	2.09	97.47
14.0	224	97.67	1.06	97.62	225	98.01	1.62	98.32
14.5	223	98.33	0.72	98.27	224	98.68	1.21	98.85
15.0	214	98.79	0.45	98.77	217	99.18	0.89	99.34
15.5	202	99.07	0.31	99.09	204	99.50	0.66	99.70
16.0	180	99.23	0.17	99.20	181	99.72	0.46	99.94
16.5	146	99.33	0.12	99.32	148	99.83	0.34	100.00
17.0	104	99.45	0.11	99.46	106	99.90	0.27	100.00
17.5	65	99.70	0.30	99.71	66	99.90	0.19	100.00

A Chi Square (χ^2) analysis following the goodness of fit protocol was applied to the frequencies between predicted maturation categories and actual maturation categories for each age in the same way it was computed for boys. The frequencies for PZ represented the observed distribution and the frequencies generated from AZ scores represented the expected distribution. A Cramér's V statistic was also calculated. Table 4-23 report the results of the Chi Square analysis.

Table 4-16. Frequency of maturation categories for girls as assigned by the PPAH z-scores (PZ) and the APAH z-scores (AZ).

Age	Predicted MPS Maturation Categories from PZ			Actual Maturation Categories From AZ		
(yr)	Early	Average	Late	Early	Average	Late
4.0	18	91	16	19	87	19
4.5	20	98	19	20	94	23
5.0	24	101	20	20	104	21
5.5	23	115	16	22	108	24
6.0	24	120	20	25	113	26
6.5	18	132	22	25	119	28
7.0	27	130	18	25	127	23
7.5	24	126	28	22	126	30
8.0	28	145	19	29	136	27
8.5	32	140	25	34	138	25
9.0	28	152	27	33	149	25
9.5	31	152	28	31	153	27
10.0	33	147	38	31	158	29
10.5	33	158	29	34	153	33
11.0	37	152	35	40	151	33
11.5	37	152	33	39	149	34
12.0	42	150	34	39	149	38
12.5	45	146	35	27	165	34
13.0	36	153	36	32	155	38
13.5	34	156	35	24	166	35
14.0	32	163	29	25	167	32
14.5	32	166	25	28	169	26
15.0	29	159	26	3	184	27
15.5	20	161	21	5	174	23
16.0	23	138	19	6	151	23
16.5	17	116	13	3	123	20
17.0	10	84	10	4	86	14
17.5	11	42	12	0	58	7

The results for the Chi Square analyses for each age category revealed similar results for the girls as what were found with the boys. The χ^2 values were less than the critical values ($\chi^2_{critical}$= 5.99, alpha = 0.05, degrees of freedom = 2) at all ages of childhood revealing that the distributions of observed frequencies (PZ) were similar to expected frequencies (AZ). The χ^2 values at ages 15.0 through 17.5 years, not 17.0 years, were found to be statistically significant (exceeded $\chi^2_{critical}$= 5.99, alpha = 0.05, degrees of freedom = 2), indicating that the distributions at these ages were not similar.

Table 4-17. Results of the girls' Chi Square Analysis on frequencies of maturation categories computed from PZ and AZ. The Cramér's V statistic is also provided.

Pairings	n	*df*	χ^2	*Cramér's V*	*P*
PZ4.0 - AZ4.0	125	2	0.370	0.039	0.831
PZ4.5- AZ4.5	137	2	0.460	0.041	0.795
PZ5.0 - AZ5.0	145	2	0.430	0.039	0.807
PZ5.5 - AZ5.5	154	2	1.840	0.077	0.399
PZ6.0 - AZ6.0	164	2	1.010	0.056	0.604
PZ6.5 - AZ6.5	172	2	2.530	0.086	0.282
PZ7.0 - AZ7.0	175	2	0.720	0.045	0.698
PZ7.5 - AZ7.5	178	2	0.160	0.021	0.923
PZ8.0 - AZ8.0	192	2	1.700	0.067	0.427
PZ8.5 - AZ8.5	197	2	0.070	0.013	0.966
PZ9.0 - AZ9.0	207	2	0.710	0.043	0.701
PZ9.5 - AZ9.5	211	2	0.020	0.007	0.990
PZ10.0 - AZ10.0	218	2	1.670	0.062	0.434
PZ10.5 - AZ10.5	220	2	0.350	0.028	0.840
PZ11.0 - AZ11.0	224	2	0.180	0.020	0.914
PZ11.5 - AZ11.5	222	2	0.100	0.015	0.951
PZ12.0 - AZ12.0	226	2	0.340	0.027	0.844
PZ12.5 - AZ12.5	226	2	5.680	0.112	0.058
PZ13.0 - AZ13.0	225	2	0.300	0.026	0.861
PZ13.5 – AZ13.5	225	2	2.030	0.067	0.362
PZ14.0 – AZ14.0	224	2	1.060	0.049	0.589
PZ14.5 - AZ14.5	223	2	0.310	0.026	0.856
PZ15.0 - AZ15.0	214	2	22.970	0.232	<.0001
PZ15.5 - AZ15.5	202	2	9.600	0.154	0.008
PZ16.0 - AZ16.0	180	2	10.930	0.174	0.004
PZ16.5 - AZ16.5	146	2	11.490	0.198	0.003
PZ17.0 - AZ17.0	104	2	3.260	0.125	0.196
PZ17.5 - AZ17.5	65	2	14.880	0.338	0.001

Overall, the Cramér's *V* values were low at all ages. The association between predicted maturation categories and actual maturation categories appears to be similar for girls when compared to the boys. These results suggest that the use of the KR method for assigning girls to maturity groups is useful for ages 4.0 through 14.5 years.

CHAPTER V

DISCUSSION

One purpose of this study was to examine the accuracy of the Khamis-Roche (KR) method of predicting adult height. An additional purpose was to apply the KR method of predicting adult height to maturity estimation because this method has been prevalent in several recent research studies involving youth sports and biological maturity estimation.

This chapter will first focus on the statistic used to determine the accuracy of the prediction method, the median absolute deviation (MAD). This chapter will also address the results of the research questions separately.

Median Absolute Deviation

The accuracy of the KR method utilized the median absolute deviation. Khamis (2007b) described this as a criterion of median errors. Each research participant had an absolute value determined on the difference between the measured adult stature and the predicted stature. This allows the error in prediction to be revealed, albeit, in absence of a direction (positive or negative) of error.

The MAD, as defined by Khamis (2007a) is the median absolute deviation of $|y - \hat{y}|$, where y represents the true adult stature and $\hat{y}$ represents the predicted adult stature for an individual of a given age and gender. Therefore, for a given age and gender, $P[|y - \hat{y}| < \text{MAD}] = 0.50$, by definition of a median. Algebraically, the MAD, or 50th percentile, is represented below:

$$P[-\text{MAD} < y - \hat{y} < \text{MAD}] = 0.50$$

$$P[\hat{y} - \text{MAD} < y < \hat{y} + \text{MAD}] = 0.50$$

Consequently, when the MAD is added to and subtracted from the predicted adult stature, an interval is obtained within which 50% of the actual adult statures lie. This is effectively the 50% confidence interval, and the MAD is referred to as the 50% error bounds (Khamis, 2007a). Exactly the same procedure was repeated for the 90% error bounds in order to obtain the 90th percentile. The formulae for the 90% error bounds are represented as follows:

$$P[-\text{MAD} < y - \hat{y} < \text{MAD}] = 0.90$$

$$P[\hat{y} - \text{MAD} < y < \hat{y} + \text{MAD}] = 0.90$$

Use of the MAD for accuracy of prediction method has been espoused by the Roche-Wainer-Thissen (RWT) method (see page 27 in Chapter 2 for a discussion of this method). The MAD has also been used in other studies that utilized the RWT method (Khamis & Guo, 1993; Khamis & Roche, 1995a) or an aspect of that method, such as the Khamis-Roche (1994) method or modification of that method (Wainer et al., 1978). The absolute error of estimate is independent of the prediction method's tendency to over-estimate or underestimate adult stature (Khamis & Guo, 1993), which is how many prediction methods report their data.

The appeal to using the 50% and 90% error bounds appears to be the range within which the predictions for 50% and 90% of actual adult statures will lie, respectively. Wainer, Roche, and Bell (1978), for example, reported use of the RWT method substituting skeletal age with chronological age. A modest decrease in prediction accuracy was reported that alluded to little predictive ability of the GP skeletal age. The use of the 50% and 90% error bounds allowed them to test RWT prediction accuracy by making substitutions for SA or paternal height. Chronological age was substituted for skeletal age and a population mean was substituted for the paternal height. These substitutions, they reported, had little effect on the accuracy of the RWT.

Wainer, Roche, and Bell (1978) also reported, as figures, for the 50% and 90% error bounds for the RWT method with and without the substitutions that were referred to above. The 50% error bounds were much closer to each other than the 90% error bounds.

Validating the KR Method

Research Question 1: *What is the validity of the Khamis-Roche method (or how accurate is the method) of predicting adult height as applied to a mid-Michigan sample of boys?*

The first research question addresses whether or not the Khamis-Roche Method can accurately predict adult height for a group of mid-Michigan boys. The accuracy is relative in the sense that all prediction is associated with error. The error, therefore, is the salient aspect of answering this question. Is the method valid, or does the KR method purport to predict adult height for boys with a similar level of error?

The average of the MAD for the Fels sample was slightly less (about a 0.16 cm difference) than the average of the MAD for MPS boys. There was also no great disparity between the standard deviations about those mean values (0.07 cm). The average of the 90% error bounds, however, illustrated a greater spread of errors with the MPS boys than with the Fels boys. This probably accounts for the higher values at the 90% error bounds for MPS boys.

While the ANOVA for condensed means did not confirm statistically similar samples, the MAD for MPS boys is within acceptable error limits for predicting adult height. The Bayley tables (1946), for example, reported an error of 2.5 cm from adult height with 60% of the sample population for boys at age 15 years. Bayley (1946) did not use the MAD; however, the reported age for adolescent boys is similar to the overall error of 50% of the population for boys when using KR method to predict adult height. It should be noted that Bayley's original tables cited improved prediction during adolescence. Therefore, the 2.5 cm error from age 15 is less than what would be reported for younger ages using the Bayley tables.

Overall, the mean and median differences between the Fels sample and MPS sample are not that vast. The spread of the data, however, is greater in the MPS sample. This is evident from plotting the age-specific 50% and 90% error bounds (Figure 4-2). The shape and pattern reflect the values and similar plots reported previously (Khamis & Roche, 1994; Wainer et al., 1978).

Differences Between the Fels Sample and the MPS Sample.

In the Fels Longitudinal Study, several differences exist that can perhaps explain the statistically significant differences between the two samples. The first of these possibilities in differences include anthropometrics. Stature is a primary predictor variable in the RWT and KR prediction of adult height. The Fels Longitudinal Study utilized a recumbent length and the MPS sample utilized a standard upright stature for height (see Appendix A for exact procedures). This difference in stature measurements has been reported as negligible due to a high degree of association between them (Malina et al., 2004; Roche & Davila, 1972; Roche et al., 1983). The difference between statures at age 18 years and 25 years, for example, is very little (Roche, 1980).

All methods for the prediction of adult stature estimate stature at 18 years (Roche & Sun, 2003). Therefore, the KR method was reapplied to MPS sample utilizing 18 year stature and not final adult height. The differences in MAD values for age categories for MPS boys improved slightly when 18 year statures were used as final adult height when compared to their actual adult height. There were 78 MPS boys from the 205 sample that had an 18 year stature less than their actual adult height that occurred beyond age 18 years. MAD values were recalculated with 18 year statures. Table 5-1 reveal descriptive statistics for MAD values for boys with 18 year adult statures (MPS-18) and for boys utilizing their adult height beyond 18 years (MPS-AH).

The average of the MAD values for MPS-AH and MPS-18 were 2.32 (±0.62) and 2.23 (±0.61), respectively. While the average of the MAD improved, the difference is only slightly better. Figure 5-1 illustrates the MPS-AH and MPS-18 MAD or 50% error bounds. It is evident that the MADs are similar from 4.0 to 11.5 years. The biggest difference appears around 12.0 years with the MAD-18 values lower at all ages until 17.5 years. The ANOVA for condensed means was also re-applied to the Fels boys sample with the MPS-18 MAD values. There were no statistically significant differences ($p > .05$, $F_{(2, 223)} = 0.904$) between the means of MPS-18 boys and Fels boys. This result confirms that the KR method can predict 18 year statures with relative accuracy with applied to the MPS sample.

Table 5-1. Mean, standard deviation, and median values for absolute deviation (MAD) at each age of measurement for the MPS sample of boys with actual adult height (MPS-AH) and a MPS boys sample with 18-year statures (MPS-18).

	MPS-AH				MPS-18			
Age (yr)	n	Mean	SD	Median	n	Mean	SD	Median
4.0	91	3.74	3.04	2.82	91	3.58	2.94	2.80
4.5	101	3.62	2.99	2.95	101	3.39	2.85	2.79
5.0	117	3.28	2.74	2.59	117	3.18	2.65	2.42
5.5	128	3.35	2.82	2.50	128	3.19	2.73	2.49
6.0	134	3.27	2.86	2.37	134	3.09	2.75	2.45
6.5	142	3.23	2.73	2.36	142	3.10	2.56	2.43
7.0	154	3.14	2.56	2.31	154	2.96	2.44	2.26
7.5	165	3.08	2.57	2.32	165	2.94	2.43	2.39
8.0	169	2.94	2.54	2.20	169	2.78	2.37	2.07
8.5	176	2.99	2.75	2.22	176	2.84	2.57	2.32
9.0	183	2.99	2.66	2.14	183	2.81	2.46	2.26
9.5	187	2.98	2.65	2.16	187	2.79	2.46	2.08
10.0	189	2.99	2.66	2.12	189	2.77	2.47	2.09
10.5	197	2.95	2.66	1.88	197	2.76	2.47	1.92
11.0	196	2.90	2.73	1.87	196	2.71	2.53	1.90
11.5	197	3.19	2.89	2.17	197	2.92	2.71	2.15
12.0	199	3.35	2.87	2.55	199	3.11	2.72	2.34
12.5	202	3.76	3.20	2.82	202	3.47	3.11	2.51
13.0	201	3.92	2.99	3.09	201	3.59	2.92	2.82
13.5	201	4.09	2.84	3.37	201	3.69	2.76	3.09
14.0	201	4.03	2.74	3.37	201	3.63	2.60	3.22
14.5	201	3.65	2.48	3.12	201	3.27	2.25	3.03
15.0	199	3.19	2.42	2.69	199	2.79	2.08	2.39
15.5	195	2.72	2.26	2.11	195	2.34	1.80	1.94
16.0	193	2.21	1.99	1.73	193	1.84	1.46	1.57
16.5	192	1.72	1.76	1.20	192	1.36	1.10	1.03
17.0	178	1.27	1.59	0.74	178	0.83	0.81	0.62
17.5	157	1.61	1.29	1.23	158	1.18	0.72	1.04

Another difference is perhaps in the timing that measurements were taken. Fels participants were measured within two weeks of each birthday to four years of age, within three weeks of the fifth and sixth birthdays, and within one month of each birthday thereafter (Roche et al., 1983). MPS participants were measured seasonally in the winter months (December and January) and in the summer (June and July). Rates of growth not only vary quite a bit among children and vary considerably with the season of the year as well. Children typically gain more in stature during the spring and summer than during the fall and winter (Malina et al., 2004). The differences in the timing of these measurements are probably most evident during rapid periods of growth, such as the adolescent growth spurt.

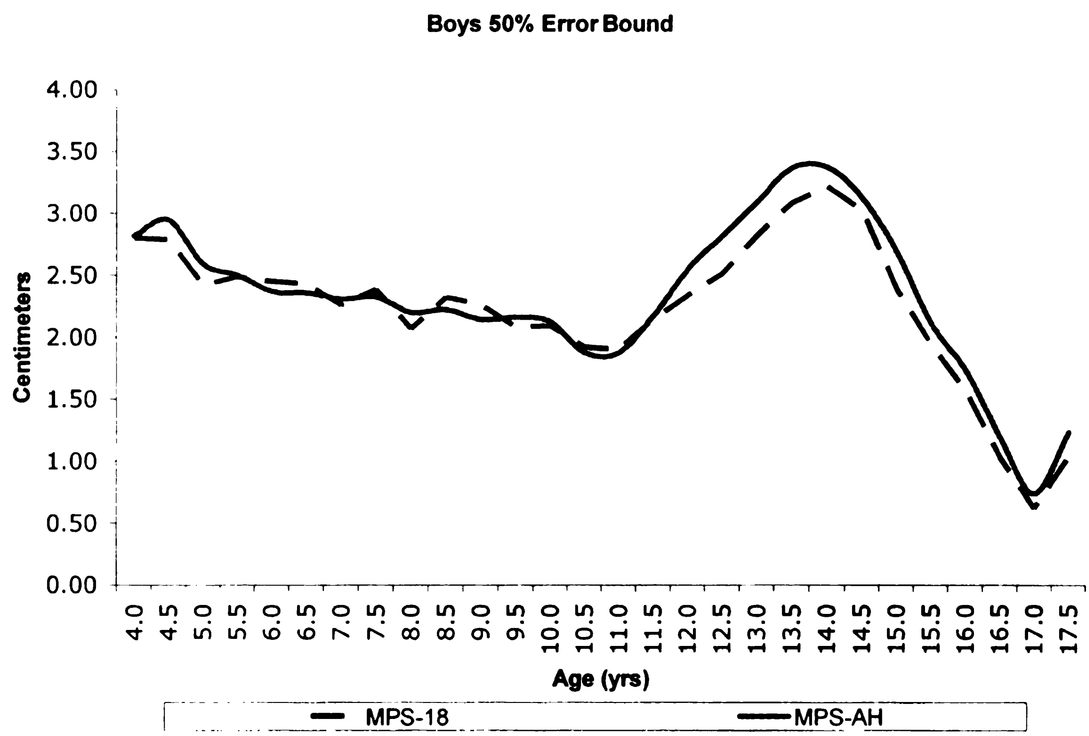

Figure 5-1. Boys MAD or 50% error bounds from MPS-18 and MPS-AH.

In addition to measuring the youth participants at Fels, the investigators also measured the parents of their sample with the same methods as the boys and girls. The MPS sample relied upon self-reported, retrospective investigation of parental height. While efforts were made to reduce measurement error by an acceptable protocol (Epstein, Valoski, Kalarchian, & McCurley, 1995), exact measurement is undoubtedly the more preferable approach..

Median error data were provided by Khamis (2007a) utilizing a Fels sample, albeit using the RWT method. Those data are listed in Table 5-2 in order to compare results for the Fels sample and the MPS sample. The median errors were also smoothed using two different methods. A general method called multivariate semi-metric smoothing (MS^2) and multivariate cubic spline smoothing with one knot [$MCS^2(1)$] have been provided. Information on these two methods have been studied and reported elsewhere (Khamis & Guo, 1993). Khamis and Guo (1993) found the $MCS^2(1)$ to be superior the MS^2 method of smoothing. The data for MPS and Fels boys have been plotted for graphical representation of the data (see Figure 5-2).

The MAD values were higher for MPS boys at all age categories except 5.5, 10.5, 11.0, and 17.0 years, respectively, when compared to MS^2 median values. When comparing MPS boys with $MCS^2(1)$, the comparison is the same as MS^2, except at age 5.5 where MPS and $MCS^2(1)$ have the same value. The MAD values for the MPS boys decreased until age 11.0 years, increased until age 14.0 years, then decreased thereafter. The MPS boys revealed their highest MAD values at the ages of 13.0-15.0 years. The pattern of values was more consistent for the Fels boys, but decreased after age 13.5 years. Figure 5-2 illustrates relative similarity between Fels and MPS boys until age 11.5 years where MPS boys appear to, on average, initiate their growth spurt in height. Fels boys appear to begin their growth spurt a year later. While both samples of boys appear to lose predictive accuracy during the growth spurt, the difference is substantially greater in the MPS boys. It has been reported that CA substituted for SA only suffers slight deterioration in predictive accuracy. This appears to be more substantial during the pubertal growth spurt.

Table 5-2. Median absolute deviation values for MPS and Fels boys at each age of measurement. The Median errors for a sample of Fels boys were provided by Khamis (2007a).

Age (yr)	n	MPS	MS^2	$MCS^2(1)$
4.0	91	2.82	2.51	2.46
4.5	101	2.95	2.67	2.51
5.0	117	2.59	2.51	2.50
5.5	128	2.50	2.55	2.50
6.0	134	2.37	2.31	2.20
6.5	142	2.36	2.17	2.23
7.0	154	2.31	2.10	2.09
7.5	165	2.32	2.21	2.19
8.0	169	2.20	1.94	1.96
8.5	176	2.22	1.84	2.00
9.0	183	2.14	2.03	2.06
9.5	187	2.16	1.99	2.03
10.0	189	2.12	1.87	1.87
10.5	197	1.88	2.09	2.17
11.0	196	1.87	2.11	2.13
11.5	197	2.17	2.10	2.07
12.0	199	2.55	2.12	2.03
12.5	202	2.82	1.99	2.21
13.0	201	3.09	2.27	2.22
13.5	201	3.37	2.43	2.45
14.0	201	3.37	1.97	2.04
14.5	201	3.12	1.91	1.95
15.0	199	2.69	1.72	1.40
15.5	195	2.11	1.20	1.22
16.0	193	1.73	1.30	1.41
16.5	192	1.20	1.09	0.70
17.0	178	0.74	0.92	0.58
17.5	157	1.23	0.89	1.10

The average of the MAD across all ages was also calculated. The average of the MAD for MPS boys was 2.32 (±0.62) and the average of the MAD reported by Khamis and Roche (1994) for the Fels sample was 2.16 (±0.55). The average of the MAD for

MS^2 and $MCS^2(1)$ are 1.96 (±0.48) and 1.94 (±0.52), respectively. Again, these values were calculated with the RWT method and are lower due to the use of skeletal age as a predictor variable.

The MPS values for 50% error bounds and 90% error bounds are within acceptable values of error in prediction. For most common prediction methods, those that use SA, there is a 3 to 5 centimeter range of error (Malina et al., 2004). Median errors for the BP method are reported to be 4.0 cm, the RWT reported median errors between 2.5 – 3.0 cm, and the TW method reported errors to be 4 cm (Bayley & Pinneau, 1952; Roche & Sun, 2003; Roche et al., 1975; Tanner et al., 1983).

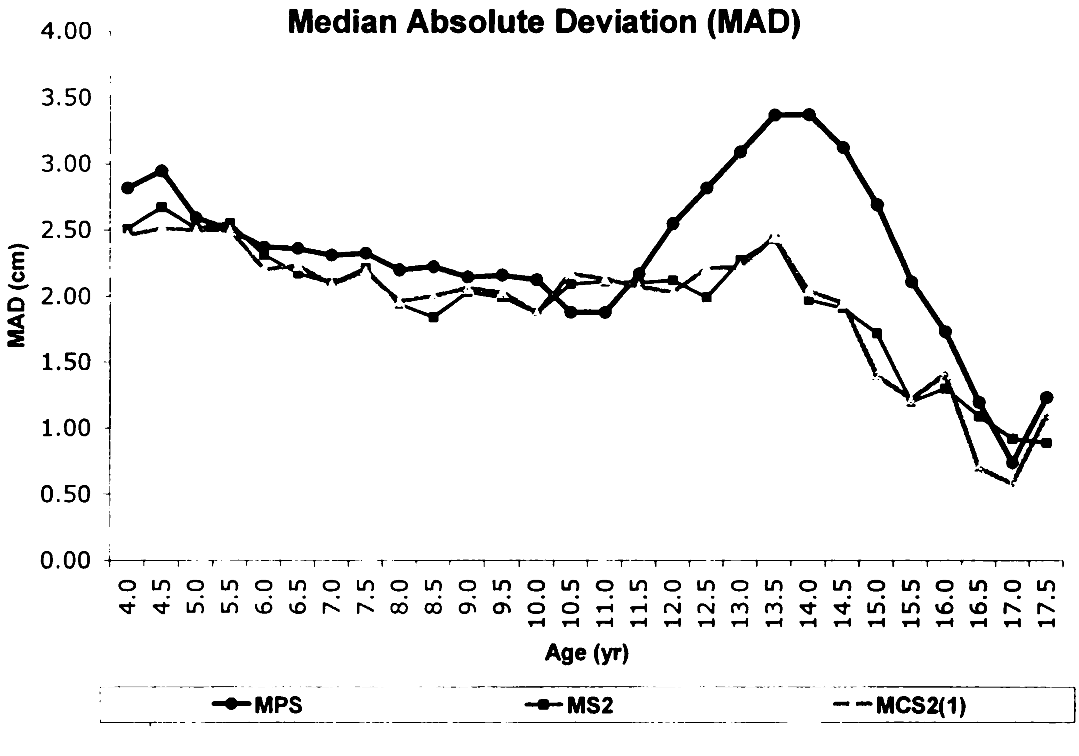

Figure 5-2. Median absolute deviation for MPS and Fels boys. The MAD for Fels boys were generated from the RWT method with two different forms of smoothing, MS^2 and $MCS^2(1)$.

In populations of short, normal, slow-maturing, yet normal (absent of growth pathology) boys (SNSMC), the RWT method provided an absolute error of estimate of 3.4 ± 2.3 cm (Brämswig et al., 1990; Khamis & Roche, 1995a). The average MAD for SNSMC boys and normal boys was 1.72 (± 0.60) and 1.71 (± 0.61), respectively. These methods, however, use skeletal age as a predictor variable. The Beunen-Malina method (Beunen et al., 1997), a noninvasive height prediction method, predicts adult height for adolescent boys with a 3.5 to 4.0 cm error range (Roche & Sun, 2003). The MPS boys had similar values for median errors to methods that used SA and methods that did not.

Research Question #2: *What is the validity of the Khamis-Roche method (or how accurate is the method) of predicting adult height as applied to a mid-Michigan sample of girls?*

The second research question pertains to the accuracy of the KR method of predicting adult height when applied to a sample of mid-Michigan girls. The 50% and 90% error bounds are lower for MPS girls than for MPS boys. There is a difference of about 0.4 cm between Fels girls (Khamis & Roche, 1994) and MPS girls for average of the MAD and about 0.5 cm difference in average of 90% error bounds. Average of the MAD for normal Fels girls, as reported by Khamis and Roche (1995), was 1.39 (± 0.50) and 1.61 (±0.59) for short, normal, slow maturing (SNSMC) girls. Mean absolute errors for Fels girls was reported as 3.2 ± 2.9 cm by Khamis and Guo (1993) using the RWT method. The median absolute errors for RWT were similar to the TW1 method, reporting a range of 2.9 ± 1.8 cm, but not statistically significant (Brämswig et al., 1990).

The MAD for the MPS sample was plotted against median absolute errors provided by Khamis (2007a) with a sample of Fels girls, albeit using the RWT prediction method (see Figure 5-3). The data is listed in Table 5-3. .

Table 5-3. Mean, standard deviation, and median values for absolute deviation for girls at each age of measurement. Median errors for absolute deviation (MAD) are also provided for comparison (Khamis, 2007a).

	MPS Girls (cm)				Median Errors for Fels Girls (cm)	
Age (yr)	n	Mean	SD	Median	MS^2	$MCS^2(1)$
4.0	125	3.13	2.42	2.94	2.26	2.39
4.5	137	3.21	2.37	2.88	2.50	2.43
5.0	145	3.10	2.35	2.55	2.51	2.43
5.5	154	3.07	2.29	2.45	2.40	2.57
6.0	164	3.07	2.31	2.63	2.18	2.11
6.5	172	2.94	2.08	2.51	2.00	2.12
7.0	175	2.82	2.11	2.48	2.19	2.19
7.5	157	2.79	2.08	2.30	2.01	2.05
8.0	192	2.74	2.00	2.42	2.13	1.81
8.5	197	2.60	1.93	2.23	2.22	1.88
9.0	207	2.68	1.91	2.41	2.19	1.99
9.5	211	2.75	2.25	2.38	1.91	2.05
10.0	218	2.75	2.01	2.36	1.75	1.79
10.5	220	2.91	2.14	2.54	1.65	1.82
11.0	224	2.95	2.19	2.51	1.89	1.81
11.5	222	2.95	2.17	2.60	1.83	2.18
12.0	226	3.07	2.25	2.72	1.83	2.32
12.5	226	3.36	7.71	2.38	2.01	1.86
13.0	225	2.56	2.03	2.06	1.82	1.38
13.5	225	2.25	1.77	1.81	1.30	0.94
14.0	224	1.87	1.59	1.56	1.08	1.04
14.5	223	1.52	1.27	1.27	1.02	1.07
15.0	214	1.25	1.05	1.17	0.73	0.71
15.5	202	1.13	0.98	1.07	0.56	0.65
16.0	180	1.07	0.73	1.05	0.54	0.47
16.5	146	1.01	0.66	1.06	0.40	0.53
17.0	104	0.89	0.73	0.85	0.39	0.70
17.5	65	0.66	0.94	0.49	1.07	0.70

It has been shown that CA can be substituted for SA with only a slight deterioration in prediction accuracy (Wainer, Roche, & Bell, 1975) and it is expected that the MAD for RWT to be more accurate than the KR prediction method. Figure 4-6 illustrates this difference in accuracy at nearly all ages. The values are closest in childhood until about age 9 when comparing MPS and Fels girls. The difference is greatest at the time of the growth spurt until about age 13.0 years. The MAD for MPS girls is more accurate at age 17.5 years. The pattern for prediction accuracy for MPS and Fels girls is similar. The prediction accuracy is greatest with increasing age, especially following the adolescent growth spurt.

When examining plots of the 50% and 90% error bounds, the shape of the curves reflect the trends in prediction accuracy. The plots for girls for Fels girls are reported by Khamis and Roche (1994) and Wainer, Roche, and Bell (1975). The 50% error bounds are more stable through childhood than the 90% error bound means at each age category. For the Fels sample and for the MPS sample of girls, there is a tendency for prediction accuracy to improve with increasing age. This is consistent with RWT and BP methods as well.

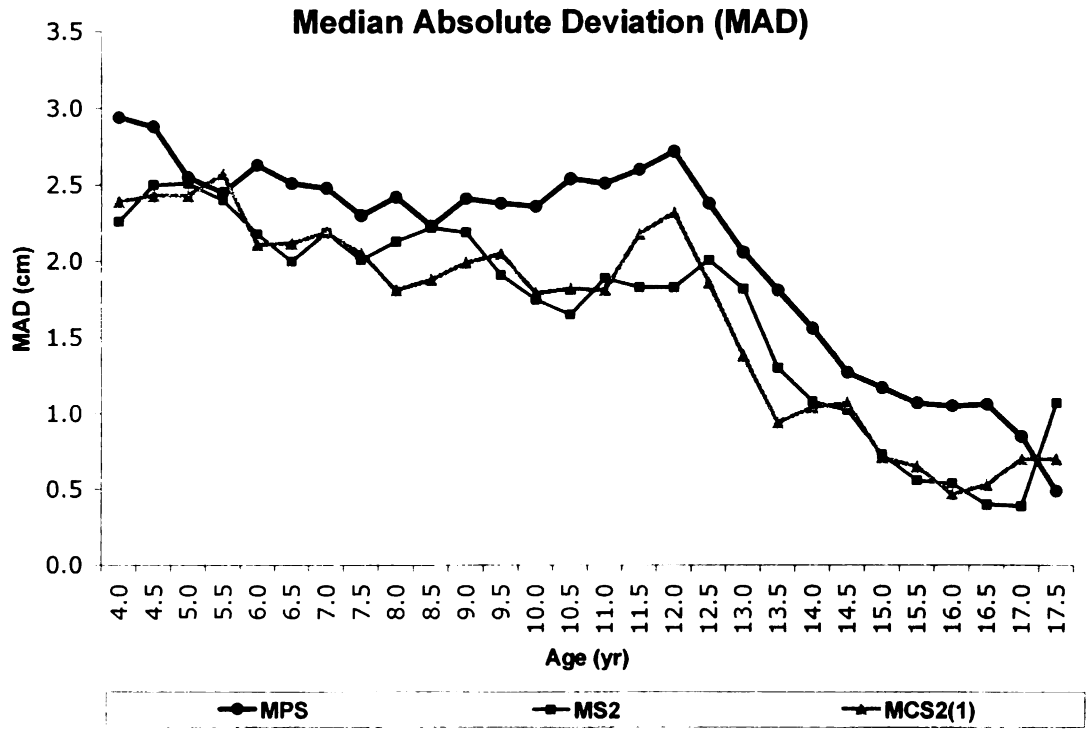

Figure 5-3. Median absolute deviation for MPS and Fels girls. The MAD for Fels girls were generated from the RWT method with two different forms of smoothing, MS^2 and $MCS^2(1)$.

The ANOVA for condensed means revealed statistically significant differences between the means for 50% and 90% error bounds of MPS and Fels samples. Despite this finding, the values are fairly similar and exhibit a relatively similar spread around the average of the MAD. The average of the MAD and average of 90% error bounds fall within acceptable error range for predicting adult height.

<u>**Research Question 3:**</u> *How accurate is the Khamis-Roche method when comparing early-, average-, and late-maturing boys and girls.*

The accuracy of the KR adult height prediction method was addressed with respects to rate of maturation for boys and girls. Rate of maturation is an important determinant for growth (Bayer & Bayley, 1959; Bayley, 1962). It is necessary for any prediction of adult height to have a maturity component. Cameron (2004) writes:

> "... prediction of adult height is not simply a process of predicting a one-dimensional variable – height; it is, in fact, a process of predicting two dimensions – height and maturity, i.e., the height of the individual at full maturity. Thus, it is necessary to use indicators of both height and maturity in a prediction technique." (p. 361-362)

The more successful prediction methods, RWT, BP, and TW, were strengthened by the use of skeletal age as a predictor variable. The KR method was developed based on the work of Roche, Wainer, and Bell (1975) that reported only a slight deterioration in prediction accuracy when SA was replaced by CA.

The current study sought to examine the accuracy of the prediction for early-, average-, and late-maturing boys and girls. The KR method was applied to a sample of boys and girls grouped by rate of maturation as assessed by the age by which adult height was achieved. Prediction accuracy was improved when early-, and late-maturing boys and girls were separated from the average-maturing groups. The result of separating the sample of boys and girls into maturation categories show that average-maturing individuals have improved accuracy in prediction. The median of absolute errors at each chronological age approximated the MAD for Fels boys and girls. In addition, the average of the MAD for average-maturing boys and girls were closer to the corresponding Fels sample. The average of the MAD reported by Khamis and Roche (1994) for boys and girls was 2.16 (±0.55) cm and 1.67 (±0.65) cm, respectively. The average-maturing MPS boys and girls' average of the MAD was 2.10 (±0.65) and 1.87 (±0.58), respectively. MPS late-maturing girls, however, have improved accuracy of prediction at age 14.5 years to 17.5 years over the average-, and early-maturing girls. Prediction accuracy has been found to improve for girls during puberty.

Maturation categories for boys and girls were determined by age of attaining adult height. Reported ages for attaining adult height are limited by criteria that determine adult stature. Growth studies tend to cease collecting data around the age when boys and girls complete schooling and are no longer available for data collection. With this in mind, the average reported age for completing adult height for boys and girls are 16 years, and 18 years, respectively (Malina et al., 2004). Average age for attaining adult height for MPS girls was 16.7 (±1.1) years and the average age for MPS boys was 18.3 (±1.3) years. The disadvantage to using age of attaining adult height to separate a sample into maturation categories is the lack of precedence.

The most appropriate variable for this study would have been strengthened by using peak height velocity (PHV). Peak height velocity and its association with growth of various body dimensions and stature are well documented for boys and girls (Bielicki & Koniarek, 1984; Bielicki & Welon, 1973; Malina et al., 2004; Nicolson & Hanley, 1953). Peak height velocity and age at peak height velocity are more commonly used as indicators of maturation due to their relationship with other anthropometric variables. PHV and components of the growth velocity curve require longitudinal data. While this study utilized longitudinal data, the velocity of the growth curve was not calculated. The complexity of mathematics necessary for smoothing growth curves was beyond the scope of this examination. The investigator recognizes the contribution of mathematics and smoothing techniques that would strengthen this study, however. The strength of using the KR method to predict height is that it is reasonable for practitioners in kinesiology to utilize it because it does not employ complex mathematics.

Application of the Khamis-Roche Method and Biological Maturity Estimation

There are several reasons why the Khamis-Roche method for predicting adult height has received so much attention in recent years. First, it is a noninvasive method for predicting adult height. With the findings by Wainer, Roche, and Bell (1975), substituting chronological age for skeletal age successfully without severe degradation of prediction accuracy has provided a viable option for kinesiology practitioners and researchers to estimate adult height without needing an X-ray for skeletal age estimation.

Another reason that makes the KR method attractive is the ease of measurement. While knowledge and practice on any anthropometric variable is implicit in its use, the measures are relatively easy to do accurately with minimal training. Thus, this method is a realistic option for kinesiology practitioners in the areas of physical education and youth sports as well as for researchers in kinesiology.

The KR method for predicting adult height has also received a lot of attention in recent years as a noninvasive method of estimating biological maturity status. The predominant method for estimating maturity status has utilized the KR method of predicting adult height in order to estimate somatic maturation via a percentage of adult height (Battista et al., 2003; Cumming, 2002; Dompier, 2005; Malina, Cumming et al., 2005) while others have estimated peak height velocity (Malina, Claessens et al., 2006; Mirwald et al., 2002). While each of these methods has reported favorable results, there has been a lack of evidence with longitudinal data.

The z-score was used as a means assigning boys and girls to early-, average-, or late-maturing categories based on the percentage or predicted percentage of adult height attained at various chronological ages. This method was chosen for several reasons. First, the z-scores allow a set of measurements from children in a sample who may vary in age and sex to be combined together (Frongillo, 2004). Second, this method was also selected based on past application of other studies investigating KR as a method of biological maturity estimation (Battista et al., 2003; Cumming, 2002; Dompier, 2005; Malina et al., 2004; Malina, Cumming et al., 2005; Malina, Morano et al., 2005; Morano, 2003).

The use of z-scores for analytic purposes, however, can be problematic. Frongillo (2004) reported that a pattern of growth in a reference, both in terms of central tendency and variability can differ from the sample at hand over time due to various factors. Further, sex and age adjustments that may be needed in analyses might better be made by including covariates for sex and age in the analysis. This study addressed each sex separately so there was no need to adjust for sex as a covariate.

In previous studies, such as the ones mentioned previously, the calculation of the z-score utilized a reference sample (Bayer & Bayley, 1959). Table 5-4 lists the mean and standard deviation for PPAH by Bayer and Bayley (1959) for boys and girls, respectively. Note that the reference data is provided in half-year increments starting at age 9.0 years. Age increments of whole years were provided only from age 4.0 to 8.0 years. The PPAH was used to calculate a z-score (BZ) using the Bayer and Bayley (1959) reference data.

Table 5-4. Reference data (mean, standard deviation) for percent of adult height achieved at successive chronological ages (Bayer & Bayley, 1959) for boys and girls.

	Boys			Girls		
Age (yr)	n	Mean	SD	n	Mean	SD
4.0	22	57.72	1.38	22	57.16	1.20
5.0	23	61.60	1.49	23	66.24	1.45
6.0	23	65.31	1.58	23	70.29	1.60
7.0	23	69.08	1.60	22	74.28	1.61
8.0	22	72.40	1.68	23	77.57	1.87
9.0	22	75.61	1.68	21	81.19	2.00
9.5	21	77.21	1.66	20	83.03	2.13
10.0	22	78.40	1.76	23	84.76	2.42
10.5	23	79.82	1.77	22	86.85	2.71
11.0	23	81.30	1.94	21	88.65	2.88
11.5	23	82.54	2.00	21	90.81	3.06
12.0	20	84.00	2.23	22	92.61	3.27
12.5	21	85.43	2.49	21	94.72	2.61
13.0	23	87.32	3.02	18	95.96	2.15
13.5	21	89.22	3.57	18	97.17	1.70
14.0	20	91.00	3.96	19	98.27	1.24
14.5	20	92.60	3.85	19	98.74	0.93
15.0	20	94.60	3.74	21	99.31	0.68
15.5	21	96.00	3.31	21	99.54	0.48
16.0	22	97.09	2.71	21	99.62	0.35
16.5	20	97.95	2.12	20	99.75	0.34
17.0	20	98.79	1.43	22	99.95	0.25
17.5	20	99.28	1.01	19	99.91	0.25

This reference has been utilized in the past for several reasons. First, the Bayer and Bayley (1959) reference data have been used frequently as a reference source in recent research (Battista et al., 2003; Cumming, 2002; Cumming et al., 2006; Dompier, 2005; Malina, Cumming et al., 2005; Morano, 2003) with relative success. Second, the Bayer and Bayley (1959) reference provides data for boys and girls. Finally, comparisons at 6 month intervals from ages 9.0 to 17.5 years are available for boys and girls. Yearly comparisons, on the whole year, were available from ages 4.0 to 9.0 years. Other data, such as those from the Harvard Longitudinal Study, have been published

(Bayley, 1962), but in whole year increments and not semi-annually. A disadvantage, however, is the number of boys and girls that make up this reference sample. The largest number of any group of boys or girls in an age category is no bigger than 23.

Research Question 4: *Does the Khamis-Roche method accurately provide biological maturity estimation by separating early-, average-, and late-maturing boys with a predicted percentage of adult height when compared to actual percentage of adult height?*

The Khamis-Roche method of predicting adult height was used to predict adult height of boys enrolled in the Motor Performance Study from ages 4.0 to 17.5 years. The PAH was used to determine the PPAH.

The PPAH for MPS data are similar to their APAH. The data for MPS boys approximate the similarly published data (see Table 5-5). The Chi Square analyses at each age confirmed that the Khamis-Roche method of predicting adult height assigned boys as early-, average-, and late-maturing in a similar manner as when using actual adult height at most ages.

The ages where PZ did not assign boys to early-, average-, and late-maturing categories in a similar way as the AZ was during the latter stages of the adolescent growth spurt. One reason for the discrepancy is lack of predictive power using the KR method during this period for MPS boys. The results of the MAD for MPS boys, when compared to results of Fels boys by Khamis and Roche (1994), illustrate that it was during the period of adolescence where the greatest differences occurred. Another possible explanation could be the use of adult statures and 18 year statures to create percentage of adult height. However, when comparing MPS percentage of adult height with other samples (see Table 5-6), the values appear to approximate each other.

Table 5-5. Percentage of adult height (APAH) and predicted percentage of adult height (PPAH) for early-, average-, and late-maturing MPS boys.

Age	MPS APAH			MPS PPAH		
(yr)	Early	Avg	Late	Early	Avg	Late
4.0	57.76	57.07	56.03	57.98	57.39	56.98
4.5	60.43	59.20	58.00	59.96	58.57	58.96
5.0	62.35	61.33	59.72	61.87	61.49	60.84
5.5	64.39	63.13	61.70	63.93	63.42	62.86
6.0	66.28	65.03	63.58	65.78	65.27	64.78
6.5	68.19	66.87	65.34	67.58	67.05	66.56
7.0	69.97	68.62	67.03	69.31	68.80	68.27
7.5	71.86	70.42	68.96	71.11	70.53	70.07
8.0	73.56	72.03	70.47	72.84	72.22	71.69
8.5	75.22	73.72	71.95	74.38	73.83	73.24
9.0	76.84	75.36	73.44	75.96	75.40	74.74
9.5	78.46	76.84	74.96	77.49	76.86	76.18
10.0	80.17	78.40	76.32	79.05	78.32	77.53
10.5	81.75	79.86	77.75	80.58	79.77	78.85
11.0	83.41	81.32	79.25	82.17	81.29	80.31
11.5	85.17	82.84	80.51	83.88	82.87	81.75
12.0	87.03	84.49	81.94	85.64	84.53	83.24
12.5	89.52	86.30	83.30	87.80	86.31	84.78
13.0	92.05	88.45	84.80	90.01	88.36	86.49
13.5	94.24	90.70	86.45	92.13	90.52	88.39
14.0	96.33	92.98	88.35	94.12	92.67	90.45
14.5	97.66	94.99	90.53	95.73	94.75	92.68
15.0	98.89	96.51	92.60	97.19	96.38	94.72
15.5	99.42	97.74	94.36	97.94	97.60	96.38
16.0	99.90	98.53	95.95	98.73	98.47	97.70
16.5	99.93	99.12	97.15	99.06	99.11	98.70
17.0	99.90	99.51	98.02	99.66	99.71	99.54
17.5	99.95	99.75	98.71	100.33	100.42	100.41

As mentioned previously, the Bayer & Bayley (1959) reference is cited the most in recent research involving estimated maturity status utilizing percentage of adult height attained based on the prediction of adult height. The current study found that a PZ and AZ scores generated similar distributions of early-, average-, and late-maturing boys. This was confirmed by the Chi Square analysis. When the PAH for MPS boys utilized

Bayer and Bayley (1959) reference data to create z-scores (BZ), the results were much different. Table 5-7 list Chi Square results for BZ and AZ.

Table 5-6. Percentage of adult height from three different North American growth studies for early-, average-, and late-maturing boys.

Age	Harvard[1]			Berkeley[2]			Guidance[2]		
(yr)	Early	Avg	Late	Early	Avg	Late	Early	Avg	Late
4.0	59.50	58.58	58.30	60.00	58.00	58.00	59.50	58.58	58.30
4.5									
5.0	63.50	62.36	61.80	64.00	61.80	59.70	63.50	62.36	61.80
5.5									
6.0	67.40	65.94	65.30	67.80	65.20	63.80	67.40	65.94	65.30
6.5									
7.0	70.60	68.67	68.00	70.50	69.00	66.80	70.60	68.67	68.00
7.5									
8.0	74.00	71.97	71.40	73.50	72.00	69.80	74.00	71.97	71.40
8.5									
9.0	77.60	75.18	74.50	76.50	75.00	73.20	77.60	75.18	74.50
9.5									
10.0	80.60	78.17	77.20	79.70	78.00	76.40	80.60	78.17	77.20
10.5									
11.0	83.90	80.88	79.70	83.40	81.10	79.50	83.90	80.88	79.70
11.5									
12.0	87.50	84.13	82.20	87.20	84.20	82.20	87.50	84.13	82.20
12.5									
13.0	91.80	87.94	84.80	91.30	87.30	84.60	91.80	87.94	84.80
13.5									
14.0	95.30	92.07	88.70	95.80	91.50	87.60	95.30	92.07	88.70
14.5									
15.0	97.50	95.41	90.10	98.30	96.10	91.60	97.50	95.41	90.10
15.5									
16.0	98.90	97.64	95.00	99.40	98.30	95.70	98.90	97.64	95.00
16.5									
17.0	99.60	98.89	97.90	99.90	99.30	98.20	99.60	98.89	97.90
17.5				100.00					
18.0	99.90	99.59	99.20		99.80	99.20			
18.5					100.00				
19.0						99.80			
19.5						100.00			

[1] Bayley (1962), [2] Bayer & Bayley (1959)

Table 5-7. Results of Chi Square Analysis on frequencies of maturation categories computed from z-scores for PPAH and reference data [BZ] (Bayer & Bayley, 1959) and z-scores (AZ) from APAH and MPS reference data for boys.

Pairings	n	*df*	χ^2	*Cramer's V*	*p* value
BZ4.0 – AZ4.0	90	2	6.670	0.191	0.036
BZ5.0 – AZ5.0	117	2	13.050	0.236	0.002
BZ6.0 – AZ6.0	134	2	15.260	0.239	0.001
BZ7.0 – AZ7.0	154	2	18.780	0.247	<0.0001
BZ8.0 – AZ8.0	164	2	26.130	0.028	<0.0001
BZ9.0 – AZ9.0	183	2	21.650	0.591	<0.0001
BZ9.5 – AZ9.5	187	2	20.110	0.660	<0.0001
BZ10.0 – AZ10.0	189	2	13.340	0.642	0.001
BZ10.5 – AZ10.5	197	2	5.300	0.778	0.071
BZ11.0 – AZ11.0	192	2	4.040	0.758	0.133
BZ11.5 – AZ11.5	197	2	1.010	0.918	0.604
BZ12.0 – AZ12.0	198	2	9.720	0.686	0.008
BZ12.5 – AZ12.5	188	2	11.050	0.790	0.004
BZ13.0 – AZ13.0	201	2	25.120	0.710	<0.0001
BZ13.5 – AZ13.5	201	2	45.810	0.607	<0.0001
BZ14.0 – AZ14.0	201	2	48.230	0.690	<0.0001
BZ14.5 – AZ14.5	197	2	50.150	0.885	<0.0001
BZ15.0 – AZ15.0	199	2	32.980	0.614	<0.0001
BZ15.5 – AZ15.5	195	2	25.020	0.632	<0.0001
BZ16.0 – AZ16.0	193	2	27.800	0.796	<0.0001
BZ16.5 – AZ16.5	191	2	7.770	0.443	0.021
BZ17.0 – AZ17.0	177	2	26.280	0.606	<0.0001
BZ17.5 – AZ17.5	156	2	124.380	0.708	<0.0001

The BZ scores did not approximate AZ scores as consistently as the PZ. The χ^2 values at most ages were very high and did not confirm the findings of other studies that predicted adult height can be a reasonable indicator of maturity status. It appears that using BZ scores is only accurate from ages 4.0 to 6.0, 10.0 to 12.5 years, and at age 16.5 years for boys. Most of the evidence that support percentage of predicted mature height attained at various chronological ages utilizes samples of boys. The sample of boys is compared to reference samples, such as Bayer & Bayley (1959) and CDC growth charts for United States reference samples.

Research Question 5: *Does the Khamis-Roche method accurately provide biological maturity estimation by separating early-, average-, and late-maturing girls with a predicted percentage of adult height when compared to actual percentage?*

This study examined the accuracy of the prediction of adult height as a means of classifying girls as early-, average-, or late-maturing on the basis of percentage of adult height. The results for the girls match those of the boys in that the KR method of predicting adult height can estimate maturity status with reasonable accuracy at most ages. Also similar to the boys, the accuracy of maturity estimation is more apparent in childhood and early stages of puberty. The Chi Square statistic confirmed distributions of predicted percentage of adult height against actual percentage of adult height.

The data for girls are not as extensive as they are for boys. There are more reference data for percentage of adult height for boys than there are for girls. Table 5-8 list APAH and PPAH for early-, average-, and late-maturing MPS girls. Those data are compared to a sample of California girls (Bayley, 1962).

The MPS girls reported smaller MAD values than did MPS boys. The values for median errors for MPS girls were similar to Fels girls with both KR method and RWT method. While an ANOVA did not find the Fels sample to be similar to MPS sample, the errors are within acceptable range of reported errors of other studies. Therefore, it is not surprising that MPS predicted percentage of adult height could approximate distributions of maturation categories in the similar was as the actual percentage of adult height. Like the MPS boys, the MPS girls applied the PAH to the Bayer and Bayley (1959) reference sample to create BZ scores and corresponding maturational categories. The BZ and AZ for MPS girls employed a Chi Square statistic on the frequencies. The results revealed significant differences between the two samples at most ages. The distributions were not similar at ages 9.5 to 17.5 years, except age 11.0 years. The V statistic reported weaker associations than PZ and AZ associations. Table 5-8 list results of the Chi Square for BZ and AZ.

There is a paucity of evidence to support the use of KR as a biological maturity estimator for girls. Battista et. al (2003) reported favorable results for boys and girls participating in youth soccer. Additionally, Cumming et al. (2006) support using PPAH as a biological maturity estimator as their sample matched similar characteristics exhibited in other reported studies that used different maturation indicators. Most studies, however, have examined boys when using PPAH as a noninvasive maturity estimator.

Conclusions

It is evident in current research that there is a clear and present need for the noninvasive method of predicting adult height and maturity estimation. This study has reviewed research which states that previous standards and variables necessary for predicting adult height have outgrown what is ethically and medically acceptable for data collection. The SA variable that is prominent in the BP, RWT, and TW methods is difficult to attain in the present age when concern for physical and psychological safety to children is necessary (i.e., exposure to radiation for X-ray examination). This concern is also evident in maturity evaluation standards (i.e., secondary sex characteristics) that may cause a form of psychological trauma or discomfort to children. There are also concerns for costly examinations, the need for qualified personnel, and extensive training for the accurate estimation of maturity stages.

Table 5-8. Reported percentage of adult height (APAH) and predicted percentage of adult height (PPAH) for early-, average-, and late-maturing MPS girls. Data for a sample of California girls is also provided (Bayley, 1962).

Age	MPS APAH			MPS PPAH			Berkeley Girls		
(yr)	Early	Avg	Late	Early	Avg	Late	Early	Avg	Late
4.0	63.21	61.15	59.72	62.13	61.31	60.94	64.90	61.80	59.80
4.5	65.49	63.38	61.78	64.32	63.62	63.21			
5.0	67.65	65.53	63.73	66.55	65.69	65.23	69.30	66.20	63.90
5.5	69.75	67.60	65.75	68.57	67.68	66.92			
6.0	71.80	69.62	67.85	70.63	69.63	69.25	73.40	79.30	67.80
6.5	73.91	71.57	69.79	72.69	71.66	70.90			
7.0	75.84	73.45	71.58	74.42	73.49	72.68	76.00	74.00	71.50
7.5	77.85	75.32	73.35	76.34	75.69	74.73			
8.0	79.73	77.08	75.11	78.14	76.99	76.16	79.50	77.50	74.50
8.5	81.59	78.85	76.94	80.05	78.73	78.09			
9.0	83.51	80.59	78.72	82.03	80.59	79.89	83.50	80.70	77.70
9.5	85.24	82.22	80.41	83.72	82.18	81.30			
10.0	87.25	83.88	81.96	85.53	83.55	82.76	87.90	84.40	81.00
10.5	89.52	85.75	83.58	87.79	85.54	84.51			
11.0	91.80	87.67	85.31	90.27	87.60	86.48	92.90	88.40	84.90
11.5	93.70	89.82	87.22	92.06	89.49	88.17			
12.0	95.87	92.00	89.09	94.02	91.47	90.03	96.60	92.90	88.20
12.5	97.41	94.18	91.13	95.63	93.57	92.23			
13.0	98.31	95.71	92.96	96.88	95.37	94.20	98.20	96.50	91.10
13.5	99.13	97.09	94.72	97.80	96.67	95.86			
14.0	99.63	98.07	96.02	98.40	97.64	97.11	99.10	98.30	95.20
14.5	99.90	98.74	97.20	98.79	98.31	98.01			
15.0	99.97	99.26	98.05	99.08	98.77	98.62	99.50	99.10	97.80
15.5	99.92	99.63	98.62	99.26	99.07	99.02			
16.0		99.83	99.14		99.23	99.22	99.90	99.60	98.90
16.5		99.94	99.36		99.33	99.34	100.00		
17.0		99.98	99.66		99.44	99.48		100.00	99.60
17.5		99.97	99.80		99.67	99.73			
18.0									100.00

Table 5-9. Results of Chi Square Analysis on frequencies of maturation categories computed from z-scores for PPAH and reference data [BZ] (Bayer & Bayley, 1959) and z-scores from APAH and MPS reference data for girls [AZ].

Pairings	n	*df*	X^2	*Cramer's V*	*p* value
BZ4.0 - AZ4.0	125	2	10.850	0.208	0.004
BZ5.0 - AZ5.0	145	2	4.380	0.123	0.112
BZ6.0 - AZ6.0	164	2	6.880	0.145	0.032
BZ7.0 - AZ7.0	175	2	16.020	0.214	0.000
BZ8.0 - AZ8.0	192	2	7.920	0.144	0.019
BZ9.0 - AZ9.0	207	2	9.180	0.149	0.010
BZ9.5 - AZ9.5	211	2	33.570	0.282	<0.0001
BZ10.0 - AZ10.0	218	2	28.880	0.257	<0.0001
BZ10.5 - AZ10.5	220	2	30.100	0.262	<0.0001
BZ11.0 - AZ11.0	224	2	12.560	0.167	0.002
BZ11.5 - AZ11.5	222	2	24.250	0.234	<0.0001
BZ12.0 - AZ12.0	226	2	21.440	0.218	<0.0001
BZ12.5 - AZ12.5	226	2	40.380	0.299	<0.0001
BZ13.0 - AZ13.0	225	2	34.580	0.278	<0.0001
BZ13.5 – AZ13.5	225	2	51.890	0.340	<0.0001
BZ14.0 – AZ14.0	224	2	37.580	0.290	<0.0001
BZ14.5 - AZ14.5	223	2	19.680	0.210	<0.0001
BZ15.0 - AZ15.0	214	2	51.140	0.346	<0.0001
BZ15.5 - AZ15.5	202	2	59.120	0.383	<0.0001
BZ16.0 - AZ16.0	180	2	97.650	0.521	<0.0001
BZ16.5 - AZ16.5	146	2	115.230	0.628	<0.0001
BZ17.0 - AZ17.0	104	2	158.640	0.873	<0.0001
BZ17.5 - AZ17.5	65	2	43.640	0.579	<0.0001

The benefits of noninvasive estimation of adult height and maturity status have also been reviewed. The KR method of predicting adult height has been applied to several research studies involving youth sports participants. These studies have reported favorable results by comparing their predictions to reference samples. Lack of longitudinal support on maturity estimation by percentage of predicted adult height was the incentive of this study.

This study has shown that the KR method can predict adult height of MPS boys and girls with reasonable accuracy at most ages of childhood although not as accurately as with the Fels sample. The accuracy of prediction is much more suspect during the adolescent period. This study has also shown that rate of maturation is an important consideration in the prediction accuracy. The early-, and late-maturing samples of boys and girls reported higher errors and lower predictability at all ages. The MAD for average-maturing boys and girls was closest to approximating the Fels sample.

This study has also shown that the predicted percentage of adult height of the MPS sample approximated the actual percentage of adult height. The prediction of adult height using the KR method assigned boys and girls to early-, average-, and late-maturing categories with reasonable accuracy during childhood and early adolescence. The inaccuracy of this method at later stages of adolescence reflects the greater errors and predictive variability during this time for boys and girls.

CHAPTER VI

SUMMARY AND RECOMMENDATIONS

Summary

The current body of research, along with the results of this study, reflects the increasing interest in noninvasive estimation of maturity. The need for an accurate prediction of adult height is useful in research involving youth in sports and physical activity so that it can be applied in professional practice. The advantage of the KR method is its ease of application. Care must be taken, however, when examining the results. The following statements summarize the results of this study:

1. The KR method for predicting adult height is more accurate for Fels boys than for MPS boys.
2. When comparing the 50% and 90% error bounds, the means for MPS boys and Fels boys are significantly different statistically when true adult height is compared to the 18 year stature of Fels boys. When 18 year statures for both samples are compared, the populations are statistically similar.
3. The KR method for predicting adult height is more accurate for MPS girls than it is for MPS boys.
4. The KR method is more accurate in predicting the adult height of Fels girls than MPS girls.
5. It has been shown in this study that rate of maturation is an important consideration in the prediction of adult height. Rate of maturation is a significant determinant of prediction accuracy for both boys and girls.

Average-maturing boys and girls produced lower median errors than early- and late-maturing boys and girls.

6. The KR method can be used with relative accuracy to assign boys and girls to maturation categories from 4.5 years to 15.0 years. In the latter stages of adolescence, for boys and girls, the method is less accurate.

Recommendations

Recently, the concept of maturity offset has been introduced (Mirwald et al., 2002). It is generally used as a means of estimating PHV. The offset is the time before PHV or after PHV. The results of this new, noninvasive, estimation of maturity status are few and equivocal. Malina, Claessens, van Aken, Thomis, LeFevre, Philippaerts, and Beunen (2006) studied maturity offset in elite gymnasts. This study was longitudinal in nature and compared estimated timing of PHV and actual PHV. They reported limitations of maturity offset when applied to female gymnasts. Limited yet promising use of predicting PHV in female gymnasts was also reported (Nurmi-Lawton et al., 2004).

Future research on the topic of noninvasive methods of predicting adult height is promising. Moreover, the application of the prediction of adult height for maturity estimation is even more promising. The number of recent studies to employ the KR method, for example, is testament to increasing demand for such a method. The results of this study, therefore, suggest consideration of prediction of adult height with maturity estimation. Can the concept of maturity offset be useful in predicting adult height or interpreting adult height? Can accurate reference samples be generated for interpreting adult height predictions with a predicted maturity indicator? Future research in this area is needed to decrease the prediction errors. By improving adult height prediction methods, the maturity estimations will also improved when using percentage of adult height.

This study also recommends continued research using boys and girls. Most of the studies using the noninvasive maturity estimation have examined boys. There are less data for girls.

The current research on maturity estimation is also limited to youth participating in various athletic endeavors (i.e., American football, soccer, and gymnastics). Research has shown that size, strength, and skill mismatches are rather common in many youth sports (Malina & Beunen, 1996). This point adds credence and support for using maturity estimation to reduce injury, equalize playing opportunity, and foster continued skill development. The need for maturity estimation can go beyond youth sports. The need to foster skill development is evident in physical education. Many physical education classrooms have a wide range of skill level, especially where physical education is mandatory for all students. Research in physical education that allows teachers to group children by biological maturity level is non-existent. The KR method of predicting adult height has an advantage in ease of data collection and computation.

APPENDIX A

Physical Growth (Anthropometry) Procedures

Appendix A
Description of Anthropometric Procedures

Weight. The child is instructed to stand in the middle of the platform with the arms hanging freely downward and aligned with the mid-axillary line. Weight is recorded to the nearest pound.

Standing Height. Measurements for height require the child to stand against a wall with the heels together and contacting the wall. The arms are allowed to hang freely and inline with the mid-axillary line. The head position is placed in the Frankfurt Horizontal Plane. The free-standing anthropometer (2 meter) is placed parallel to the wall at the mid-frontal plane with the sliding arm free to move down to the cranial vertex. The score is recorded in millimeters.

Sitting Height. The child sits on a bench (measuring 30 centimeter in height) that is placed against a wall with his pr her back against the wall as well. The child is instructed to assuming a sitting position first by sitting, leaning forward, sliding the hips back as far as possible, and then sitting upright. The feet of the child are placed so that the thighs are perpendicular to the trunk and parallel to the floor. The head was placed in the Frankfurt Horizontal Plane and the anthropometer is placed parallel to the wall at the mid-frontal place with the sliding arm free to be brought down onto the cranial vertex. The measurement is recorded in millimeters.

Biacromial (Shoulder) Breadth. The child stands with his or her back to the examiner. The acromion processes are palpated with the index fingers. One end of the sliding caliper is placed just to the left of the left acromion process and the other end was moved until it was just to the right of the right acromion process. The caliper is held so that the ends pointed up slightly and little pressure is applied. The measurement is recorded in millimeters.

Bicristal (Hip) Breadth. Measurement of the hips requires the child to stand with his or her back to the examiner. The crest of each ilium is palpated with the index fingers at the mid-axillary line. The points of the calipers are placed on the lateral side of each crest and pressed firmly in order to depress the fat over the bone. The measurement is recorded in millimeters.

Acrom-Radiale (Upper Arm) Length. The length of the left upper arm is measured with a bow caliper. The child is instructed to stand upright with the arms hanging freely at the sides, shoulders drawn back, and elbows flexed to 90 degrees to place the ulnar surface of the forearms and hands in a horizontal plane. The palms face each other and the thumbs point upward. The fixed end of bow caliper is placed on the superior-lateral aspect of the acromion process and the free end of the caliper is positioned to the radial groove on the lateral side of the elbow. The measurement is recorded in millimeters.

Radio-Stylion (Forearm) Length. The length of the left lower arm is measured with a bow caliper. The measuring position for the arm is the same as for the shoulder-elbow length measurement. The child stands upright, arms hanging freely at the sides, shoulders drawn back, and elbows flexed to 90 degrees. The palms of the hands should be facing each other and the thumbs pointing upward. One end of the capliers are placed on the groove between the lateral condyle of the humerus and the radius and the other is placed on the top of the styloid process of the radius. The measurement is recorded in millimeters.

Arm Girth. The midpoint of the left upper arm is located by palpating the lateral tip of the acromion process and the most distal aspect of the olecranon process. These two bony landmarks are marked, measured, and the midpoint marked. This is done by having the child stand upright, shoulders drawn back, and arms hanging freely downward by the sides, elbows extended. The circumference is measured by placing the measuring tape around the arm so that it is touching the skin (not compressing soft tissues) perpendicular to the long axis of the arm at the midpoint. The measurement is recorded in millimeters.

Thigh Girth. To find the midpoint of the anterior thigh, the child is instructed to place the left foot upon a bench so that the knee is flexed at 90 degrees. A measuring tape is placed along the longitudinal axis of the thigh at the inguinal crease and proximal border of the patella. The midpoint is marked. The child is then directed to stand with the feet about 10 centimeters apart. He or she should be upright, head in the Frankfurt Horizontal Plane, shoulders drawn back, and arms hanging freely downward at the sides. The thigh circumference is measured by placing the tape perpendicular to the longitudinal axis of the thigh at the midpoint mark. The thigh muscles should be relaxed and care should be made to not compress soft tissues. The measurement is recorded in millimeters.

Calf Girth. The calf circumference is be taken at the maximum girth. The measuring tape is held perpendicular to the long axis of the lower left leg, overlapped at the zero point, and moved up and down to locate the maximum girth point. Care is taken to not depress the soft tissues. The measurement is recorded in millimeters

Triceps Skinfold. The skinfold measurement is taken at the midpoint of the upper arm girth. When the midpoint is located, a mark on the posterior aspect of the arm is made. The child should be standing upright, shoulders drawn back, and arms hanging loosely to the sides. A double fold of subcutaneous fat is made at the midline of the left posterior upper arm by grasping with the skin with the index finger and thumb. The double fold is pulled forward proximal to the mark. The skinfold calipers are placed on the mark about 1 centimeter below the fingers grasping the skin. The measurement is recorded to the nearest 0.5 millimeters.

Subscapula Skinfold. The child is directed to stand upright with the shoulders drawn back, head in the Frankfurt Plane, and arms hanging loosely downward at the sides. The inferior angle of the left shoulder blade is palpated. A mark is made 1 centimeter inferior to the inferior angle of the scapula. The skinfold is pulled parallel to the natural cleavage lines of the skin. The measurer uses the index finger and thumb to pull the skinfold forward. The calipers are placed on the mark, about 1 centimeter from the fingers holding the skinfolds. The measurement is recorded to the nearest 0.5 millimeters.

Umbilical Skinfold. The umbilical skinfold is also known as the abdominal skinfold. The child is instructed to stand upright with the arms loosely hanging down at the sides of the body. The left side skinfold is located 3 centimeters from the midpoint of the umbilicus and 1 centimeter inferior to that point. A horizontal skinfold is pulled forward with the thumb (superior part of the double fold) and index finger. The measurement is recorded to the nearest 0.5 millimeters.

APPENDIX B

Forms for Scheduling MPS Participants

MEASUREMENT APPOINTMENT FORM

DAY: ___________ DATE: ____________ TIME: ___________

Time	Family Last Name	Child's Name	ID Number	Phone Number	Follow Up
.00					
:10					
:20					
:30					
:40					
:50					
:00					
:10					
:20					
:30					
:40					
:50					
:00					

APPENDIX C

IRB Approval Letter

MICHIGAN STATE
UNIVERSITY

Initial IRB Application Determination *Exempt*

January 29, 2007

To: John HAUBENSTRICKER
213 IM Sports Circle
MSU

Re: **IRB # X06-1074** Category: EXEMPT 1, 4
Approval Date: January 18, 2007

Title: VALIDATION AND APPLICATION OF NONINVASIVE PREDICTION OF ADULT HEIGHT.

The Institutional Review Board has completed their review of your project. I am pleased to advise you that **your project has been deemed as exempt** in accordance with federal regulations.

Letter was reprinted to reflect the correct exempt category.

The IRB has found that your research project meets the criteria for exempt status and the criteria for the protection of human subjects in exempt research. **Under our exempt policy the Principal Investigator assumes the responsibilities for the protection of human subjects** in this project as outlined in the assurance letter and exempt educational material. The IRB office has received your signed assurance for exempt research. A copy of this signed agreement is appended for your information and records.

Renewals: Exempt protocols do not need to be renewed. If the project is completed, please submit an ***Application for Permanent Closure***.

Revisions: Exempt protocols do not require revisions. However, if changes are made to a protocol that may no longer meet the exempt criteria, a new initial application will be required.

Problems: If issues should arise during the conduct of the research, such as unanticipated problems, adverse events, or any problem that may increase the risk to the human subjects and change the category of review, notify the IRB office promptly. Any complaints from participants regarding the risk and benefits of the project must be reported to the IRB.

Follow-up: If your exempt project is not completed and closed after three years, the IRB office will contact you regarding the status of the project and to verify that no changes have occurred that may affect exempt status.

Please use the IRB number listed above on any forms submitted which relate to this project, or on any correspondence with the IRB office.

Good luck in your research. If we can be of further assistance, please contact us at 517-355-2180 or via email at IRB@msu.edu. Thank you for your cooperation.

Sincerely,

Peter Vasilenko, Ph.D.
BIRB Chair

c: Wesley Waggener
138 IM Sports Circle
Department of Kinesiology

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CRIRB: crirb@msu.edu

APPENDIX D

Letter of Informed Consent and Telephone Script

MICHIGAN STATE
U N I V E R S I T Y

VALIDATION AND APPLICATION OF A
NONINVASIVE PREDICTION OF ADULT HEIGHT

Dear Parent,

You are being contacted because your child or children were participants in the Motor Performance Study conducted by faculty members in the Department of Kinesiology at Michigan State University. First, we would like that thank you for your support of our study. Since 1967, we have been dedicated to studying the interrelationships among physical growth, biological maturation, and gross motor skill acquisition. Your support and participation have allowed us to learn many interesting phenomena regarding these relationships and pass them along to countless students and the academic community. As part of the study, we measured your children on 13 growth dimensions and 7 motor performance tasks. From these data, we have not only been able to study these variables independently, but how they influence each other.

As an extension of this study, we are examining a method used to predict adult height in which the measurements of growth collected on your child or children will be utilized. In order for us to do this, we need the parental heights of all of the children that have completed their growth measurements at Michigan State. Thus, you are being asked to participate in this study by providing us with information about your adult height.

DEPARTMENT OF
KINESIOLOG
Y
College of
Education
Michigan State
University
IM Sports Circle
East Lansing, MI
48824-1049
tel 517.355.4730
fax 517.353.2944

Enclosed with this letter, you will find a card asking for you to provide your adult height, when you were your tallest. It also asks you to list the names of your child or children who participated in the Motor Performance Study. By returning this card with the information requested in the enclosed, stamped envelope, you indicate your voluntary agreement to participate. If you do not wish to participate, please return the card uncompleted. A return within two weeks is requested. By agreeing to participate, your privacy will be protected to the maximum extent allowable by law. Information collected or provided to the Motor Performance Study will be treated with confidentiality. You should also know that at any time following the submission of your height data you may withdraw from the study without prejudice from the investigators.

Again, we thank you for your continued support of the Motor Performance Study. It is greatly appreciated. If you have any questions regarding this study, please contact either of the investigators at the telephone numbers listed below.

Sincerely,

MSU is an affirmative-action, equal-opportunity institution.

Wesley R. Waggener, MS, CSCS
Doctoral Candidate
Secondary Investigator
Department of Kinesiology
Michigan State University
517-749-6676

John L. Haubenstricker, PhD
Professor Emeritus
Principal Investigator
Department of Kinesiology
Michigan State University
517-351-4514

Sample Mailing Card

Motor Performance Study
Michigan State University
Noninvasive Prediction of Adult Height.

By writing your name and providing your adult height (when you were at your tallest) in feet and inches, you consent to participate in the study.

Mother's name: ______________________________Ft:___In.____

Father's name: ______________________________Ft:___In.____

Names of participating children: ____________________________

____

Thank you for your participation.
(Please return this card in the enclosed, stamped envelope.)

PHONE SCRIPT

PARENT; "Hello" (Answering the telephone)

INVESTIGATOR: "Hello, Mr. or Mrs. Last Name?"

PARENT: "Yes."

INVESTIGATOR: "My name is Wesley Waggener. I am calling on behalf of Dr. John Haubenstricker and myself. We are with the Motor Performance Study in the Department of Kinesiology at Michigan State University. How are you today?"

OR ... "My name is Wesley Waggener and I am a graduate student of Dr. John Haubenstricker. We are with the Motor Performance Study in the Department of Kinesiology at Michigan State University. How are you today?"

PARENT: (Allow for response)

INVESTIGATOR: "On behalf of Dr. Haubenstricker and the Motor Performance Study Investigators, I would like to thank you for your faithful participation over the years. For 37 years, since the inception of the MPS in 1967, we have learned many interesting phenomena about the growth and motor development of children. This would not have been possible without your help"

"I am calling to see if you have received a letter from us describing what we are currently studying with the MPS data."

"As an extension of this study, we are examining a method to predict adult height in which the measurements of growth collected on your child or children will be utilized. In order for us to do this, we need the parental heights of all of the children that have completed their growth measurements at Michigan State. Thus, you are being asked to participate in this study by providing us with your (parental) height information."

"By providing me your adult height, when you were at your tallest, you indicate your voluntary agreement to participate. I want to assure you that by agreeing to participate, your privacy will be protected to the maximum extent allowable by law. Any of the information collected or provided to the Motor Performance Study will be treated with confidentiality. You should also know that at any time following the submission of your height you may withdraw from the study, without prejudice from the investigators."

"Do you wish to participate?"

ALLOW FOR RESPONSE

PARENT: "Yes."

INVESTIGATOR: "I just need to know how tall you are/were when you were at your tallest. Most likely this was when you were in your 20s or 30s."

PARENT: (height in feet and inches)

INVESTIGATOR: "Is your husband/wife available? May I speak with him/her?" [If the spouse is available, the script above is repeated. If the spouse is not available, ask if the parent knows the tallest height of the spouse.]

INVESTIGATOR As a double check on our records, we have (names of children) participating in the Motor Performance Study. Is this correct?

PARENT: "Yes." (If "no", get corrected information.)

INVESTIGATOR: "Again, I would like to thank you for your participation and continued support of the Motor Performance Study. Thank you so much, and have a great day."

PARENT: "Good bye."

REFERENCES

REFERENCES

Ambler, G. (2002). Overgrowth. *Best Practice and Research Clinical Endocrinology and Metabolism, 16*(3), 519-546.

AreaConnect. (2004). From *http://lansingmi.areaconnect.com/statistics.htm*.

Bar, A., Linder, B., Sobel, E. H., Saenger, P., & DiMartino-Nardi, J. (1995). Bayley-Pinneau method of height prediction in girls with central precocious puberty: Correlation with adult height. *The Journal of Pediatrics, 126*(6), 955-958.

Battista, R. A., Cumming, S. P., & Malina, R. M. (2003). Body size and estimated maturity status of youth soccer players of both sexes. *Medicine and Science in Sports and Exercise, 35*(5), S23.

Bayer, L. M., & Bayley, N. (1959). *Growth diagnosis: Selected methods for interpreting and predicting physical development from one year to maturity.* Chicago, IL: The University of Chicago Press.

Bayley, N. (1946). Tables for predicting adult height from skeletal age and present height. *Journal of Pediatrics, 28*, 49-64.

Bayley, N. (1962). The accurate prediction of growth and adult height. *Modern Problems in Paediatrics, 7*, 234-255.

Bayley, N., & Pinneau, S. R. (1952). Tables for predicting adult height from skeletal age: Revised for use with the Greulich-Pyle hand standards. *Journal of Pediatrics, 40*, 423-441.

Beunen, G. P., Malina, R. M., Lefevre, J., Claessens, A. L., Renson, R., & Simons, J. (1997). Prediction of adult stature and noninvasive assessment of biological maturation. *Medicine and Science in Sports and Exercise, 29*(2), 225-230.

Bielicki, T., & Koniarek, J. (1984). Interrelationships among certain measures of growth and maturation rate in boys during adolescence. *Annals of Human Biology, 11*, 201-210.

Bielicki, T., & Welon, Z. (1973). The sequence of growth velocity peaks of principal body dimensions in girls. *Materia y i Prace Antropoligiczne, 86*, 3-10.

Bock, R. D., & Thissen, D. (1984). Statistical problems of fitting individual growth curves. In F. E. Johnston, A. F. Roche & C. Susanne (Eds.), *Physical Growth and Maturation, Methodologies and Factors* (pp. 265-290). New York: Plenum.

Brämswig, H. J., Fasse, M., Holthoff, M. L., von Lengerke, H. J., von Petrykowski, W., & Schellong, G. (1990). Adult height in boys and girls with untreated short stature and constitutional delay of growth and puberty: Accuracy of five different mothods of height prediction. *Journal of Pediatrics, 117*(6), 886-891.

Cara, J. F., Kreiter, M. L., & Rosenfield, R. L. (1992). Height prognosis of children with true precocious puberty and growth hormone deficiency: Effect of combination therapy with gonadotropin releasing hormone agonist and growth hormone. *The Journal of Pediatrics, 120*(5), 709-715.

Center for Disease Control and Prevention. (2001). CDC Growth Charts. http://www.cdc.gov/growthcharts.

Clemons, T. (2000). A look at the inheritance of height using regression toward the mean. *Human Biology, 72*(3), 447-454.

Cole, T. J. (1996). Some questions about how growth standards are used. *Hormone Research, 45*(Suppl 2), 18-23.

Cole, T. J. (2000). Galton's midparent height revisited. *Annals of Human Biology, 27*(4), 401-405.

Cumming, S. P. (2002). *A bio-psychosocial investigation of self-determined motivation in recreational and travel youth soccer programs.* Unpublished Doctoral Dissertation, Michigan State University, East Lansing.

Cumming, S. P., Battista, R. A., Standage, M., Ewing, M. E., & Malina, R. M. (2006). Estimated maturity status and perceptions of adult autonomy support in youth soccer players. *Journal of Sports Sciences, 24*, 1039-1046.

de Waal, W. J., Greyn-Fokker, M. H., Stijnen, T., van Gurp, E. A., de Munick Keizer-Schrama, S. M., Aarsen, R. S., et al. (1996). Accuracy of final height prediction and effect of growth-reductive therapy in 362 constitutionally tall children. *Journal of Clinical Endocrinology and Metabolism, 81*(3), 1206-1216.

de Waal, W. J., Stijnen, T., Lucas, I. S., van Gurp, E. A., de Muinck Keizer-Schrama, S. M., & Drop, S. L. S. (1996). A new model to predict final height in constitutionally tall children. *Acta Pædiatrica, 85*(8), 889-893.

Decker, R., Partsch, C.-J., & Sippell, W. (2002). Combined treatment with Testosterone (T) and Ethinylestradiol (EE2) in constitutionally tall boys: Is treatment with T plus EE2 more effective in reducing final height in tall boys than T alone? *Journal of Clinical Endocrinology and Metabolism, 87*, 1634-1639.

Dompier, T. P. (2005). *The validity of a noninvasive method of maturity estimation and intrinsic risk factors for injury in youth football players: Analysis of the 2002 and 2003 seasons.* Unpublished Doctoral Dissertation, Michigan State University, East Lansing, MI.

Drayer, N. M. (1997). Clinical usefulness of bone age determination in the management of tall stature. *Acta Paediatrica Supplement, 423*(115-6).

Epstein, L. H., Valoski, A. M., Kalarchian, M. A., & McCurley, J. (1995). Do children lose and maintain weight easier than adults: A comparison of child and parent weight changes from six months to ten years. *Obesity Research, 3*(5), 411-417.

Erling, A., Wiklund, I., & Wikland, K. A. (2002). Psychological functioning in boys of short stature: Effects of different levels of growth hormone secretion. *Acta Paediatrica, 91*, 966-971.

Frongillo, E. A. (2004). Univariate and bivariate growth references. In R. C. Hauspie, N. Cameron & L. Molinari (Eds.), *Methods in Human Growth Research.* Cambridge, England: Cambridge University Press.

Galton, F. (1886). Regression towards the mediocrity in hereditary stature. *Journal of the Anthropological Institute of Great Britain and Ireland, 15*, 246-263.

Gardner, L. I. (1975). The child with "excessive" height prediction. *American Journal of Diseases in Childhood, 129*, 17-18.

Gasser, T. H., Köhler, W., Müller, H. G., Kneip, A., Largo, R. H., Molinari, L., et al. (1984). Velocity and acceleration of height growth using kernel estimation. *Annals of Human Biology, 11*, 397-411.

Georgopoulos, N. A., Markou, K. B., Theodoropoulou, A., Vagenakis, G. A., Benardot, D., Leglise, M., et al. (2001). Height velocity and skeletal maturation in elite female rhythmic gymnasts. *Journal of Clinical Endocrinology and Metabolism, 86*(11), 5159-5164.

Giles, E., & Hutchinson, D. L. (1991). Stature- and age-related bias in self-reported stature. *Journal of Forensic Science, 36*(3), 765-780.

Gruelich, W. W., & Pyle, S. I. (1959). *Radiographic Atlas of Skeletal Development of the Hand and Wrist* (2nd ed.). Stanford, CA: Stanford University Press.

Haubenstricker, J. L., & Branta, C. F. (1997). The relationship between distance jumped and developmental level on the standing long jump in young children. In J. E. Clark & J. H. Humphrey (Eds.), *Motor Development: Reserach & Reviews* (Vol. 1, pp. 64-85). Reston, VA: NASPE Publications.

Haubenstricker, J. L., Branta, C. F., & Seefeldt, V. D. (1999). History of the Motor Performance Study and Related Programs. In J. L. Haubenstricker & D. L. Feltz (Eds.), *100 Years of Kinesiology: History, Research, and Reflections.* (pp. 103-125). East Lansing, MI: Michigan State University.

Hauspie, R. C., Vercauteren, M., & Susanne, C. (1997). Secular changes in growth and maturation: An update. *Acta Paediatrica Supplement, 423*, 20-27.

Healy, M. J. R. (1978). Statistics of growth standards. In F. Falkner & J. M. Tanner (Eds.), *Human growth 1: Principles and prenatal growth* (pp. 169-181). New York: Plenum.

Himes, J. H., & Roche, A. F. (1982). Reported versus measured adult statures. *American Journal of Physical Anthropology, 58*(3), 335-341.

Himes, J. H., Roche, A. F., Thissen, D., & Moore, W. M. (1985). Parent-specific adjustments for evaluation of recumbent length and stature of children. *Pediatrics, 72*(2), 304-313.

Hintz, R. L. (1996). Issues in final height prediction. *Acta Paediatrica, Suppl 417*, 51-52.

Hoang, T., & Parsons, V. (1984). Fitting growth curve allowing for periodicities. In J. Borms, R. Hauspie, A. Sand, C. Susanne & M. Hebbelinck (Eds.), *Human Growth and Development* (pp. 807-813). New York: Plenum Press.

Hochberg, Z., Leiberman, E., Landau, H., Koren, R., & Zadik, Z. (1994). Age as a determinant of the impact of growth hormone therapy on predicted adult height. *Clinical Endocrinology, 41*, 331-335.

Hunt, L., Hazen, R. A., & Sandberg, D. E. (2000). Perceived versus measured height. Which is the stronger predictor of psychosocial functioning? *Hormone Research, 53*(3), 129-138.

Joss, E. E., Temperli, R., & Mullis, P. E. (1992). Adult height in constitutionally tall stature: Accuracy of five different height prediction methods. *Archives of Diseases in Childhood, 67*(11), 1357-1362.

Karlberg, J. (1984). Mathematical differentiation of three separate components of the growth curve. In J. Borms, R. Hauspie, A. Sand, C. Susanne & M. Hebbelinck (Eds.), *Human Growth and Development* (pp. 797-802). New York: Plenum Press.

Karlberg, J. (2002). Secular trends in pubertal development. *Hormone Research, 57*(5-6), 19-30.

Karlberg, J., & Luo, Z. C. (2000). Estimating the genetic potential in stature. *Archives of Diseases in Childhood, 82*(3), 270.

Kato, S., Ashizawa, K., & Satoh, K. (1998). An examination of the definition 'final height' for practical use. *Annals of Human Biology, 25*(3), 263-270.

Katzmarzyk, P. T., Mahaney, M. C., Blangero, J., Quek, J. J., & Malina, R. M. (1999). Potential effects of ethnicity in genetic and environmental sources of variability in the stature, mass, and body mass index of children. *Human Biology, 71*(6), 977-987.

Khamis, H. (2007a). Personal Communication.

Khamis, H. (2007b). Personal Communication. "Comparison of the MS2 method and the MSC2(1) method for adult stature prediction."

Khamis, H., & Roche, A. F. (1994). Predicting adult stature without using skeletal age: The Khamis-Roche method. *Pediatrics, 94*, 504-507.

Khamis, H. J., & Guo, S. (1993). Improvement in the Roche-Wainer-Thissen stature prediction model: A comparative study. *American Journal of Human Biology, 5*, 669-679.

Khamis, H. J., & Roche, A. F. (1994). Predicting adult stature without using skeletal age: The Khamis-Roche Method. *Pediatrics, 94*(4), 504-457.

Khamis, H. J., & Roche, A. F. (1995a). Growth outcome of "normal" short children who are retarded in skeletal maturation. *Journal of Pediatric Endocrinology and Metabolism, 8*(2), 85-96.

Khamis, H. J., & Roche, A. F. (1995b). Predicting adult stature without using skeletal age: The Khamis-Roche method (Published Erratum). *Pediatrics, 95*, 457.

Kirkland, J. L., Gibbs, A. R., Kirkland, R. T., & Clayton, G. W. (1981). Height predictions in girls with idiopathic precocious puberty by the Bayley-Pinneau Method. *Pediatrics, 68*(2), 251-252.

Largo, R. H., Gasser, T. H., Prader, A., Stuetzle, W., & Huber, P. J. (1978). Analysis of the adolescent growth spurt using smoothing spline functions. *Annals of Human Biology, 5*, 421-434.

Lenko, H. L. (1979). Prediction of adult height with various methods in Finnish children. *Acta Paediatrica Scandinavia, 68*, 85-92.

Luo, Z. C., Albertsson Wikland, K., & Karlberg, J. (1998). Target height as predicted by parental heights in a population-based study. *Pediatric Research, 44*(4), 563-571.

Luo, Z. C., Low, L., & Karlberg, J. (1999). A comparison of target height estimated and final height attained between Swedish and Hong Kong Chinese children. *Acta Paediatrica, 88*(3), 248-252.

Maes, M., Vanderweghe, M., Du Caju, M., Ernould, Bourguignon, J. P., & Massa. (1997). A valuable improvement of adult height prediction methods in short normal children. *Hormone Research, 48*, 184-190.

Malina, R. M. (1996). Anthropometry, strength and motor fitness. In S. J. Ulijaszek & C. Mascie-Taylor (Eds.), *Anthropometry: The Individual and the Population* (pp. 160-177). Cambridge: Cambridge University Press.

Malina, R. M., & Beunen, G. (1996). Matching opponents in youth sports. In O. Bar-Or (Ed.), *The child and adolescent athlete* (pp. 202-213). Oxford, England: Blackwell Science.

Malina, R. M., & Bouchard, C. (1991). *Growth, Maturation, and Physical Activity* (Vol. 1). Champaign, IL: Human Kinetics.

Malina, R. M., Bouchard, C., & Bar-Or, O. (2004). *Growth, Maturation, and Physical Activity* (2nd ed.). Champaign, IL: Human Kinetics.

Malina, R. M., Bouchard, C., & Beunen, G. (1988). Human growth: Selected aspects of current research on well-nourished children. *Annual Reviews of Anthropology, 17*, 187-219.

Malina, R. M., Claessens, A. L., Van Aken, K., Thomis, M., Lefevre, J., Philippaerts, R., et al. (2006). Maturity offset in gymnasts: Application of a prediction equation. *Medicine and Science in Sports and Exercise, 38*, 1342-1347.

Malina, R. M., Cumming, S. P., Morano, P. J., Barron, M., & Miller, S. J. (2005). Maturity status of youth football players: A noninvasive estimate. *Medicine and Science in Sports and Exercise, 37*(6), 1044-1052.

Malina, R. M., Koziel, S., & Bielicki, T. (1999). Variation in subcutaneous adipose tissue distribution associated with age, sex, and maturation. *American Journal of Human Biology, 11*(2), 189-200.

Malina, R. M., Morano, P. J., Barron, M., Miller, S. J., & Cumming, S. P. (2005). Growth status and estimated growth rate of youth football players: A community-based study. *Clinical Journal of Sports Medicine, 15*(3), 125-132.

Malina, R. M., Morano, P. J., Barron, M., Miller, S. J., Cumming, S. P., & Kontos, A. P. (2006). Incidence and player risk factors for injury in youth football. *Clinical Journal of Sports Medicine, 16*(3), 214-222.

Marubini, E. (1978). Mathematical handling of long-term longitudinal data. In F. Falkner & J. M. Tanner (Eds.), *Human Growth 1: Principles and prenatal growth* (pp. 209-225). New York: Plenum Press.

Matsuoka, H., Sato, K., Sugihara, S., & Murata, M. (1999). Bone maturation reflects the secular trend in growth. *Hormone Research, 52*(3), 125-130.

Mészáros, J., Szmodis, I., Mochácsi, J., & Szabó, T. (1984). Prediction of final stature at the age of 11-13 years. *Children and Sport*, 31-36.

Mirwald, R. L., Baxter-Jones, A. D., Bailey, D. A., & Beunen, G. P. (2002). An assessment of maturity from anthropometric measurements. *Medicine and Science in Sports and Exercise, 34*(4), 689-694.

Morano, P. J. (2003). *Injury in youth football: prevalence, incidence, and biological risk factors.* Unpublished Doctoral Dissertation, Michigan State University, East Lansing.

Murata, M. (1997). Population-specific reference values for bone age. *Acta Paediatrica Supplement, 423*, 113-114.

Nicoletti, I. (1988). Prediction of adult height and somatotype during childhood. In R. M. Malina (Ed.), *Young Athletes: Biological, Psychological, and Educational Perspectives.* Champaign, IL: Human Kinetics.

Nicolson, A. B., & Hanley, C. (1953). Indices of physiological maturity derivation and interrelationships. *Child Development, 24*, 3-38.

Nurmi-Lawton, J. A., Baxter-Jones, A. D., Mirwald, R. L., Bishop, J. A., Taylor, P., Cooper, C., et al. (2004). Evidence of sustained skeletal benefits from impact-loading exercise in young females: A 3-year longitudinal study. *Journal of Bone and Mineral Research, 19*, 314-322.

Onat, T. (1975). Prediction of adult height of girls based on the percentage of adult height at onset of secondary sexual characteristics, at chronological age, and skeletal age. *Human Biology, 47*, 117-130.

Onat, T. (1983). Multifactorial prediction of adult height of girls during early adolescence allowing for genetic potential, skeletal and sexual maturity. *Human Biology, 55*(2), 443-461.

Oosting, J., & Negelkerke, N. J. D. (1984). Fitting growth curves using constrained splines. In J. Borms, R. Hauspie, A. Sand, C. Susanne & M. Hebbelinck (Eds.), *Human Growth and Development* (pp. 803-806). New York: Plenum Press.

Post, E. M., & Richman, R. A. (1981). A condensed table for predicting adult stature. *Journal of Pediatrics, 98*(3), 440-442.

Preece, M. A. (1988a). Prediction of adult height: Methods and Problems. *Acta Paediatricia Scandinavia, Suppl 347*, 4-11.

Preece, M. A. (1988b). Prediction of adult height: Methods and Problems. *Acta Paediatrica Scandinavia, Suppl 347*, 4-11.

Preece, M. A. (1996). The genetic contribution to stature. *Hormone Research, 45* (Suppl 2), 56-58.

Preece, M. A., & Baines, M. J. (1978). A new family of mathematical models describing the human growth curve. *Annals of Human Biology, 5*, 1-24.

Roche, A. F. (1980). Prediction. In F. E. Johnston, A. F. Roche & C. Susanne (Eds.), *Human physical growth and maturation, methodologies and factors* (pp. 1-364). New York: Plenum Publishing Corporation.

Roche, A. F. (1995). *Executive summary of workshop to consider secular trends and possible pooling of data in relation to the revision of the NCHS growth charts.* Hyattsville, MD: National Center for Health Statistics.

Roche, A. F., Chumlea, W. C., & Thissen, D. (1988). *Assessing the Skeletal Maturity of the Hand-Wrist: Fels Method.* Springfield, IL: Charles C. Thomas.

Roche, A. F., & Davila, G. (1972). Late adolescent growth in stature. *Pediatrics, 50*, 874-880.

Roche, A. F., & Sun, S. (2003). *Human growth: Assessment and interpretation*. Cambridge: Cambridge University Press.

Roche, A. F., Tyleshevski, F., & Rogers, E. (1983). Noninvasive measurements of physical maturity in children. *Research Quarterly, 54*(4), 364-371.

Roche, A. F., Wainer, H., & Thissen, D. (1974). *Predicting adult stature for individuals*. (Vol. 3). New York: S. Karger.

Roche, A. F., Wainer, H., & Thissen, D. (1975). The RWT method for the prediction of adult stature. *Pediatrics., 56*(6), 1026-1033.

Roche, A. F., & Wettenhall, H. N. B. (1977). Stature prediction in short boys. *Australian Paediatrics Journal, 13*, 261-264.

Roemmich, J. N., Blizzard, R. M., Peddada, S. D., Malina, R. M., Roche, A. F., Tanner, J. M., et al. (1997). Longitudinal assessment of hormonal and physical alterations during normal puberty in boys. IV: Predictions of adult height by the Bayley-Pinneau, Roche-Wainer-Thissen, and Tanner-Whitehouse methods compared. *American Journal of Human Biology, 9*, 371-380.

Shuttleworth, F. K. (1939). The physical and mental growth of girls and boys age six to nineteen in relation to age at maximum growth. *Monographs of the Society for Research in Child Development, 4*(3, Serial No. 22).

Sodhi, H. S., Malhotra, M. S., & Saini, K. S. (1982). Talent selection for sports during childhood based on stature. *SNIPES Journal, 5*(4), 100-106.

Sorva, R., Tolppanen, E. M., Lankinen, S., & Perheentupa, J. (1989). Growth evaluation: parent and child specific height standards. *Archives of Diseases in Childhood, 64*(10), 1483-1487.

Südfeld, H., Kiese, K., Heinecke, A., & Brämswig, J. H. (2000). Prediction of growth response in prepubertal children treated with growth hormone for idiopathic growth hormone deficiency. *Acta Paediatrica, 89*(1), 34-37.

Tanner, J. M. (1976). Charts for the diagnosis of short stature and low growth velocity, allowance for height of parents and prediction of adult height. *Birth Defects Original Article Series, 12*(6), 1-13.

Tanner, J. M., Goldstein, H., & Whitehouse, R. H. (1970). Standards for children's height at ages 2:9 years allowing for height of parents. *Archives of Disease in Childhood, 45*, 755-762.

Tanner, J. M., Healy, M. J. R., Goldstein, H., & Cameron, N. (2001). *Assessment of Skeletal Maturity and Prediction of Adult Height (TW3 Method)* (3rd ed.). London: Saunders.

Tanner, J. M., Landt, K. W., Cameron, N., Carter, B. S., & Patel, J. (1983). Prediction of adult height from height and bone age in childhood. *Archives of Disease in Childhood, 58*, 767-776.

Tanner, J. M., Whitehouse, R. H., Marshall, W. A., & Carter, B. S. (1975). Prediction of adult height from height, bone age, and occurrence of menarche, at ages 4 to 16 with allowance for midparent height. *Archives of Disease in Childhood, 50*(14), 14-26.

Tanner, J. M., Whitehouse, R. H., Marshall, W. A., Healy, M. J. R., & Goldstein, H. (1975). *Assessment of Skeletal Maturity and Prediction of Adult Height (TW2 Method)*. London: Academic Press.

Tanner, J. M., Whitehouse, R. M., & Healy, M. J. R. (1962). *A New System for Estimating Skeletal Maturity from the Hand and Wrist, with Standards Derived from a Study of 2,600 Healthy British Children*. Paris: International Children's Centre.

Tanner, J. M., Whitehouse, R. M., & Takaishi, M. (1966a). Standards from birth to maturity for height, weight, height velocity, and weight velocity: British children 1965, part II. *Archives of Disease in Childhood, 41*, 613-635.

Tanner, J. M., Whitehouse, R. M., & Takaishi, M. (1966b). Standards from birth to maturity for height, weight, height velocity, and weight velocity: British children, 1965, Part I. *Archives of Disease in Childhood, 41*, 454-471.

Todd, T. W. (1937). *Atlas of Skeletal Maturation*. St. Louis: Mosby.

van Teunenbroek, A., de Waal, W., Roks, A., Chinafo, P., Fokker, M., Mulder, P., et al. (1996). Compuer-aided skeletal age scores in healthy children, girls with Turner syndrome, and in children with constitutionally tall stature. *Pediatric Research, 39*(2), 360-367.

Wainer, H., Roche, A. F., & Bell, S. (1978). Predicting adult stature without skeletal age and without paternal data. *Pediatrics, 61*(4), 569-572.

Walker, R. N. (1974). Standards for somatotyping children: I. The prediction of young adult height from children's growth data. *Annals of Human Biology, 1*(2), 149-158.

Welon, Z., & Bielicki, T. (1971). Further investigations of parent-child similarity in stature, as assessed from longitudinal data. *Human Biology, 43*(4), 517-525.

Wright, C. M., & Cheetham, T. D. (1999). The strengths and limitations of parental heights as a predictor of attained height. *Archives of Diseases in Childhood, 81*(3), 257-260.

Zachmann, M., Sobradillo, B., Frank, M., Frisch, H., & Prader, A. (1978). Bayley-Pinneau, Roche-Wainer-Thissen, and Tanner height predictions in normal children and in patients with various pathologic conditions. *Journal of Pediatrics, 93*(5), 749-755.

Zadik, Z., Segal, N., & Limony, Y. (1997). Final height prediction models for pubertal boys. *Acta Paediatrica Supplement, 417*, 53-56.

Żarów, R. (1997). Adult height prediction in boys by various methods. *Biology of Sport, 14*(3), 193-198.