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Methods for Predicting Adult Body Height – Part 1

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ABSTRACT

This review article outlines the development of methods for predicting adult height from the first method developed by Nancy Bayley in 1946 to a proprietary method published at the turn of the 20th century. It focuses on the importance of adult height prediction, an analysis of the variables considered in the different methods, and presents the values of the adult height prediction coefficients for boys and girls in the Zarow equations version I and II (Z_1 and Z_2). This is part one of the review, the second part will discuss methods developed after 2000.

Keywords: Adult body height; Boys; Girls; Methods; Prediction; Calendar age; Body height; Body weight; Average height of parents; Skeletal age.

1. Introduction

Predicting adult body height is important information for physicians, psychologists, educators, coaches and, especially in the pre-adolescence and adolescence during puberty, and for children and their parents. It has practical applications in auxological diagnosis, in the prevention of growth disorders in children with an atypical rate of puberty, especially in short stature. It is also important in sport, where training with children and adolescents is carried out before growth is complete, and the height they reach as athletes may be a feature that favours or hinders good performance in certain sports. From a philosophical point of view, science is capable of prediction insofar as it can establish the conditions for the recurrent course of certain processes. The content of the term 'foresight' is expressed by the term 'anticipation of the future'. This refers to prediction on a scientific basis. Thus, forecasting is the prediction, based on scientific grounds, of the course and state of possible (probable) future events, facts or phenomena; in this case, the prediction of adult height.

1.1. Study objectives

The aim of this study is to: (i) an overview of the most important body height prediction methods, (ii) an analysis of the characteristics considered in the various forecasting methods, (iii) evaluation of height disorders as a source of negative emotions in social relationships, (iv) presentation of the practical applicability of methods taking skeletal age into account, and (v) presentation of the Zarow method in the Z_1 and Z_2 versions for boys and girls.

2. Methods and Materials

The primary research method was an analysis of the available literature on the subject. Using keywords; body height, boys, girls, methods, prediction, calendar age, body weight, average parental height, skeletal age,, sexual maturity, collated in different configurations, databases such as Google Scholar, MEDLINE (PubMed), SPORTDiscus with Full Text, Academic Search Complete, Health Source - Consumer Edition were reviewed, and the article presents the most important methods for predicting adult growth. The time period is from 1946 to 2000.

3. Results and Discussion

Predicting adult height has a long history of more than 70 years. The first method was developed by Nancy Bayley in 1946 [1]. The author presented tables for predicting adult body height on the basis of current body height and skeletal age and a percentage of the adult height obtained at that age was used to calculate the predicted height. In 1952, Bayley, together with Pinneau, used the radiological atlas of skeletal development of the hand and wrist developed by Greulich and Pyle in assessing skeletal age and recalculated the percentages of adult body height obtained at a given skeletal age in groups of boys and girls with early, average and delayed development [2]. Predictive accuracy, with the new skeletal age tables, was more favourable compared to the earlier Todd tables.

In 1966, Garn presented a simple method for determining adult body height based on height at a given age and the value of a multiplier (coefficient) different for urban boys and girls aged 1 to 18 years [3]. A few years later, Welon [4] developed a forecasting method based on multivariate regression using developing electronic computing techniques. Multivariate regression not only makes it possible to determine the degree of determination of the projected height on the basis of a given set of child characteristics, but it also gives assessments of the weight of individual characteristics in the forecast. The traits (variables) included in the prognosis according to Welon are summarised in Table 1. The author presented regression equations taking into account different combinations of traits for girls aged 8 to 14 years. Another Polish method is proposed by Milicerowa [5,6]. This method takes into account the height of the body at a given metric age and an assessment of the rate of development based on the degree of sexual maturity (development of pubic hair in both sexes, breasts in girls and external genitalia in boys). Depending on the rate of development, we read off the percentage of body height up to the time of examination from appropriate tables or nomograms and calculate the adult body height from the proportions.

In 1975, two methods were published: RWT and TW. American authors Roche, Wainer and Thissen [7] - from the first letters of their names the acronym of the RWT method - determined the body height that can be reached at 18 years of age. Of the many variables analysed that influence adult height using the stepwise regression method, they identified four: body length, body weight, skeletal age of the hand and wrist, and mean parental height, which were the independent variables in the multiple regression equations. Using this method, we could determine body height from 1 year of age to 16 years of age for boys, and from 1 year of age to 14 years of age for girls, at three-month intervals. If the person was measured standing up, 1.25cm is added to the resulting measurement value and this result is multiplied by the age-appropriate body length factor [8]. A limitation of the use of the RWT method is the need for radiographs. As suggested by the authors, up to 13 years of age for boys and up to 8 years of age for girls, bone age can be replaced by calendar age with a slight reduction in the accuracy of the prediction.

The authors of the TW method are Tanner, Withehouse, Marschall and Carter [9] and Tanner et al. [10]. Regression coefficients are presented for calendar age, the child's current body height and bone age calculated from the development of the long bones of the hand and the distal radial and ulnar epiphyses (RUS) from 4 years of age, at six-month intervals. At 11-14.5 years of age, regression equations for menstruating and not yet menstruating girls are included in the method. A general characterisation of these several forecasting methods has been made primarily because these proposals have largely set the directions for the search for the most optimal methods with

the least prediction error. The most frequently presented methods in the English, French literature are the Bayley-Pinneau method (abbreviated BP), the Roche-Wainer and Thissen method (RWT), the Tanner et al. method (TW1, TW2) - [11-30] and others. In Poland, the Milicer method and, to a lesser extent, the Welon method, as well as the RWT, TW1, TW2 methods, were used most frequently [31-40] and others.

Table 1 summarises the majority of adult height prediction methods and the variables used in these methods. As can be seen, the authors of each method take into account different variables (characteristics) affecting the accuracy of the predicted adult body height, which shows significant inter-individual variation. Inter-individual variation in body height (phenotypic variance) is due to different life conditions during progressive periods of development - childhood and adolescence (environmental component of variance) and to individual, genetically programmed predispositions to have a higher or lower adult body height, to grow faster or slower (genetic component of variance). Also, certain interactions and correlations between genotype and environment influence inter-individual variation. The multiplicity and heterogeneity of the interaction of factors and mechanisms thus determines the possibility of realising an individual's growth potential and the variability of body height in the population.

Growth disorders are often a source of negative emotions and disruptions in social interactions. Extremely tall and extremely short children become objects of attention from others. Particularly short height raises many problems, as this element of physique is included in patterns of physical attractiveness quite strictly [41-43]. Not fitting into height standards leads to a so-called difference complex and a lowered self-esteem of the "notion of self" - one of the personality's self-regulatory mechanisms. Low stature does not prejudge a child's maladaptation. To some extent, knowledge of the course of sexual maturation and the possibility of determining adult body dimensions, as well as preventive measures, can alleviate emotional states and trigger certain compensatory mechanisms [41-44].

The growth of most children is characterised by considerable regularity and assessment of the level and rate of development can predict adult size. The basis of virtually every method - with the exception of a few based only on parental body height, e.g., the Karkus method [45] - is knowledge of current body height. This is confirmed by the analysis of Pearson's linear correlation coefficients between adult body height (girls at 18 years, boys at 24 years) and height in subsequent years [46] - Table 2. The data are from the Krakow continuous study of 145 girls and 138 boys, conducted between 1976 and 1998 and in 1994 [47,48]. The values of the linear correlation coefficients indicate that the correlation is high and very high [49,50]. These values are similar to data from other studies [51,13,4] and range from 0.70, 0.80, 0.90, with a tendency to decrease during sexual maturation.

Considering the assessment of developmental rate, we can divide the methods into those that take into account skeletal maturity (skeletal age) and those that analyse other measures of developmental rate (Table 1). Such a division reflects the applicability of the different methods, and there are various attempts to modify methods based on the skeletal criterion. The evaluation of roentgenograms and the determination of a child's skeletal age should be performed by a radiologist, and the taking of roentgenograms, mainly of the hand and wrist, is limited for the purposes of medical diagnosis in various syndromes associated with growth disorders. The assessment of the rate of puberty on the basis of the age of appearance of successive stages (degrees) of development of lunate hair in both sexes and breasts in girls according to the Tanner scale is a method that is more readily available.

Table 1. The methods of prediction adult body height

Method (abbreviation)	Years	Variables
Bayley (B)	1946	CA, BH, SA (Todd)
Bayley and Pienneau (BP)	1952	CA, BH, SA (Greulich, Pyle)
Garn (G)	1966	CA, BH, AHP
Welon (W)	1971	CA, BH, SA (Tanner, Withehouse) SM, AHP, AFM, AEC, S
Milicer (M)	1971	CA, BH, SM
Frish and Nagel (FN)	1974	CA, BH, AFM
Tanner, Whitehouse, Marshall and Carter (TW1)	1975	CA, BH, AFM SA (Tanner, Withehouse RUS),
Roche, Wainer and Thissen (RWT)	1975	CA, BL, BW, AHP, SA (Greulich, Pyle)
Filipsson and Hall (FH)	1975	CA, BH, DA
Tanner, Landt, Cameron, Carter and Patel (TW 2)	1983	CA, BH, AFM, IBH, RCSA, SA (Tanner, Withehouse RUS),
Hulanicka and Szczotka (HS)	1985	CA, BH, SA (Tanner, Withehouse) SM, AFM
Khamis and Roche (KR)	1994	CA, BH, BW, AHP
Waal, Stijnen, Lucas, Gurp, Keizer-Schrama and Drop	1996	CA, BH, SA (Greulich, Pyle), SA (Tanner, Withehouse RUS), TH, AFM
Żarów (Z)	1996	CA, BH, BW, AHP, SM
Beunen, Malina, Levevre, Cleassens, Renson and Simons (BM)	1997	CA, BH, SH, TS, SS

*/Variable abbreviations used: Calendar age (CA); Body height (BH); Skeletal age (SA); Sexual maturity (SM); Age of first menstruation (AFM); Increase in body height (IBH); Rate of change of skeletal age (RCSA); Dental age

(DA); Average height of parents (AHP); Somatotype (S); Assessment of environmental conditions (AEC); Body length (BL); Body weight (BW); Sitting height (SH); Target height (TH); Triceps skinfold (TS); and Subscapular skinfold (SS).

Table 2. Pearson linear correlation coefficients between adult height (girls aged 18, boys aged 24) and height in successive years [46]

Age	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0
Girls	0.77	0.77	0.74	0.68	0.64	0.65	0.73	0.87	0.96	0.99		
Boys	0.76	0.77	0.79	0.79	0.78	0.74	0.69	0.68	0.77	0.88	0.96	0.99

Frisch and Nagel [52] propose predicting the adult height of girls based on the age of first menstruation and the height gained at that time. Filipsson and Hall [53] consider body heights and dental age; Wainer, Roche and Bell [54] consider that skeletal age can be substituted for calendar age, and the lack of height data for either parent for the arithmetic mean of the population. In Poland, Hulanicka and Szczotka [55], based on a continuous study in Wrocław, attempted to develop a prediction of adult body height based on the skeletal criterion. The variables analysed were body height at a given age, skeletal maturity, age of onset of sexual maturity stages and age of menarche. The prediction attempts made in boys gave unsatisfactory results, as the prediction was subject to a large error, as the authors themselves wrote about (p.15). Therefore, one of the co-authors of this article (RŻ) presented his own method of prediction for boys, which is most fully presented in the paper “Prediction of adult body height in boys” [56].

The prediction of adult body height for boys and girls according to Zarow (Z) is based on a multiple regression model. Predictive equations for boys aged 6.5 to 16 years were calculated for different sets of characteristics, with the greatest predictive value being provided by equations taking into account a boy's current height and weight at a given age, the average height of his parents and, from the age of 11, also an assessment of sexual maturation based on the time of appearance of stage II and IV of pubic hair development according to Tanner. For girls aged 6.5 to 15 years, equations are presented that also take into account the girl's current height and weight at a given age, the average height of the parents and, from age 10, also an assessment of sexual maturation based on stage II breast development and the age of onset of the first menstruation.

The simplified assessment of sexual maturity is an attempt to replace skeletal age at puberty, where there is variation in the rate of development that affects the value of predicted body height. As the paper is in Polish, the values of the coefficients of the traits for the equations with the height and body weight of boys and girls, and the average height of their parents (version Z_1), as well as the equations that additionally take into account sexual maturity (version 2 - Z_2) are presented here in Tables 3 - 4. On the other hand, Tables 5 and 6 show the coefficients for girls as published in full in the "Anthropology Practice Guide" [46].

Table 3. Values of coefficients for predicting adult body height of boys according to Zarow's prediction equations (version 1 - Z_1, Krakow Longitudinal Growth Study 1976-1994, N= 138)

Age (years))	**Body height (cm)**	**Body weight ciała (kg)**	**Average height of parents (cm)**	**Free expression (constants)**
	x_1	x_2	x_3	x_0
6.5	1.319	-0.810	0.321	-14.826
7.0	1.186	-0.665	0.343	-8.705
7.5	1.049	-0.481	0.370	-3.271
8.0	1.101	-0.493	0.347	-8.118
8.5	1.118	-0.469	0.327	-9.886
9.0	1.076	-0.442	0.321	-6.374
9.5	1.018	-0.406	0.324	-2.514
10.0	0.996	-0.379	0.312	-0.255
10.5	0.936	-0.320	0.316	3.661
11.0	0.883	-0.309	0.339	5.139
11.5	0.834	-0.307	0.366	5.798
12.0	0.800	-0.318	0.387	5.865
12.5	0.703	-0.272	0.430	9.730
13.0	0.642	-0.243	0.464	10.545
13.5	0.571	-0.206	0.492	13.835
14.0	0.576	-0.185	0.470	14.230
14.5	0.580	-0.154	0.441	15.268
15.0	0.659	-0.147	0.371	12.139
15.5	0.729	-0.116	0.290	10.828
16.0	0.840	-0.113	0.202	5.087

Table 4. Values of coefficients for predicting adult body height of boys according to Zarow's prediction equations (version 2 – Z_2, Krakow Longitudinal Growth Study 1976-1994, N= 138)

Age (years)	**Body height (cm)**	**Body weight ciała (kg)**	**Average height of parents (cm)**	**Assessment of sexual maturation/*/ 1,2,3)**	**Free expression (constants)**
	x_1	x_2	x_3	x_4	x_0
11.0	0.927	-0312	0.288	-7.933	15.434
11.5	0.858	-0.291	0.343	-2.599	8.445
12.0	0.848	-0.276	0.345	-3.201	7.952
12.5	0.843	-0.242	0.352	-3.741	5.575
13.0	0.816	-0.191	0.359	-4.649	6.402
13.5	0.774	-0.157	0.390	-4.463	4.923
14.0	0.761	-0.089	0.373	-5.415	7.758
14.5	0.739	-0.091	0.292	-4.575	21.815
15.0	0.806	-0.097	0.274	-4.850	13.777
15.5	0.882	-0.073	0.174	-6.079	18.593
16.0	0.954	-0.072	0.090	-6.318	19.778

*/Sexual maturity assessment: 1. Stage II pubic hair absent; 2. Stage II pubic hair present, stage IV pubic hair absent; and 3. Stage IV pubic hair present.

Table 5. Values of coefficients for predicting adult body height of girls according to Zarow's prediction equations (version 1 - Z_1, Krakow Longitudinal Growth Study 1976-1988, N= 127)

Age (years)	**Body height (cm**	**Body weight ciała (kg)**	**Average height of parents (cm)**	**Free expression (constants)**
	x_1	x_2	x_3	x_0
6.5	1.251	-0.683	0.067	20.567
7.0	1.170	-0.616	0.160	9.999
7.5	0.978	-0.509	0.230	17.524
8.0	1.074	-0.537	0.171	13.301
8.5	0.936	-0.499	0.240	16.612
9.0	0.961	-0.485	0.214	14.958
9.5	0.836	-0.425	0.266	19.706

10.0	0.805	-0.381	0.266	20.640
10.5	0.724	-0.382	0.316	22.218
11.0	0.708	-0.344	0.306	23.091
11.5	0.705	-0.370	0.316	21.677
12.0	0.740	-0.355	0.316	14.174
12.5	0.769	-0.355	0.310	10.006
13.0	0.847	-0.314	0.249	4.675
13.5	0.863	-0.262	0.236	1.076
14.0	0.934	-0.185	0.149	-0.577
14.5	0.965	-0.157	0.114	-1.871
15.0	1.006	-0.092	0.061	-4.014

Table 6. Values of coefficients for predicting adult body height of girls according to Zarow's prediction equations (version 2 – Z_2, Krakow Longitudinal Growth Study 1976-1988, N= 127)

Age (years)	**Body height (cm)**	**Body weight ciała (kg)**	**Average height of parents (cm)**	**Assessment of sexual maturation/* 1,2,3)**	**Free expression (constants)**
	x_1	x_2	x_3	x_4	x_0
10.0	0.807	-0.381	0.265	-0.310	20.825
10.5	0.755	-0.288	0.258	-4.196	29.456
11.0	0.750	-0.250	0.225	-2.737	30.907
11.5	0.749	-0.309	0.246	-2.389	28.502
12.0	0.818	-0.257	0.218	-2.660	20.070
12.5	0.839	-0.296	0.235	-2.121	13.790
13.0	0.972	-0.200	0.133	-3.711	8.739
13.5	0.913	-0.180	0.183	-3.004	6.196
14.0	0.973	-0.126	0.113	-3.205	5.315
14.5	0.988	-0.134	0.097	-2.906	4.494
15.0	0.999	-0.087	0.062	-2.022	2.751

*/Sexual maturity categories: 1) Stage II breast development has not occurred; 2) Stage II has already occurred and there is no menarche; and 3) Menarche has already occurred.

In each of the methods presented, there is a smaller or larger forecast error. The prediction error is the difference between the predicted body height at a given age and the actual height reached in adulthood, after the growth process has been completed. Positive differences indicate an overestimation and negative differences an underestimation of the predicted body height. A relatively small prediction error is obtained for healthy children with even development, with no clear changes in growth rate. The Zarow method has been verified in a number of MSc theses and, for the Polish population, the prediction error was lower than other methods. A comparative analysis of the magnitude of the forecast error with other methods will be the subject of another paper.

4. Summary

This article presents an overview of the most important methods for predicting adult body height of girls and boys. Height prediction is made for a single individual at a specific point in his development. However, at the same time, in order to develop any prognostic method, it is necessary to have longitudinal studies of a large group of girls and boys conducted over a relatively long period of time, and preferably from the early years of life until the end of the growth process. There are relatively few such studies in Poland and around the world. The 1976-1994 Cracow studies of children aged 6 to 18 years and boys additionally at the age of 24 years made it possible to analyze in detail the course of the level and rate of growth and formed the basis for the development of equations predicting adult body height using the Zarow method, which are presented in this work. It is worth mentioning that the study continues, with 103 women and 122 men examined in 2004 and 47 women and 67 men in 2022.

In forecasting methods, there is a methodological dilemma, consisting of the proportion between the number of features (variables) included in the method, the accuracy of forecasting - the size of the forecast error, and the practical utility (application) of the method. In multiple regression methods, the measure that allows you to control the accuracy of forecasting and reduce the number of variables is, among other things, the coefficient of determination of the forecast R^2.

About this will be in the second part of the article, will also be discussed methods developed in the last 25 years - from 2000 to 2024, attempts to modify existing methods, based on the analysis of growth curves, automatic determination of bone age or methods incorporating artificial intelligence. A comparative analysis of the magnitude of the prognosis error in different methods will be carried out.

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Competing Interests Statement

The authors declare no competing financial, professional, or personal interests.

Consent for publication

The authors declare that they consented to the publication of this study.

Authors' contributions

Both the authors took part in literature review, analysis and manuscript writing equally.

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