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RESEARCH ARTICLE

Height growth of Mexican boys by geographic region: an evaluation based on nationally representative data of ENSANUT 2012 and 2018*

Luis Alberto Flores[1], Luz Dinorah González-Castell[2] and Sudip Datta Banik[3]

[1]Laboratory of Physical Activity for Health, Facultad de Ciencias de la Cultura Física, Universidad Autónoma de Chihuahua, Mexico, Chihuahua, Mexico, [2]Child and Adolescent Nutrition Department, Centro de Investigación en Nutrición y Salud, Instituto Nacional de Salud Pública, Cuernavaca, Morelos, Mexico and [3]Department of Human Ecology, Centro de Investigación y de Estudios Avanzados (Cinvestav) del IPN, Cinvestav, Merida, Mexico.
Corresponding author: Sudip Datta Banik; Email: dattabanik@cinvestav.mx

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Abstract

Existing research on human growth in Mexico is regionally focused, creating a gap in the understanding of growth patterns of children and adolescents at national level and regional variation. The objective of the present study was to characterize the height growth curve of the Mexican population by geographic area and to cluster the states of the Mexican Republic according to their somatic maturation characteristics, based on a national representative sample of boys. Data on age, height, socioeconomic level, and geographic area of 25,365 boys were obtained from the National Health and Nutrition Survey 2012 (ENSANUT) and ENSANUT 2018, carried out in 32 Mexican states. Both surveys had representative samples. Preece–Baines 1 model was applied to fit height growth curves. Biological parameters were estimated; principal component analysis and cluster analysis were performed to group Mexican states based on these biological parameters. The estimated age at peak height velocity (PHV) was 12.3 years in the sample. Significant regional differences in the timing and tempo of PHV among Mexican boys were observed. Boys in the northern region experienced PHV at an earlier age and had a shorter duration of growth compared with boys in the central and southern regions. Boys in the central region had a longer duration of growth and a later age of PHV compared with the boys in the southern region. The cluster that included the southern states of the country showed estimated lower adult height and earlier somatic maturation. A lower height was found in the low and low-middle socioeconomic levels compared with the medium-high and high socioeconomic levels. Future research in Mexico should focus on longitudinal studies to analyse the timing and tempo of growth and maturation, considering the impacts of environmental and genetic factors. Public health strategies should account for geographic variations.

Keywords: human growth curve; peak height velocity; Mexican children

Introduction

Human growth that generally takes place in the first 18–20 years of life (Cameron, 2021; Malina *et al.*, 2004) is characterized by relatively smooth, continuous, and non-linear biological process (Cameron, 2021). Two of the most important indicators of growth in adolescence are the peak height velocity (PHV), which refers to the highest increment of height at a particular age of an individual, and the percentage of adult height (individual's final height achieved at a specific age) that is commonly estimated using different mathematical models like Preece–Baines 1 (PB1) model.

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Both PHV and estimated percentage of adult height are the indicators of timing (chronological age at which a maturational event occurs) of biological maturation, in addition to the fact that they allow identifying the maturation status, that is, whether an individual is early or late in the growth process (Malina *et al.*, 2018).

It has been observed that the presence of PHV at an early age is associated with a higher level of adiposity and an increased risk of becoming overweight and obese during adolescence (Alberga *et al.*, 2012). In turn, body weight gain and high body fat during childhood are associated with an early onset of puberty and an early occurrence of PHV (Buyken *et al.*, 2009).

One of the first studies to model height growth was developed by Bayley in 1956 among North American children and adolescents (Bayley, 1956); however, its sample size was limited. Subsequently, studies developed by Tanner in 1976 using the data from a British population and in 1985 using data from a North American population made it possible to establish reference values for the height growth velocity curve, which has been used globally (Tanner and Davies, 1985; Tanner and Whitehouse, 1976).

The PB1 is one of the mathematical models to fit growth curves that had been used in longitudinal series of data of children and adolescents in the United Kingdom (Preece and Baines, 1978), Belgium (Hauspie *et al.*, 1980b; Hauspie and Wachholder, 1986; Wachholder and Hauspie, 1986), West African (Gambian) villages (Billewicz and McGregor, 1982), Aboriginal Australia (Brown and Townsend, 1982), rural India (Satyanarayana *et al.*, 1989), urban India (Hauspie *et al.*, 1980a), and Guatemala (Bogin *et al.*, 1990). However, the PB1 model had also been applied to several cross-sectional studies worldwide (Dasgupta and Das, 1997; Khongsdier and Mukherjee, 2003; Mao *et al.*, 2011; Mirzaei-Salehabadi and Sengupta, 2012, 2013; Zemel and Johnston, 1994). Further studies analysed growth velocity patterns in other populations such as in Japan (Suwa *et al.*, 1992), South Korea (Chae *et al.*, 2013), India (Khadilkar *et al.*, 2019) and Brazil (Leite-Portella *et al.*, 2017). In addition, it has been observed that PHV tends to present variation among individuals and between regions within the same country (Yokoya and Higuchi, 2014).

In Mexico, studies in auxology are limited. Some of the main works in this area are those documented by Faulhaber in 1984 and 1985, highlighting how the Mexican populations showed to have a lower velocity and earlier growth of body dimensions, compared with those reported from developed countries, because of the environmental and lifestyle conditions, as well as genetic aspects (Faulhaber, 1984, 1989).

Other studies in recent decades focused on secular changes in height in the Mexican populations. Malina *et al.* (2009) found in a population of indigenous communities in Oaxaca that final height increased from 1978 to 2000 from 157.6 cm to 160.2 cm, with the PHV observed at an earlier age, from 15.0 years to 13.7 years. Peña-Reyes *et al.* (2002) observed a secular gain of height in urbanized children aged 6–12 years from Veracruz and Sonora between 1.1 cm and 1.5 cm/decade compared with the height of children from Mexico City measured in 1926. On the other hand, Datta Banik *et al.* (2017), in a more recent work, observed an early occurrence of PHV in boys and girls from Merida, Yucatán, 12.4 years and 11.0 years, respectively. An early age of onset of menarche was associated with excess weight and body fat in girls (Datta Banik, 2022). Some other reports on secular trends of anthropometric characteristics (height, weight, body mass index) in Yucatán populations are available. However, the studies did not explain height growth and maturity patterns, representing the populations from Yucatán and the region. A study reported secular changes and economic transformations in Yucatán (Siniarska and Wolanski, 1999) where a review of the literature showed height data from the Maya Preclassic period to the 19th-century populations. A review of the general trends in size of Maya populations of the Yucatan Peninsula from the Preclassic to 2010 reported changes in the adult stature and discussed the issue from the perspective of human ecology (Azcorra Pérez *et al.*, 2022). Another recent study from a rural Maya community in Yucatán reported a significant increase in the height of boys and girls from 1986 to 2022 (Azcorra *et al.*, 2023).

The earlier studies, which evaluated height growth patterns, representing specific regions of Mexico, did not emphasize the differential characteristics of somatic maturation in the different regions of the country. This is relevant due to the diversity that exists in the Mexican Republic in terms of sociodemographic, economic, and nutritional conditions and characteristics, and their interrelationships with growth and maturation process that are sensitive to these environmental factors (Zemel and Johnston, 1994).

In this background, the objective of the present study was to characterize the height growth curve of the Mexican populations by geographic regions and to cluster the states of the Mexican Republic according to their somatic maturation characteristics, based on a national representative sample of boys in the ENSANUT 2012 and 2018.

Methods

The present study used data from the National Survey of Health and Nutrition (ENSANUT in Spanish acronym) conducted in 2012 and 2018, in Mexico, by the National Institute of Public Health (INSP) and the National Institute of Statistics and Geography (INEGI). Both surveys, conducted across the 32 states of the country, had probabilistic sampling designs that allowed drawing valid statistical inferences representing national level, rural and urban areas, and region (North, Central, Mexico City and Metropolitan area, and South). Weighting factors were calculated to estimate the total elements in the population to ensure that the sample size was statistically representative. More details had been published in other reports (Romero-Martínez *et al.*, 2013, 2019).

Socioeconomic level index was constructed through the principal component analysis (PCA), based on housing characteristics and possession of household belongings. The index was designed in the ENSANUT methods and was reported in earlier publications (Romero-Martínez *et al.*, 2013, 2019). In the present study, the index was divided into four categories: low, medium-low, medium-high, and high.

A total of 18,219 boys from the ENSANUT 2012 database and 7,146 boys from the ENSANUT 2018 database, aged between 1.50 years and 18.49 years, were included in the study. For our analysis, the datasets of 2012 and 2018 were combined to apply the PB1 non-linear model, which is described later, to fit the height growth curve, based on cross-sectional data. The variables were height (cm), decimal age, and the participants' residence in the state of Mexican Republic. Height measurements were recorded following standard protocols (Habicht, 1974; Lohman *et al.*, 1988), as explained in the ENSANUT 2018 report (Shamah-Levy *et al.*, 2020). Age groups were classified based on rounded decimal ages (e.g., 6 years: decimal age between 5.50 years and 6.49 years).

Statistical analyses

First, the PB1 model (Preece and Baines, 1978) was applied to the height data representing the 32 Mexican states. The PB1 is a five-parameter mathematical non-linear model used to fit height growth data. The mathematical function is as follows:

$$y = h1 - \frac{2(h1 - h0)}{e^{S0(t-\theta)} + e^{S1(t-\theta)}}$$

where t = age in years, h1 = adult height (cm) or asymptotic value that represents the unique parameter with biological interpretation, h0 = height at PHV (cm), S0 and S1 = prepubertal and pubertal rate constants, h0 = height constant (cm) at age theta (θ), and theta = age (years) constant at peak velocity.

Furthermore, biological parameters, including (1) age at take-off (years), (2) height at take-off (cm), (3) velocity at take-off (cm/year), (4) age at PHV (years), (5) height at PHV (cm), and (6) velocity at PHV (cm/year) were estimated.

The PB1 model has been validated for its application to cross-sectional data in males, both in the general population (Zemel and Johnston, 1994) and among athletes (Flores and Fragoso, 2024).

Once the biological parameters were estimated, a PCA was conducted, accepting eigenvalues greater than one. Additionally, mean and standard deviation values for the six estimated biological parameters and for adult height (h1 derived from PB1 parameters) were calculated, along with the Pearson correlation coefficients among these variables. PCA was run to reduce the dimensionality, to identify correlated variables, and to find a more accurate and meaningful grouping in the cluster analysis.

Subsequently, cluster analyses were performed to group the data from Mexican states based on biological parameters and adult height, utilizing the Ward criterion. Statistical measures including R^2, cubic clustering criterion, pseudo F value, and pseudo *T*-square value were employed to determine the number of clusters. Similarity and distance calculations were also carried out. Statistical analyses were done using SAS software version 9.0, with a confidence level of 95%.

Results

Goodness of fit of PB1 model

The PB1 model converged successfully in less than 9 iterations for each of the 32 Mexican states. Additionally, all models demonstrated a high R^2 value of 0.99. The average prediction error was 0.27 cm. Furthermore, the relationship between the height values estimated by each model and the observed height values in the 32 states, using linear regression, showed an R^2 value of $\geq$0.95.

Descriptive data and correlations

The PB1 model was applied to estimate the growth curve of boys' height across all 32 Mexican states, with a maximum of 14 iterations. Table 1 displays the average mathematical and biological parameters for each state. The highest estimated adult height values were observed in Chihuahua, Sinaloa, and Nayarit, with measurements of 175.7 cm, 172.6 cm, and 172.4 cm, respectively. Conversely, the shortest height values were found in Chiapas, Yucatan, and Oaxaca, with measurements of 163.2 cm, 163.6 cm, and 164.2 cm, respectively. Additionally, the earliest age at PHV was identified in Nuevo León, Baja California Sur, and Mexico City, with ages 11.4 years, 11.6 years, and 11.7 years, respectively. On the other hand, relatively delayed age at PHV values were observed in Sonora, Guerrero, and Zacatecas, with ages 13.0 years, 12.9 years, and 12.8 years, respectively.

Socioeconomic variation in adult height and growth patterns

In terms of socioeconomic levels, the adult height of individuals in the low and medium-low categories averaged 167.47 cm and 169.4 cm, respectively. Conversely, for those in the medium-high and high categories, the average adult height was 172.38 cm and 172.53 cm, respectively, representing a 5 cm difference between the low and high socioeconomic groups ($p < 0.05$). In rural areas, adult height averaged 168.09 cm, while in urban areas, it was 170.27 cm ($p < 0.05$). PHV occurred at an average age of 12.56 years in rural areas and 12.31 years in urban areas ($p < 0.05$).

Table 1. Mathematical and Biological Parameters Estimated for 32 States of the Mexican Republic

State	Mathematical parameters					Biological parameters					
	H1	H0	S0	S1	Theta	Age at PHV	Age at TO	Height at PHV	Height at TO	Velocity at PHV	Velocity at TO
Baja California Sur	171.7	158.2	0.10	0.72	13.2	11.6	8.36	149.0	129.4	6.3	5.6
Nuevo León	170.5	155.3	0.09	0.70	12.8	11.45	7.54	146.5	122.7	6.7	5.6
Ciudad de México (CDMX)	170.3	156.0	0.10	0.85	12.6	11.7	7.84	149.4	125.0	7.4	5.6
Nayarit	172.4	157.6	0.10	0.77	13.1	12.0	7.98	150.2	125.5	7.0	5.5
Querétaro	170.4	156.8	0.10	0.72	13.4	12.0	8.48	148.1	127.6	6.2	5.5
Guanajuato	170.1	156.9	0.11	0.82	13.2	12.1	8.48	149.9	128.2	6.7	5.4
Chihuahua	175.7	162.5	0.10	0.62	14.5	12.2	9.68	150.3	136.5	5.6	5.4
Hidalgo	167.2	154.5	0.11	0.82	13.0	11.9	8.47	147.4	127.1	6.5	5.4
Tamaulipas	170.5	157.2	0.10	0.78	13.3	12.1	8.50	149.8	128.6	6.5	5.4
Estado de México	169.7	156.4	0.10	0.78	13.5	12.3	8.63	149.2	127.5	6.5	5.3
Sinaloa	172.6	158.7	0.10	0.76	13.5	12.7	8.50	151.3	128.7	6.5	5.3
Coahuila	170.4	158.3	0.11	0.93	13.3	12.4	8.99	152.6	132.0	6.9	5.2
Campeche	166.9	154.2	0.10	0.76	13.3	12.0	8.52	146.7	127.0	6.1	5.2
Durango	171.5	158.8	0.11	0.89	13.5	12.6	8.92	152.9	131.3	6.9	5.2
Baja California	170.9	158.4	0.11	0.83	13.6	12.5	8.91	151.8	131.3	6.4	5.2
Jalisco	170.2	157.5	0.11	0.87	13.4	12.5	8.79	151.5	130.0	6.7	5.2
Aguascalientes	172.4	158.0	0.10	0.88	13.4	12.6	8.68	153.1	129.6	7.1	5.1
Tabasco	167.0	153.8	0.10	0.91	12.9	12.1	8.33	148.3	125.4	7.2	5.1
Colima	170.9	159.0	0.11	0.94	13.4	12.6	9.08	153.6	133.3	6.8	5.0
Morelos	167.8	155.7	0.11	0.96	13.2	12.4	8.86	150.6	129.7	7.0	5.0
Puebla	166.7	154.1	0.11	0.88	13.3	12.4	8.71	148.3	126.9	6.7	5.0
Tlaxcala	167.7	155.7	0.11	0.95	13.4	12.6	9.03	150.5	130.0	6.8	5.0

(*Continued*)

Table 1. (*Continued*)

	Mathematical parameters					Biological parameters					
State	H1	H0	S0	S1	Theta	Age at PHV	Age at TO	Height at PHV	Height at TO	Velocity at PHV	Velocity at TO
Michoacán	169.1	156.7	0.11	0.98	13.3	12.6	8.95	151.8	130.2	7.2	5.0
Zacatecas	171.0	158.5	0.11	1.03	13.4	12.8	9.16	154.0	132.1	7.5	4.9
Quintana Roo	165.8	153.3	0.10	0.88	13.3	12.4	8.63	147.8	126.6	6.6	4.9
Oaxaca	164.2	151.8	0.11	0.96	13.1	12.4	8.65	146.9	125.3	7.0	4.8
Yucatán	163.6	151.6	0.11	0.92	13.3	12.5	8.80	146.5	125.8	6.6	4.8
Veracruz	166.3	154.4	0.11	1.06	13.1	12.5	8.91	150.2	129.1	7.4	4.8
San Luis Potosí	167.3	155.4	0.11	1.09	13.3	12.7	9.14	151.3	130.2	7.5	4.7
Sonora	171.6	159.5	0.11	1.11	13.5	13.0	9.40	155.5	134.0	7.8	4.7
Chiapas	163.2	150.6	0.10	1.02	13.2	12.6	8.76	146.2	123.8	7.5	4.7
Guerrero	165.8	153.5	0.11	1.04	13.4	12.9	9.09	149.7	127.6	7.4	4.6
Socioeconomic level											
Low	167.5	154.7	0.1	0.8	13.6	12.5	8.8	148.1	127.1	6.4	5.1
Medium-low	169.4	156.3	0.1	0.9	13.1	12.2	8.5	150.0	128.1	6.8	5.3
Medium-high	172.4	159.5	0.1	1.0	13.6	13.0	9.2	154.9	132.2	7.6	4.9
High	172.5	159.5	0.1	0.8	13.4	12.3	8.8	152.5	131.4	6.6	5.4
Area											
Urban	170.3	157.0	0.1	0.8	13.3	12.3	8.6	150.4	128.4	6.7	5.3
Rural	168.1	155.5	0.1	0.9	13.4	12.6	8.8	149.9	128.3	6.8	5.0
All sample	169.1	156.2	0.1	0.9	13.3	12.3	8.7	150.0	128.7	6.8	5.1

h1 = adult height, h0 = height at peak height velocity, S0 = velocity constant of prepubertal growth, S1 = velocity constant of pubertal growth, PHV = peak height velocity; TO = Take-off.

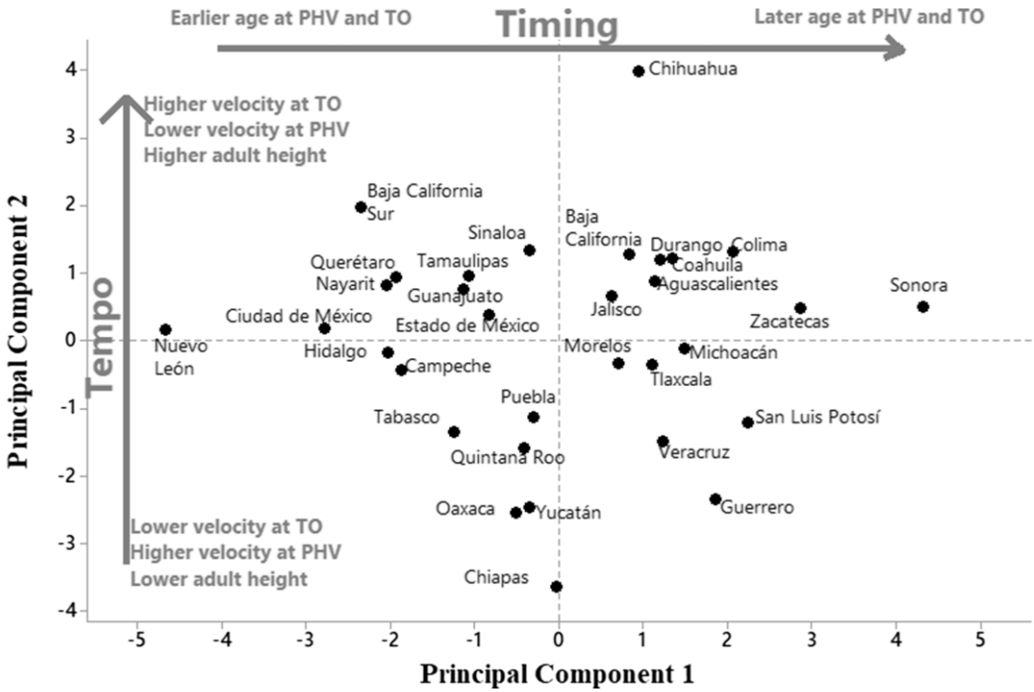

Figure 1. Scatter plot of the principal component analysis based on the two main principal components, which were used as biological parameters of Preece–Baines model (age at peak height velocity (PHV), age at take-off (TO), height at PHV, height at TO, velocity at PHV, velocity at TO) and a mathematical parameter that indicates adult height (h1).

Biological parameter correlations

A significant Pearson correlation coefficient was found between adult height and the biological parameters: height at PHV ($r = 0.600$, $p < 0.001$), height at take-off ($r = 0.574$, $p < 0.001$), and velocity at take-off ($r = 0.622$, $p < 0.001$). This suggests that boys with a higher velocity at take-off tend to reach a greater adult height.

Moreover, age at PHV was directly correlated with age at take-off ($r = 0.800$, $p < 0.001$) and inversely correlated with the velocity at take-off ($r = -0.854$, $p < 0.001$). Velocity at PHV showed an inverse correlation with the velocity at take-off ($r = -0.591$, $p < 0.001$), indicating that boys who experienced accelerated growth at the onset of adolescence (take-off) tend to reach their PHV earlier but with slower growth.

Principal component analysis

The PCA revealed that PC1 accounted for 50% of the variance and was associated with variables related to the timing of somatic maturity, including age at PHV, age at take-off, height at PHV, and height at take-off (eigenvalue = 3.48). PC2 explained 34% of the variance and was linked to the tempo of somatic maturity. Variables for PC2 included adult height (h1), height at take-off, velocity at PHV, and velocity at take-off (eigenvalue = 2.38). Figure 1 shows a scatter plot of the first two principal components, as well as the distribution of Mexican states.

Cluster analysis

A cluster analysis was performed to group the Mexican states based on the observed biological parameters. Table 2 shows the 31 number of clusters and their respective similarities and

Table 2. Number of Clusters, Clusters Joined, and Statistics for the Estimated Number of Clusters

Number of cluster	Cluster joined		Frequency	R^2	Similarity	Distance	Cubic clustering criterion	Pseudo F value	Pseudo T^2
17	Morelos	Tlaxcala	2	1.00	97.8	0.4	–	318.0	–
11	Guanajuato	Tamaulipas	2	1.00	96.8	0.6	–	206.0	–
4	Campeche	Hidalgo	2	1.00	95.0	0.9	–	119.0	–
20	Oaxaca	Yucatán	2	1.00	94.8	1.0	–	97.5	–
21	Puebla	Quintana Roo	2	1.00	94.1	1.1	–	82.9	–
2	Baja California	Coahuila	2	1.00	93.4	1.2	–	72.4	–
14	Jalisco	Michoacán	2	1.00	92.9	1.3	–	65.4	–
15	Estado de México	Querétaro	2	0.99	92.6	1.4	–	61.0	–
2	2	Durango	3	0.99	92.5	1.4	–	58.7	1.3
6	Colima	Zacatecas	2	0.99	92.1	1.4	–	56.9	–
17	17	San Luis Potosí	3	0.99	92.0	1.5	–	57.8	12.0
12	Guerrero	Veracruz	2	0.99	89.8	1.9	–	52.4	–
21	21	Tabasco	3	0.99	89.1	2.0	–	49.3	3.2
1	Aguascalientes	Sinaloa	2	0.98	88.6	2.1	–	46.6	–
11	11	15	4	0.98	87.3	2.3	–	44.9	4.2
9	Ciudad de México	Nayarit	2	0.97	87.2	2.4	–	42.4	–
7	Chiapas	20	3	0.98	86.6	2.5	–	43.1	6.0
4	4	21	5	0.97	85.1	2.7	–	41.8	3.2
6	6	Sonora	3	0.96	84.4	2.9	–	41.0	3.7
3	Baja California Sur	11	5	0.96	84.0	2.9	–	41.0	3.5
2	2	14	5	0.95	79.9	3.7	–	40.2	6.3
12	12	17	5	0.94	76.5	4.3	–	38.7	7.9
9	9	Nuevo León	3	0.91	72.2	5.1	–	34.5	4.5
1	1	2	7	0.93	71.1	5.3	–	36.1	5.4
1	1	6	10	0.84	51.0	9.0	−1.5	27.2	8.5
4	4	7	8	0.88	46.4	9.8	–	29.4	16.3
3	3	9	8	0.80	45.6	10.0	−1.5	26.5	8.4
1	1	Chihuahua	11	0.73	35.1	11.9	−2.1	24.7	9.1
4	4	12	13	0.63	−3.3	19.0	−2.4	24.8	17.5
3	3	4	21	0.48	−37.7	25.3	−1.7	27.8	12.5
1	1	3	32	0.00	−193.7	54.0	0	–	27.8

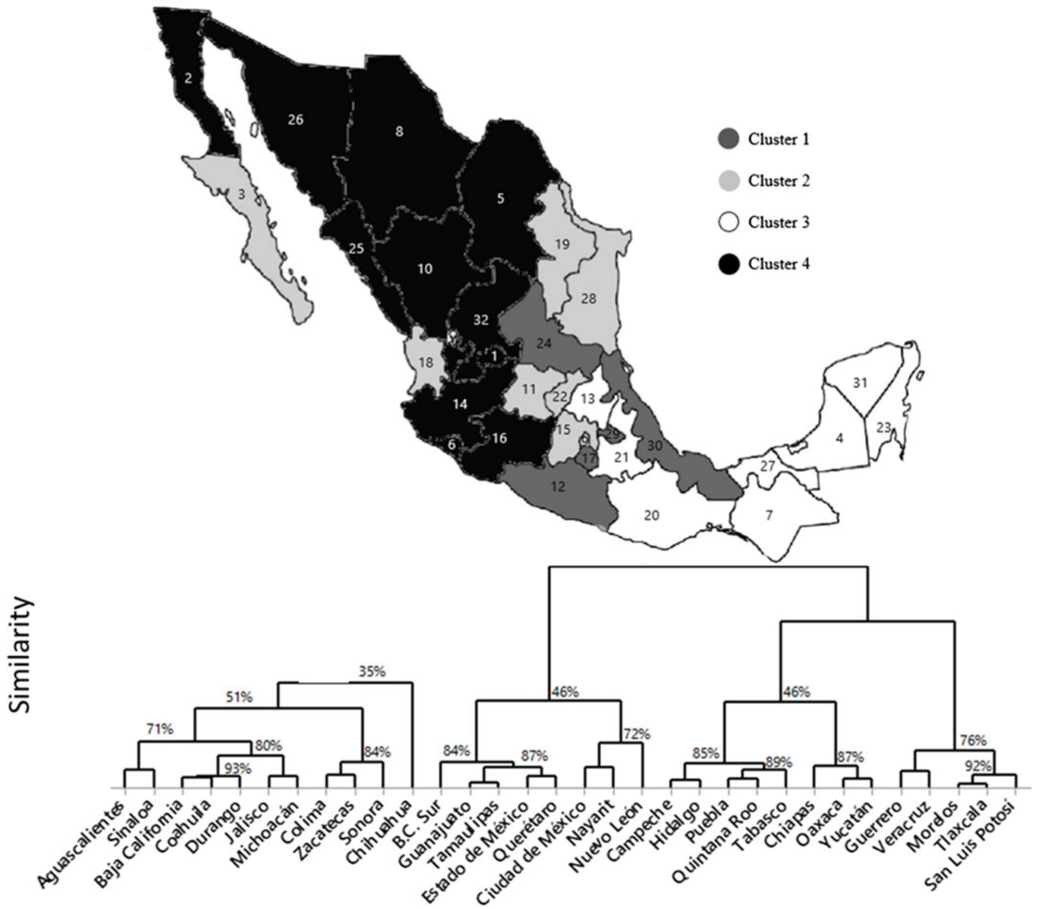

Figure 2. Dendrogram of the entire hierarchy of clustering of the Mexican states, based on biological parameters estimated from Preece–Baines 1 and map of the Mexican Republic with the states grouped by cluster. (1) Aguascalientes, (2) Baja California, (3) Baja California Sur, (4) Campeche, (5) Coahuila, (6) Colima, (7) Chiapas, (8) Chihuahua, (9) Ciudad de México, (10) Durango, (11) Guanajuato, (12) Guerrero, (13) Hidalgo, (14) Jalisco, (15) Estado de México, (16) Michoacán, (17) Morelos, (18) Nayarit, (19) Nuevo León, (20) Oaxaca, (21) Puebla, (22) Querétaro, (23) Quintana Roo, (24) San Luis Potosí, (25) Sinaloa, (26) Sonora, (27) Tabasco, (28) Tamaulipas, (29) Tlaxcala, (30) Veracruz, (31) Yucatán, (32) Zacatecas.

differences. First, similarities between Morelos and Tlaxcala (98%); Guanajuato and Tamaulipas (97%); Campeche and Hidalgo (95%); Oaxaca and Yucatán (95%); Puebla and Quintana Roo (94%); Baja California, Coahuila, and Durango (92%); Jalisco and Michoacán (93%); Estado de México and Querétaro (93%); and Colima and Zacatecas (92%) were observed. On the other hand, Chihuahua was the state that presented low similarity with the rest of the states, followed by Nuevo León and Baja California Sur. To decide the final number of clusters, the R^2 value of 0.8 was considered, and all states were grouped into five clusters, but Chihuahua was the only exception. To join Chihuahua, the R^2 was 0.73, and the final four clusters were as follows (Figure 2):

Cluster 1: Comprising Morelos, Tlaxcala, San Luis Potosí, Guerrero, and Veracruz, with a similarity of 76%. This group displayed relatively delayed age at take-off, lower growth velocities, delayed age at PHV, and estimated lower adult height.

Cluster 2: Comprising Guanajuato, Tamaulipas, Estado de México, Querétaro, Mexico City (CDMX), Nayarit, Baja California Sur, and Nuevo León, with a similarity of 46%. This group exhibited earlier somatic maturity in terms of age at take-off and age at PHV, with higher growth velocity at take-off and lower velocity at PHV. Adult height tended to be high in this cluster.

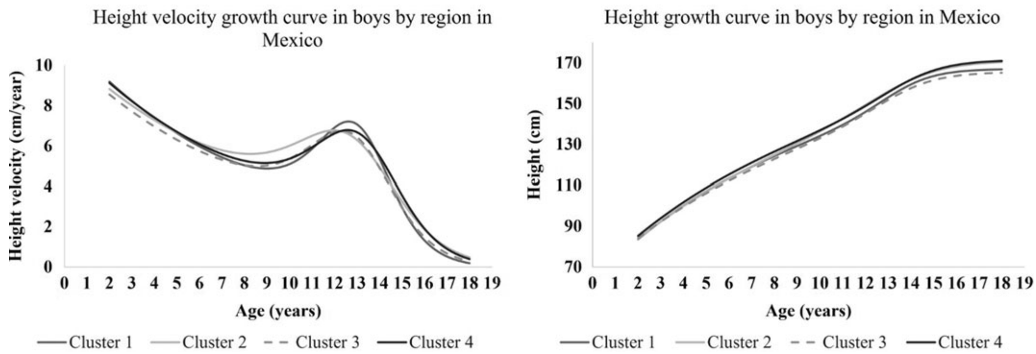

Figure 3. Height velocity growth curve (left) and height growth curve (right) in boys, by clusters in Mexico.

Cluster 3: Consisting of Campeche, Hidalgo, Oaxaca, Yucatán, Puebla, Quintana Roo, Tabasco, and Chiapas, with a similarity of 46%. Like Cluster 2, somatic maturity occurred earlier but with lower growth velocity at take-off and higher velocity at PHV. Adult height tended to be lower in this cluster.

Cluster 4: Involving Baja California, Coahuila, Jalisco, Michoacán, Durango, Colima, Zacatecas, Aguascalientes, Sinaloa, Sonora, and Chihuahua, with a similarity of 35%. This was the most populous and diverse cluster, characterized by higher estimated adult height, later somatic maturity, higher growth velocity at take-off, and lower velocity at PHV. In this cluster, take-off occurred at a later age with lower velocity, and age at PHV was relatively delayed with higher velocity. The estimated adult height value was higher.

Figure 3 displays the height growth curve, illustrating that Cluster 2 reached PHV at an earlier age (11.96 years, $p = 0.01$), compared with Clusters 1 and 4, both at 12.6 years ($p < 0.001$). Cluster 3 exhibited a higher age at PHV than Cluster 2 but a lower age at PHV than Clusters 1 and 4 ($p < 0.05$), with an age of 12.3 years. For adult height, Clusters 2 and 4 had the highest values, measuring 171.0 cm and 171.3 cm, respectively ($p < 0.01$), while Clusters 3 and 1 had the lowest values, measuring 165.5 cm and 167.0 cm, respectively ($p < 0.01$).

Discussion

The present study is the first one to describe the cluster of the states of the Republic of Mexico according to the physical growth patterns and biological maturation characteristics of boys. The number of final clusters was 4, where the 32 states of Mexico were grouped, observing a grouping slightly similar to the geographic distribution, mainly for Clusters 3 and 4 that included the southern states of the country (in addition to Puebla and Hidalgo) and the northern and central-western states of the country (except Baja California Sur and Nayarit), respectively.

The main findings related to the maturation characteristic variations observed in the 32 Mexican states were as follows: (a) difference of height at the beginning of adolescence (take-off) of 13.8 cm, at the peak of growth velocity of 9.3 cm, and at the end of growth (reaching adult height) of 12.5 cm; (b) age at PHV ranging from 11.4 years to 13.0 years; (c) growth velocity ranging from 5.6 cm/year to 7.8 cm/year at PHV; and (d) duration of the growth acceleration phase (from take-off to PHV) ranged ranging from 2.5 years (Chihuahua) to 4.0 years (Nayarit).

It was interesting to compare the results obtained in the present study with others representing different populations. The age at take-off (8.7 years) and age at PHV (12.3 years) values in the present study (estimated in the entire sample) were lower than that recorded among boys of Guatemala (10.05 years and 13.66 years, respectively) (Bogin *et al.*, 1990), China (9.3 years and 12.6 years, respectively) (Mao *et al.*, 2011), and in the Third Harvard Study (10.9 years and

14.1 years, respectively) (Zemel and Johnston, 1994). The age at PHV of Colombian boys was 12.71 years (Cossio-Bolaños *et al.*, 2021). In the present study, the height growth velocity at the age of PHV ranged from 5.6 cm/year among boys from Chihuahua to 7.8 cm/year in boys of Sonora with an average value of 6.8 cm/year in the entire sample that was lower than the value recorded among boys from Merida (7.11 cm/year) (Datta Banik *et al.*, 2017) and was much lower than that recorded in the sample from Guatemala (9.52 cm/year) (Bogin *et al.*, 1990). The velocity at PHV recorded among boys in other studies from China (6.91 cm/year) (Mao *et al.*, 2011), Third Harvard Study (9.1 cm/year) (Zemel and Johnston, 1994), and Colombia (7.43 cm/year) (Cossio-Bolaños *et al.*, 2021) was higher than the value obtained in the present study in Mexico. The estimated value of final or adult height in the present study ranged between 163.2 cm in boys of Chiapas and 175.7 cm in the peers from Chihuahua with an average value of 169.1 cm in the sample that was lower than the estimated value obtained in the sample from Merida (172.87 cm) (Datta Banik *et al.*, 2017) and much lower than 177.18 cm, the estimated final height of boys in Guatemala (Bogin *et al.*, 1990). Estimated adult height values using the PB1 model in other studies from China (175.08 cm) (Mao *et al.*, 2011), Third Harvard Study (172 cm) (Zemel and Johnston, 1994), and Colombia (170.85 cm) (Cossio-Bolaños *et al.*, 2021) were also higher than that of the boys in Mexico. The secular trend of skeletal maturation in relation to PHV was studied in Denmark (Caspersen and Sonnesen, 2020); the estimated values of the age and velocity at PHV were 14.35 years and 9.42 cm/year, respectively, in the sample of boys during 1969–1973, and the same estimated values were 13.82 years and 10.2 cm/year, respectively, in the sample during 1996–2000. In a study among 6–18-year-old schoolchildren in Spain, the PB1 was fitted for height data, and estimated values for boys were as follows: age at take-off, 10.83 years; velocity at take-off, 6.07 cm/year; age at PHV, 13.74 years; PHV, 6.07 cm/year; height at PHV, 161.22 cm; and final height, 176.23 cm (Rosique Gracia *et al.*, 2001). In a recent study among Peruvian children and adolescents, the estimated values for boys in the overall sample were as follows: age at PHV, 9.68 years; PHV, 5.88 cm/year; and final height, 153.06 cm (Santos *et al.*, 2019), which were lower than the results obtained in the present study. In a study among Argentine children and adolescents aged 2–18 years, height growth data fitted to PB1 model estimated age at PHV 13.6 years, PHV 6.4 cm/year, and final height 173.7 cm in boys (Cuestas *et al.*, 2020); the values were higher except marginally lower velocity at PHV than the results of the same parameters obtained in the present study. Gomula *et al.* (2021) reported secular trends of biological parameters derived from fitted PB1 model of height growth data of Polish boys in the samples of 1966, 1978, 1988, and 2012. They observed changes in values from 1966 to 2012: a decline in the age at take-off (10.8–9.3 years), age at PHV (14.4–13.0 years), and velocity at PHV (7.72–7.21 cm/year) and an increase in the values of velocity at take-off (4.25–5.3 cm/year), height at PHV (157.5–159.8 cm), and estimated adult height (172.4–179.4 cm). In a study among Portuguese adolescent basketball players (boys), the estimated age at PHV was observed to be correlated with maturity status: 13.45 years (total sample), 12.2 years in early maturers, 13.3 years among on-time, and 14.6 years in late maturers (Fragoso *et al.*, 2021). Therefore, the results obtained for the same biological parameters in the present study were different: earlier age at take-off and age at PHV, lower velocity at take-off and PHV, and lower estimated final height, compared with other studies mentioned above.

The variability in somatic maturity characteristics that we found in the present study has also been observed by Malina *et al.* (2018); the data represent the indigenous populations from 22 states of the Mexican Republic, where the authors found a slightly lower height in the South Pacific (Guerrero and Oaxaca) and southwestern states (Campeche, Chiapas, Quintana Roo, Tabasco, and Yucatán), compared with the north, central, and south Gulf states (Puebla and Veracruz), and lowest height was observed in the southwestern states. Likewise, the southeastern states were precisely grouped into Cluster 3 of the present study, a cluster characterized by a low final height and an early onset of adolescence. This variation in different regions of Mexico has also been evidenced in other studies where childhood obesity was evaluated. Little *et al.* (2019) analysed the prevalence of overweight and obesity in Mexican indigenous and mestizo children and adolescents, where the highest prevalence was found in the southeastern region of Mexico and the lowest in northern part of the country. A high prevalence of overweight and obesity in that region is, in part, conditioned by the short stature recorded particularly in the southeastern region, while body weight differed minimally in different regions of Mexico (Malina *et al.*, 2018). Datta Banik (2022) observed in a Maya population of Yucatán (located in the southeastern region of Mexico) that short stature was associated with early maturation and high levels of adiposity, aspects that apparently characterize this region, located in Cluster 3 of the present study.

In addition, it has been reported that the largest number of indigenous language-speaking populations of Mexico live in the southeastern region of the country, and the states are Oaxaca (31.2%), Chiapas (28.2%), and Yucatán (23.7%) (INEGI, 2022). It has been observed that indigenous children and adolescents present lower height during prepuberty than non-indigenous peers, after adjusting for biological characteristics of a mother and household socioeconomic conditions (Vilar-Compte *et al.*, 2020), besides household food insecurity, but the dietary diversity could be a protective factor against stunting (Cuevas-Nasu *et al.*, 2019).

Differences in height have been observed in the Mexican children according to socioeconomic level (Vilar-Compte *et al.*, 2020); the authors studied children from 8 to 9 years and followed up to age 15–16 years and reported how height could vary up to 5 cm between those living in moderate (128.7cm) and extreme poverty (125.2cm), compared with those who were not in the below poverty level (130.1cm). In Mexico, it is estimated that there are approximately 40% of children with stunting who represent low and very low socioeconomic levels, living in a rural region of southern Mexico (Cuevas-Nasu *et al.*, 2020). Similar results have been observed by Datta Banik *et al.* (2014) in children from Merida, Yucatán, where greater height and lean mass were found among those who had a family environment with a higher socioeconomic level.

On the other hand, a factor strongly associated with growth and maturation is household food security. A recent study conducted by Lechuga-Rodríguez (2022) grouped the Mexican states based on household food insecurity, observing that children living in the south of Mexico represented the poorest population, where the highest level of household food insecurity was observed. In a recent study that analysed data from the 2012 National Health and Nutrition Survey (ENSANUT) in Mexico, it was reported that moderate to severe food insecurity, low birth weight, low maternal height, and a greater number of children in the household under 5 years of age were the factors associated with stunting. In addition, higher percentage of stunting was found in the rural areas of the southern region of the country (Campos *et al.*, 2020). A decreasing trend of short stature in children under 5 years of age has also been observed in Mexico between 1988 and 2016, but it differs by area and residential status (Cuevas-Nasu *et al.*, 2018).

Finally, another finding of the present study was a relatively early age at PHV that was present in the different states compared to other populations. In Mexico, evidence is still limited; however, a study conducted by Datta Banik *et al.* (2017) observed an age at PHV of 12.4 years in boys from Merida, Yucatán, like what was observed in the present study. Studies by Faulhaber (1989) and Malina *et al.* (2004) reported the age at PHV values of 13 years and 14 years in the populations of CDMX and Oaxaca, respectively. On the other hand, it has been observed in the Mexican child population that in middle childhood (before puberty), skeletal age was delayed compared with chronological age (7–9 years), and then bone growth accelerated and skeletal age was higher than chronological age from 13 years onwards (Klünder-Klünder *et al.*, 2020). Advanced skeletal maturation observed during and at the end of puberty might be associated with higher height growth during adolescence, which was the reason behind that PHV occurring at an earlier age, together with other factors such as diet, high prevalence of childhood overweight and obesity, and environmental and hereditary factors.

The present study has some limitations since the ENSANUT was a cross-sectional survey, and it was not possible to infer causality. For that reason, more studies are needed, mainly of longitudinal in nature. In the present study, the PB1 model was applied to cross-sectional data, as it has previously been validated for such use in other studies. This model demonstrates adequate agreement with its application in longitudinal data, particularly in boys, for estimating age at PHV and final height using cross-sectional database (Flores & Fragoso, 2024; Zemel & Johnston, 1994). It has been used in several other studies also (Caspersen & Sonnesen, 2020; Cossio-Bolaños *et al.*, 2021; Cuestas *et al.*, 2020; Datta Banik *et al.*, 2017; Fragoso *et al.*, 2021; Gomula *et al.*, 2021; Mao *et al.*, 2011; Rosique Gracia *et al.*, 2001; Santos *et al.*, 2019). However, caution is advised in its application due to the observed differences in the S1 parameter between longitudinal and cross-sectional data. This disparity may lead to the misestimations of growth velocity for take-off and PHV, particularly in females. Additionally, caution is warranted when fitting the model at pre-pubertal and particularly at mid-childhood ages (5–7 years old) or in non-representative samples. These issues were considered in our study, which applied the PB1 model to a national representative sample of boys aged 2–18 years.

Based on the findings of our study, it seems to be important that the public health strategies in Mexico consider the population characteristics and needs of each geographic area. In auxology, future lines of research can be oriented towards the analysis of timing and tempo of growth and maturation in longitudinal studies with a consideration of the effects of environmental and genetic factors that might influence growth and maturation patterns.

In conclusion, in the present study, the somatic maturation characteristics of each state of the Mexican Republic were described, in addition to grouping them according to these characteristics. The age at PHV ranged from 11.4 years to 13.0 years in the male population; in addition, the southeastern region of the country had the lowest estimated adult height and relatively earlier maturation, while the northwestern region had the highest estimated adult height with relatively delayed somatic maturation timing compared with the other regions of Mexico.

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Ethical standard. The protocols for each survey were authorized by the Research Ethics, Research and Biosafety Committees of the National Institute of Public Health (INSP), Cuernavaca, Mexico. Written informed consent of adults/caregivers was requested from all participants. The usage of these data was carried out in accordance with the terms of free access.

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