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Original Research Article

Synthetic Growth Reference Charts

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Objectives: To reanalyze the between-population variance in height, weight, and body mass index (BMI), and to provide a globally applicable technique for generating synthetic growth reference charts.

Methods: Using a baseline set of 196 female and 197 male growth studies published since 1831, common factors of height, weight, and BMI are extracted via Principal Components separately for height, weight, and BMI. Combining information from single growth studies and the common factors using in principle a Bayesian rationale allows for provision of completed reference charts.

Results: The suggested approach can be used for generating synthetic growth reference charts with LMS values for height, weight, and BMI, from birth to maturity, from any limited set of height and weight measurements of a given population.

Conclusion: Generating synthetic growth reference charts by incorporating information from a large set of reference growth studies seems suitable for populations with no autochthonous references at hand yet. Am. J. Hum. Biol. 28:98–111, 2016.

INTRODUCTION

The world-wide variation in human growth is well known (Eveleth and Tanner, 1990) and has scientifically been documented since the first half of the 19th century (Quetelet, 1869). Today shortest mean final height has been measured in the Pygmy population of Congo with some 136 cm for adult women and 144 cm for adult men (Walker et al., 2006), tallest mean height was found in young modern Dutch adults with some 171 cm for adult females and 184 cm for adult males (Fredriks et al., 2000). Differences between populations are obvious at all ages: Indian children start into life with significantly less average birth weight (Subramanyam et al., 2010) than European newborns. Secular trends in height, weight, and body mass index (BMI) have been documented in European countries, in the United States since the mid-19th century, in the Southern Hemisphere and in all populations that underwent a significant socioeconomic transition (Webb et al., 2008). Variations in human growth have been attributed to genetics, to nutrition and to health-related and socioeconomic circumstances (Hermanussen, 2013). Growth even differs among populations and ethnic groups that live in close vicinity within the same geographic area. Documenting child and adolescent growth has led to a multitude of growth charts published since the early 20th century. Meanwhile, these charts are universally used in public health care as pediatric decisions on growth and failure to thrive are intricately intertwined with such charts (Olsen, 2006). Figures 1 and 2 illustrate the world-wide variation in height and BMI since 1831, and Table 1 lists the growth studies used in this analysis. Among males, modern Northern and Central Europeans are tallest at all ages. Historic male Japanese and modern boys from Papua New Guinea were the shortest. This is similar in females. Modern European females are significantly taller than modern East Asians.

Conversely, human growth curves show common characteristics. During the first year of life, infants increase in length by some 50% and almost triple in weight. Thereafter, growth rates decrease during childhood and the juvenile period (Bogin, 1999) with a minimum just before the onset of puberty. Growth again accelerates with peak height velocities roughly around the age of 11 years in girls and 13 years in boys. Growth of the long bones terminates at early adult age, whereas trunk growth may proceed into the middle of the third decade of life (Hermanussen, 2013).

This led to the idea of globally applicable growth references. At present, many countries that lack suitable references for child and adolescent growth use international (World Health Organization [WHO]) standards (http://www.who.int/childgrowth/en/; http://www.who.int/growthref/en/). The idea of growth standards goes back to recommendations of a Working Group on infant growth established by the WHO, and may be justified for infants and very young children who tend to grow similarly under modern affluent conditions. But as Khadilkar and Khadilkar (2011) state: *The disadvantage of using charts such as these (WHO charts) is that they are likely to over diagnose underweight and stunting in a large number of apparently normal children in the developing countries such as India*.

WHO standards were constructed from global samples, they average information of children and adolescents from various ethnic backgrounds, and consequently do not reflect that different modern populations may differ in mean values, standard deviations, and indicators of skewness for height, weight, and BMI.

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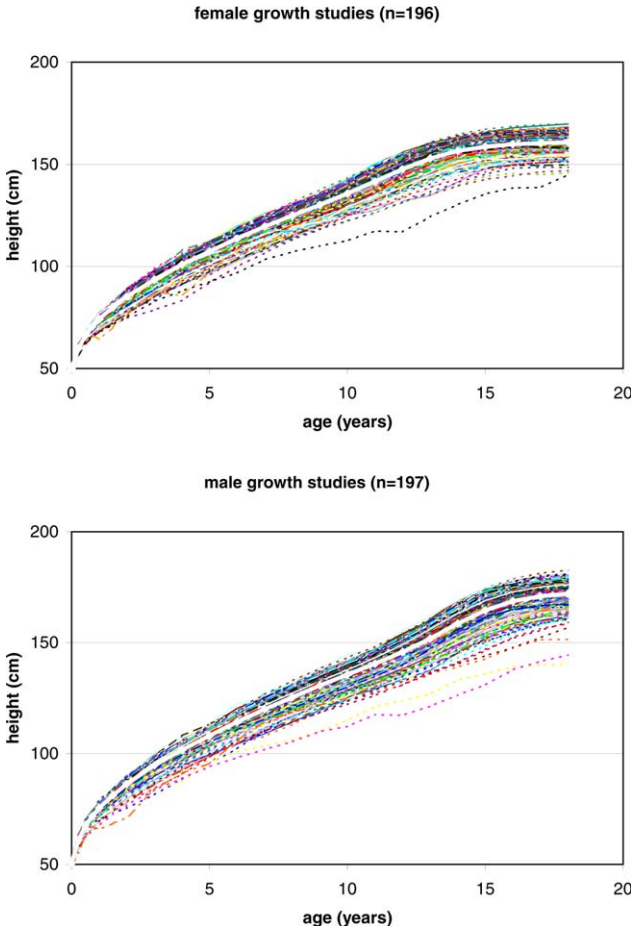


Fig. 1. World-wide variation in mean values for height.

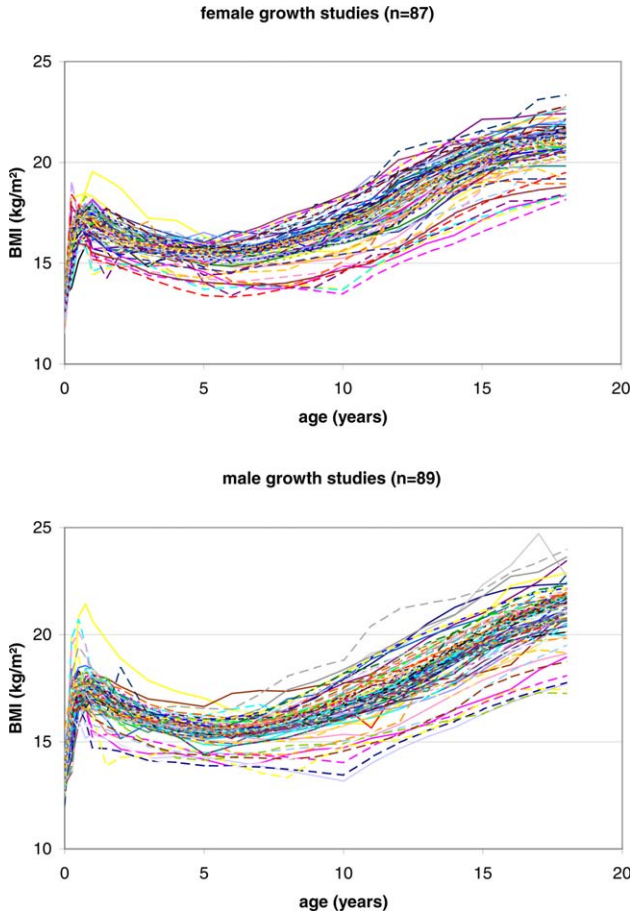


Fig. 2. World-wide variation in mean values for BMI.

Populations differ in height, weight, and BMI. As an averaged single standard/reference can never account for the diversity between populations a methodology has been created to generate "synthetic" growth reference charts (Hermanussen and Burmeister, 1999). The method allows for amalgamating global patterns of human growth with specific local information. The original method was based on 50 studies of birth measurements, 14 studies on early growth in height and weight, 40 male and 51 female childhood and adolescent growth studies, and some recent German, Japanese, and Czechoslovakian data, with altogether more than 24 million measurements. In view of the persistent need for national growth references as well as references for particular ethnic groups, we now actualize these previous approaches and further improve the methodology of generating synthetic growth reference charts.

MATERIAL AND METHODS

The current lack of availability of updated local growth reference charts led us to the following quest: to define the most likely growth curve of a population for which only a limited set of mean height, mean weight, or mean BMI values, respectively, are available, allowing us to construct "synthetic" references.

We propose an approach based on Principal Component Analysis and the Likelihood principle for generating "synthetic" references separately for height, weight, and BMI for age of any population that lacks complete annual data of these parameters. The method should be globally applicable, and it should provide the most likely growth curve separately for height, weight, and BMI for any population.

We approach this task in two steps:

1. Based on a reference combination of longitudinal and cross-sectional modern and historic growth studies with data on height and weight, we obtained global mean values and a limited number of Principal Components that characterizes the variability of growth in the reference combination.
2. This information is then used to derive estimates of means at all ages based on only a limited set of mean values (e.g., scattered measurements at school entry age, at public health institutions, at military conscription, etc.) obtained from a population of interest.

Under the assumption that limited sets of mean values represent the true development over time of the population of interest, we can apply a Bayesian rationale to find that (synthetic) curve for this population, which best

TABLE 1. List of growth studies

ar2009	Lejarraga H, del Pino M, Fano V, Caino S, Cole TJ. 2009. Arch Argent Pediatr 107:126–133.
at1959	Stracker OA. 1959. Neue Öst Z Kinderhkd. 4:145.
at2013	Gleiss A, Lassi M, Blümel P, et al. 2013. Ann Hum Biol 40:324–332.
au1963	Abbie AA. 1974. Med J Aust 1:470–471.
au1966	Kettle ES. 1966. Med J Aust 1:9721–9977.
au1971	Brown T, Barrett MJ. 1971. Med J Aust 2:29–32.
be1831	Quetelet A. 1869. Physique sociale. Tome II. Bruxelles: Muquardt.
be1870	Davenport CB. 1920. Am J Phys Anthrop III:467–475.
be1975	Wachholder A, Hauspie RC. 1986. Intern J Anthropol 1:327–338.
be2009	Roelants M, Hauspie R, Hoppenbrouwers K. 2009. Ann Hum Biol 36:680–694.
bg2010	Tomova A, Deepinder F, Robeva R, et al. 2010. Arch Pediatr Adolesc Med 164:1152–1157.
bg2011	Bulgarian Ministry of Health. 2011.
bo1975	Mueller WH, Murillo F, Palamino H, et al. 1980. Hum Biol 52(3):529–546.
br2010	Guedes DP, De Matos JA, Lopes VP, et al. 2010. Ann Hum Biol 37:574–584.
br2012	Silva S, Maia J, Claessens AL, et al. 2012. Ann Hum Biol 39:11–18.
ca1953	Pett LB, Ogilvie GF. 1956. Hum Biol 28:177–188.
ca1974	Mazess RB, Mather WE. 1975. Hum Biol 47:45–63.
ch1950	Hess K. 1950. Archiv der Julius Klaus-Stiftung 25:69–133.
ch1958	Heimendinger J. 1958. Schweizer Medizinische Wochenschrift 32/33:785–813 and Heimendinger J. 1958. Helv Paediatr Acta 13:471–478.
ch1976	Prader A, Largo RH, Molinari L, et al. 1989. Helv Paediatr Acta 43(Suppl 52):1–125.
cn1954	Chao L. 1957. Chin Med J 75:1018–1023.
cn1965	Chang KSF, Marjorie, MC, Lee DW, et al. 1965. Far East Med J 1:101–109.
cn1975	Li H, Leung SSF, Lam PKW, et al. 1999. Ann Hum Biol 26:457–471.
cn1985	Li H, Leung SSF, Lam PKW, et al. 1999. Ann Hum Biol 26:457–471.
cn1995	Li H, Leung SSF, Lam PKW, et al. 1999. Ann Hum Biol 26:457–471.
cn2013	Zong XN, Li H. 2013. PLoS One. 8:e59569.
cr1969	Villarejos VM, Osborne JA, Payne FJ, et al. 1971. J Trop Pediatr 17(monogr. 12):31–43.
cs1951	Vignerová J, Bláha P. 1998. In: Bodzsár BE, Susanne C, editors. Secular growth changes in Europe. Budapest: Eötvös University Press. p 93–107.
cs1961	Vignerová J, Bláha P. Secular growth changes in Europe. In: Bodzsár BE, Susanne C, editors. Budapest: Eötvös University Press. p 93–107.
cs1981	Vignerová J, Bláha P. 1998. Secular growth changes in Europe. In: Bodzsár BE, Susanne C, editors. Budapest: Eötvös University Press. p 93–107.
cs1991	Vignerová J, Bláha P. 1998. Secular growth changes in Europe. In: Bodzsár BE, Susanne C, editors. Budapest: Eötvös University Press. p 93–107 and Vignerova J. 2001. Pers. commun.
cu1964	Laska-Mierzejewska T. 1970. Hum Biol 42:581–597.
cy2000	Savva SC, Kourides Y, Tornaritis M, et al. 2001. Obes Res 9:754–762.
cz2001	Vignerova J, Riedlova J, Blaha P, et al. 2006. 6th Nation-wide Anthropological Survey of Children and Adolescents 2001. Czech Republic. Prague: PrF UK, SZU.
ddr1961	Sager G. 1987. Gegenbaurs Morphol Jahrb 133:203–215.
ddr1967	Oehmisch W. 1970. Deutsche Akademie für Ärztliche Fortbildung, Berlin.
ddr1970	Oehmisch W. 1976. Ärztekalender der DDR. Volk u. Berlin: Gesundheit.
ddr1986	Flügel B, Greil H, Sommer K. 1986. Anthropologischer Atlas. Tribüne. Berlin.
ddr1991	Greil H. 1997. Homo 48(1):33–53.
de1893	Pirquet C. 1913. Zeitschr Kinderheilkd O. VI:253–262.
de1933	Schlesinger E. 1930. Zschr Kinderhk 49:159–178.
de1950	Brock J. 1954. Biologische Daten für den Kinderarzt. Grundzüge einer Biologie des Kindesalters. Bd.1, 2nd ed. Berlin: Springer.
de1956	Vogt D. 1959. Arch Kinderhk 159:141–156.
de1961	Sager G. 1987. Gegenbaurs Morphol Jahrb. 133:203–215.
de1976	Engelhardt I. 1977. Normalmasse für Kinder und Jugendliche im Alter von 4 bis 16 Jahren. Diss., Ulm.
de1979	Reinken L, Stolley H, Droese W, et al. 1979. Klin Pädiatr 191:556–565; Reinken L, Stolley H, Droese W, et al. 1980. Klin Pädiatr 192:25–33; and Reinken L, Oost Gv. 1992. Klin Pädiatr 204:129–133.
de1997	Hesse V, Jaeger U, Vogel H, et al. 1997. Sozialpädiatrie 20–22 and Hesse V, Bartezky R, Jaeger U, et al. 1999. Sozialpädiatrie 542–553.
de2001	Kromeyer-Hauschild K, Wabitsch M, Kunze D, et al. 2001. Monatsschr Kinderheilkd 149:807–818.
de2004	Schwandt P, Kelishadi R, Haas GM. 2008. World J Pediatr 4:259–266 and Haas GM, Liepold E, Schwandt P. 2011. World J Pediatr 7:16–23.
de2009	Wabitsch M, Mo A, Hauner H, Kromeyer-Hauschild K, et al. 2009. Therapie der Adipositas im Kindes und Jugendalter.
de2011	Schaffrath Rosario A, Schienkiewitz A, Neuhauser H. 2011. Ann Hum Biol 38:121–130.
dk1977	Andersen E, Hutchings B, Jansen J, et al. 1982. Ugeskrift for Laeger 144:1760–1765.
dk2010	Nielsen AM, Olsen EM, Juul A. 2010. Act Paediatr 99:268–278.
ee1996	Grünberg H, Adojaan B, Thetloff M. 1998. Kasvamine ja kasvuhäired. Metoodiline juhend laste füüsilise arengu hindamiseks. Tartu Ülikool.
es1952	Muro A, Acena A, Vivanco F. 1954. Rev Clin Esp 53:360–363.
es1985	Hernández M, Castellet J, Narvaíza Jl, et al. 1988. Curvas y tablas de crecimento. Fundación F. Orbegozo., Bilbao.
es1985	Moreno Esteban B, Monereo Megias S, Moreno Esteban FJ, et al. 1987. Salud Rural IV,2.
es1993	Hernández M, Sánchez E, Sobradillo B. 1994. Curvas y tablas de crecimiento. Pers. comm.
es2003	Ferrandez Longas A. 2003. Studio longitudinal del crecimiento y desarrollo. Spain: Centro Andrea Prader. Edita Gobierno de Aragon.
es2005	Ferrandez Longas A, Baguer L, Labarta JI, et al. 2005. Pediatr Endocrinol Rev 2(Suppl 4):423–642.
es2008	Carrascosa Lezeano, Fernandez Garcia, Ferrandez Longas, et al. 2008. Estudio Transversal Espagnol de Crecimiento. Book (Yvonne Schönbeck, 2012. pers. comm.).
et1965	Dellaportas GJ. 1969. Hum Biol 41:218–222.
fi1960	Bäckström-Järvinen L. 1964. Ann Paediatr Fenni 10(Suppl), 23:7–116.
fi1971	Bäckström L, Kantero R-L. 1971. In: Hallmann N, Bäckström L, Kantero R-L, Tiisala R, editors. Studies on growth of Finish children from birth to ten years. Acta Paediatr Scand Suppl 220:9–12.
fi2011	Dunkel. 2011. Personal communication.

TABLE 1. Continued

fr1979	Sempe M. 1979. Auxologie. Methode et sequences. Paris.
fr2004	Deheeger M, Rolland-Cachera MF. 2004. Arch Pediatr 11:1139–1144.
gb1953	Provis HS, Ellis RWB. 1955. Arch Dis Child 30:328–337.
gb1965	Tanner JM, Whitehouse RH, Takaishi M. 1966. Arch Dis Child 41:454–71 and Tanner JM, Whitehouse RH, Takaishi M. 1966. Arch Dis Child 41:613–635.
gb1990	McCarthy HD, Jarrett KV, Crawley HF. 2001. Eur J Clin Nutr 55:902–907.
gb1995	Dangour AD, Schilg S, Hulse JA, et al. 2002. Ann Hum Biol 29:290–305.
gb1996	British Growth Reference 1990, revised Sept 1996. Freeman JV et al. 1995. Arch Dis Child 73:17–24. Cole TJ, et al. 1995. Arch Dis Child 73:25–29. Cole TJ, et al. 1998. Stat Med 17:407–429. Dangour AD, et al. 2002. Ann Hum Biol 29:290–293.
gm1975	Billewicz WZ, McGregor IA. 1982. Ann Hum Biol 9:309–320.
gr1928	Papadimitriou A. 1998. Personal communication.
gr1931	Papadimitriou A. 1998. Personal communication.
gr1945	Choremis CB. 1948. The childs nutrition in Greece. Acta Paediatr 36:120–128.
gr1963	Papadimitriou A. 1998. Personal communication.
gr1997	Pantsiotou SK, Koutras AD. 1997. Horm Res 53S2:31.
gr2001	Papadimitriou A. 2004. Personal communication.
gt1973	Johnston FE, Borden M, MacVean RB. 1973. Hum Biol 45:627–641.
gt1988	Martorell R, Schroeder DG, Rivera JA, Kaplowitz HJ. 1995. J Nutr 125(4 Suppl):1060S–1067S.
gy1964	Doornbos L, Jonxis JHP, Visser HKA. 1968. Hum Biol 40:396–415.
gy1996	Dangour AD. 2001. Ann Hum Biol 28:649–663.
hk1963	Leung SSF, Lau JTF, Xu YY, et al. 1996. Ann Hum Biol 23:297–306.
hk1993	Leung SSF, Lau JTF, Xu YY, et al. 1996. Ann Hum Biol 23:297–306.
hr1951	Prebeg Z, Juresa V, Kujundzic M. 1995. Ann Hum Biol 22:99–110.
hr1964	Prebeg Z, Juresa V, Kujundzic M. 1995. Ann Hum Biol 22:99–110.
hr1973	Buzina R. 1976. Am J Clin Nutr 29:1051–1059.
hr1973	Prebeg Z, Juresa V, Kujundzic M. 1995. Ann Hum Biol 22:99–110.
hr1976	Buzina R. 1976. Am J Clin Nutr 29:1051–1059.
hr1982	Prebeg Z, Juresa V, Kujundzic M. 1995. Ann Hum Biol 22:99–110.
hr1991	Prebeg Z, Juresa V, Kujundzic M. 1995. Ann Hum Biol 22:99–110.
hu1920	Bodzsár ÉB. 1998. Secular growth changes in Europe. In: Bodzsár BE, Susanne C, editors. Budapest: Eötvös University Press. p 175–205.
hu1958	Eiben O. 1988. Humanbiol Budapest Suppl. 6 and Eiben OG, Toth GA, van Wieringen JC. 2007. Hum Ecol Special Issue 15:9–16.
hu1968	Eiben O. 1988. Humanbiol Budapest Suppl 6 and Eiben OG, Toth GA, van Wieringen JC. 2007. Hum Ecol Human Ecology Special Issue 15:9–16.
hu1976	Pantó E. 1982. Anthrop Anz 40:33–44.
hu1978	Eiben O. 1988. Humanbiol Budapest Suppl 6 and Eiben OG, Toth GA, van Wieringen JC. 2007. Hum Ecol Human Ecology Special Issue 15:9–16.
hu1988	Eiben O. 1988. Humanbiol Budapest Suppl 6 and Eiben OG, Toth GA, van Wieringen JC. 2007. Hum Ecol Human Ecology Special Issue 15:9–16.
hu1994	Nemeth A, Bodzsar EB, Eiben O. 1999. Anthrop Anz 57:325–337.
hu1998	Eiben OG, Toth G. 2000. Coll Anthropol 24:431–441 and Eiben OG, Toth GA, van Wieringen JC. 2007. Hum Ecol Special Issue 15:9–16.
hu2003	Bodszar EB, Zsakai A. 2012. Body development status of Hungarian children and adolescents. Hungarian National Growth Study 2003-3006. Plantin Kiado. Budapest.
hu2006	Joubert K. No date. Results of the Hungarian Longitudinal Child Growth Study - From birth to the age of 18 years. Budapest.
hu2009	Joubert K. 2008. Personal communication.
ie1987	Hoey HMCV, Tanner JM, Cox LA. 1987. Acta Paediatr 338:1–31.
in1966	Hauspie RC, Das SR, Preece MA, et al. 1980. Ann Hum Biol 7:429–441.
in1967	Phadke MV. 1968. Ind J Med Res 56:850–857.
in1969	Ulijaszek S. 1998. Personal communictions.
in1969	Malhotra R. 1986. Thoracic adaptation of high altitude. Anthrop Anz. 44:355–359.
in1971	Raghavan KV, Singh D, Swaminathan MC. 1971. Indian J Med Res 59:648–654.
in1989	Khadilkar. 2011. Personal communication.
in1992	Reddy PYB, Papa Rao A. 2000. Ann Hum Biol 27:67–81.
in1996	Rao S. 2001. Linear components of growth among rural Indian children. In: Dasgupta P, Hauspie R, editors. Perspectives in human growth, development and maturation. Boston, Dordrecht, London: Kluwer Academic Publ.
in2000	Gerver WJM, de Bruin R, Zwaga N, et al. 2000. Acta Med Auxol 32:93–103.
in2007	Khadilkar. 2011. Personal communication.
in2010	Talwar I, Sharma K, Kapur S. 2010. Ann Hum Biol 37:536–553.
ir1992	Hosseini M, Carpenter RG, Mohammed K. 1998. Ann Hum Biol 25:237–247 and Hosseini M, Carpenter RG, Mohammed K. 1999. Ann Hum Biol. 26:527–535.
it1950	Cotellessa G, Corradi G, De Matteis F. 1951. Minerva Padiatr 3:36–40.
it2006	Cacciari E, Milani S, Balsamo AN, et al. 2006. J Endocrinol Invest 29:581–593.
jp1945	Newman MT, Eng RL. 1947. Am J Phys Anthrop NS 5:113–157.
jp1952	Hagen W. 1961. Wachstum und Gestalt. In: Hagen W, Paschau G, Paschau R, editors. Thieme: Stuttgart. p. 26–106.
jp1953	Greulich WW. 1957. Am J Phys Anthropol 15:489–515.
jp1955	Takahashi E, Atsumi H. 1955. Hum Biol 27:65–74.
jp1957	Greulich WW. 1957. Am J Phys Anthropol 15:489–515.
jp1957	Tanner JM, Hayashi T, Preece MA, et al. 1982. Ann Hum Biol 9:411–423.
jp1960	Ministry of Education, Culture, Sports, Science and Technology. Report on school health survey 2003. 2004. Tokyo: National Printing Bureau. p. 130–133 and Satake T. 2007. Personal communication.
jp1970	Ministry of Education, Culture, Sports, Science and Technology. Report on school health survey 2003. 2004. Tokyo: National Printing Bureau. p 130–133 and Satake T. 2007. Personal communication.
jp1977	Tanner JM, Hayashi T, Preece MA, et al. 1982. Ann Hum Biol 9:411–423.
jp1980	Ministry of Education, Culture, Sports, Science and Technology. Report on school health survey 2003. 2004. Tokyo: National Printing Bureau. p 130–133 and Satake T. 2007. Personal communication.

TABLE 1. Continued

jp1990	Ministry of Education, Culture, Sports, Science and Technology. Report on school health survey 2003. 2004. Tokyo: National Printing Bureau. p 130–133 and Satake T. 2007. Personal communication.
jp1998	Hattori K, Hirohara T. 2002. Am J Hum Biol 14:275–279.
jp2000	Ministry of Education, Culture, Sports, Science and Technology. Report on school health survey 2003. 2004. Tokyo: National Printing Bureau. p130–133 and Satake T. 2007. Personal communication.
lt2000	Tutkuviene. 2009. Personal communication.
ng1965	Rea JN. 1971. Hum Biol 43:46–63.
nl1956	van Wieringen JC. 1972. Review, tables and graphs in English belonging to Secular changes of growth. Leiden: Netherlands Institute for Preventive Medicine TNO.
nl1963	van Wieringen JC. 1972. Review, tables and graphs in English belonging to Secular changes of growth. Leiden: Netherlands Institute for Preventive Medicine TNO.
nl1965	van Wieringen JC. 1972. Secular changes of growth. 1964-1966 height and weight surveys in the Netherlands in historical perspective. Leiden: Netherlands Institute for Preventive Medicine TNO.
nl1966	van Wieringen JC. 1972. Review, tables and graphs in English belonging to Secular changes of growth. Leiden: Netherlands Institute for Preventive Medicine TNO.
nl1997	Fredriks AM, Buuren Sv, Burgmeijer RJF, et al. 2000. Ped Res 47:316–323.
nl2009	Schönbeck Y, Talma H, van Dommelen P, et al. 2011. PloS One 6:e27608.
no1974	Waaler PE. 1983. Acta Paediatr Suppl 308:1–41.
no2013	Júlíusson PB, Roelants M, Nordal E, et al. 2013. Ann Hum Biol 43:220–227.
p1996	Sousa B, Oliveira BM, de Almeida MD. 2012. Ann Hum Biol 39:526–529.
pt2007	Sousa B, Oliveira BM, de Almeida MD. 2012. Ann Hum Biol. 39:526–529.
pe1966	Frisancho AR. 1966. Human growth in a high altitude Peruvian population. M.A. Thesis. Pennsylvania State University.
pe1984	Leatherman TL, Carey JW, Thomas RB. 1995. Am J Phys Anthropol 97:307–321.
pe2001	Pawson IG, Hiucho L, Muro M, et al. 2001. Am J Hum Biol 13:323–340.
pg1969	Wark L, Malcolm LA. 1969. Med J Australia 2:129–136.
pg1970	Malcolm LA. 1970. Hum Biol 42:293–328.
pg1984	Norgan NG. 1995. Ann Hum Biol 6:491–513.
pg1994	Tracer DP, Sturt RJ, Sturt A, et al. 1998. Am J Hum Biol 10:483–493.
pk1989	Karlberg J, Ashraf RN, Saleemi M, et al. 1993. Acta Paediatr 390:119–149.
pk2013	Mushtaq, et al. 2012. BMC Pediatrics 12:31.
pl1938	Jasicki B. 1965. Rozwoj mlodziezy krakowskiej. Mat i Prace Antr 69 z.2:77–130. after: Woronkowicz A, Cichocka BA, Kowal M, et al. 2012. Am J Hum Biol 24:626–632.
pl1959	Wolanski N. 1961. Hum Biol 33:283–292.
pl1971	Dutkiewicz W. 1993. Antromotoryka 10:35–55.
pl1971	Krawczynski M, Krzyzaniak A. 1989. Ped Pol 64:40–52.
pl1972	Bielicki T, Hulanicka B. 1998. Secular trend in stature and age at menarche in Poland. In: Bodzsár BE, Susanne C, editors. Secular growth changes in Europe. Budapest: Eötvös University Press. p 263–279.
pl1983	Chrzanowska M, Golab S, Bochenska Z, et al. 1988. Dziecko Krakowskie. Poziom rozwoju biologicznego dzieci i mlodziezy miasta Krakowa. Monografie, AWF Krakow, 34. after: Woronkowicz A, Cichocka BA, Kowal M, et al. 2012. Am J Hum Biol 24:626–632.
pl1986	Chrzastek-Spruch H, Susanne C, Hauspie R. 1990. Stud Hum Ecol 9:179–197.
pl1986	Dutkiewicz W. 1993. Antromotoryka 10:35–55.
pl1988	Stolarczyk H, Malinowski A. 1996. Z Morph Anthrop 81:167–177.
pl1996	Bozkowa K. 2001. Medycyna wieku rozwojowego, Warszawa, Poland.
pl2010	Woronkowicz A, Cichocka BA, Kowal M, et al. 2012. Am J Hum Biol 24:626–632.
pl2011	Kulaga Z, Litwin M, Tkaczyk M, et al. 2011. Eur J Pediatr 170:599–609.
ru1976	Godina E. 1999. Personal communication.
ru1977	Godina E. 1999. Personal communication.
ru1984	Godina E. 1999. Personal communication.
ru1985	Godina E. 1999. Personal communication.
se1976	Karlberg P, Taranger J. 1976. Acta Paediatr Scand Suppl. 258:7–76.
se2002	Wikland KA, Luo ZC, Niklasson A, et al. 2002. Acta Paediatr 91:739–764 and He Q, Wikland KA, Karlberg J. 2000. Acta Paediatr 89:582–592.
se2006	Werner B, Lennart B. 2006. Acta Paediatr 95:600–613.
si1940	Stefancic M, Tomazo-Ravnik T. 1998. Secular growth changes in Europe. In: Bodzsár BE, Susanne C, editors. Budapest: Eötvös University Press. p 281–295.
si1970	Stefancic M, Tomazo-Ravnik T. 1998. Secular growth changes in Europe. In: Bodzsár BE, Susanne C, editors. Budapest: Eötvös Univerity Press. p 281–295.
si1984	Stefancic M, Arko U, Brodar V, et al. 1996. Ocena, telesne rasti in razvoja, otrok in mladine v Ljubljani. Biotechnical faculty, University of Ljublijana.
si1991	Stefancic M, Arko U, Brodar V, et al. 1996. Ocena, telesne rasti in razvoja, otrok in mladine v Ljubljani. Biotechnical faculty, University of Ljublijana.
sk1971	Prokopec M, Lipková V, Zlámalová H, et al. 1978. Cs Pediatr 33:223–227.
sk1988	Hajnis K. 1993. Anthrop Anz 51:207–224.
sk1991	Ševcíková L, J. Nováková, J. Hamade, et al.2004. Rast a vý vojové trendy slovenský ch detí a mlá dež e za posledných 10 rokov.
Sk2001	Ševcíková L, J. Nováková, J. Hamade, et al. 2004. Rast a vý vojové trendy slovenský ch detí a mlá dež e za posledných 10 rokov.
so1971	Grassivaro Gallo P, Franceschetti Mestriner M. 1980. Hum Biol 3:547–561.
th1957	Vathakanon R, Chavlittamrong B. 1978. J Med Ass Thailand 61:29–41.
th1975	Chavalittamrong B, Vathakanon R. 1978. J Med Assoc Thai 61 (Suppl 2):1–28.
th1986	Chavalittamrong B, Tantiwongse P. 1987. J Med Assoc Thai 70 (Suppl 1):1–40.
th1986	Chavalittamrong B, Tarnpradub S, Vanprapar N. 1989. J Med Ass Thai 72:185–192.
tr1999	Okten A, Can G, Kalyoncu MD. 1999. Acta Med Auxol 31:87–93.
ug1962	Burgess AP, Burgess HJL. 1964. Hum Biol 36:177–193.
usa1864	Engerman. 1998. In: Komlos J, Cuff T. Classics in anthropometric history. Scriptae Mercaturae Verlag. p 458.
usa1926	Herskovits MJ. 1927. Anthrop Anz 4:293–316.
usa1934	Meredith HV. 1935. Univ Iowa Stud Child Welf 11;3:1–128.
usa1943	Vickers V, Stuart HC. 1943. J Pediatr 22:155–170.
usa1952	Eppright ES, Sidwell VD. 1954. J Nutr 54:543–556.

TABLE 1. Continued

usa1954	Tuddenham RD, Snyder MM. 1954. University of California publications in child development. Vol 1. In: Jones HE, Landreth C, Macfarlane JW, editors. London: Cambridge University Press. p. 183–364.
usa1959	Reed RB, Stuart HC. 1959. Pediatrics 24:904–921.
usa1965	Verghese KP, Scott RB, Teixeira G, et al. 1969. Pediatrics 44:243–247.
usa1966	McCammon RW. 1970. Human growth and development. Thomas, Illinois.
usa1970	Garn M, Clark DC. 1975. Pediatrics 56:306–319.
usa1985	Himes JH, Roche AF. 1986. Hum Biol 58:737–750.
usa1985	Tanner JM, Davies PSW. 1985. J Pediatr 107:317–329.
usa1994	Ryan AS, Roche AF, Kuczmarski RJ. 1999. Am J Hum Biol 11:673–686.
usa1984	Martorell R, Malina RM, Castillo RO, et al. 1988. Hum Biol. 60:205–222.
WHO2011	http://www.who.int
za1988	Henneberg M, Louw GJ. 1998. Am J Hum Biol. 10:73–85.

represents the compromise that considers both the limited set of height, weight, or BMI values of our population of interest, and the global patterns of height, weight, or BMI obtained from the Principal Component Analysis. The new synthetically generated curves describe mean values for height, weight, and BMI from 0 to 18 years. Centiles can be added based on lists of heuristic standard deviations for height, and lists of L and S for weight and BMI (Hermanussen, 2013).

Step 1: Finding Principal Components.

The database for the suggested approach is constructed as follows. From some 2,000 growth studies originally obtained from various libraries and the author's personal archives, we selected 196 female and 197 male longitudinal and cross-sectional studies with data on height from 53 countries since 1831 (Table 1) according to the following criteria:

1. Data on mean height available from at least seven consecutive annual age groups up to the age of at least 16 years (girls), and 17 years (boys); a time span of 7 years was considered long enough for an appropriate estimate of a population's growth curve.
2. Average number of participants per age cohort > 20.
3. Representative samples; cohorts of school children from one particular school type, small war, or immediate post-war cohorts, and cohorts with no distinction between the sexes were excluded from the analysis.
4. Plausible patterns of mean height increments; studies presenting cohorts where mean height between subsequent annual cohorts decreased,or studies with unexplained large positive height increments in subsequent annual cohorts were rejected.

Studies with data on weight were selected using the same criteria. The weight studies were a subset of the height studies as all studies selected for data on weight also contained data on height. Eighty seven female and eighty nine male studies were selected for weight analysis.

Most historic growth studies only provide means of height and weight, but lack BMI. In order not to lose the historic studies for analysis, we estimated crude approximations of the mean BMI as the mean weight divided by the square of the mean height. Noting that the probability limit of this approximation meets the true value, we used 48 male and 24 female growth studies in which mean height and weight for age, and mean BMI for age was available to highlight the accuracy of this approximation. The differences between real and approximate mean values of BMI are 0.04 (SD 0.24) for both sexes, the differences are symmetrically distributed and do not depend on age (Fig. 3).

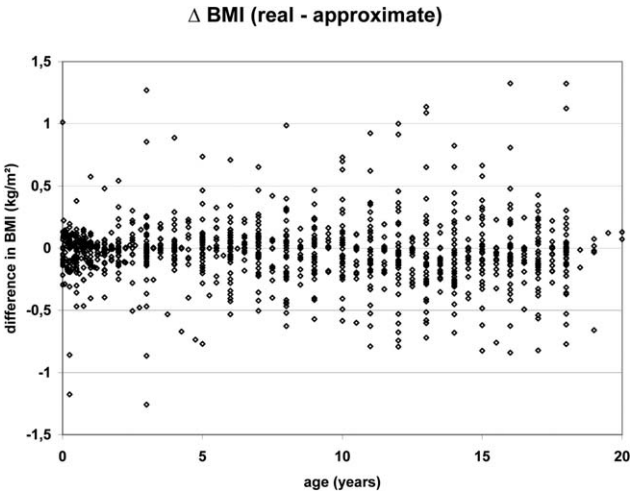


Fig. 3. Difference between observed and approximate BMI.

In spite of the criteria mentioned, the present selection of 196 female and 197 male height studies still markedly differed in design, apparent quality of execution, and sample size. Yet, we deliberately refrained from establishing more criteria than those mentioned. Otherwise, we might have lost much of the historic information. Instead, we decided to upweight large studies by doubling the 47 studies with more than 100 subjects per age cohort. Each of the large studies was then counted as two studies in the following analysis. As the incremental patterns of the mean values for height and weight were less irregular in the large studies, upweighting the large studies slightly reduced the mean variance, but did not significantly alter the outcome of the Principal Component Analysis. For reasons of plausibility, we kept the doublings of the 47 large studies for further analysis to better represent the numerical priority of these studies.

A recurring limitation observed frequently and not limited to historical cohorts is lacking information about the whole age range from birth to maturity. Several studies lack data at birth and during infancy, others end before maturity was reached, or lack certain age groups. To utilize as much information as possible and make the database accessible for Principal Component Analysis, we decided to impute missing data (Buuren, 2012), rather than to exclude incomplete datasets in order to maintain

important information from many historic studies and most studies from developing countries. We imputed 1,294 data points (means) in the height matrix of the male and 1,322 data points in the height matrix of the female studies, resulting in 196 female and 197 male full matrices with a total of 9,039 height data points, and 4,048 data points on weight and BMI at 0-0.25-0.5-0.75-1.0-1.5-2-3-4-5-6-7-8-9-10-11-12-13-14-15-16-17-18 years of age. To check adequacy of imputation and point at characteristics of the used datasets, mean values for height of all studies (only age 2–18 years) underwent Preece–Baines modeling (Preece and Baines, 1978). Although several other techniques exist to model growth from birth to maturity (e.g., Hauspie and Molinari, 2004, and the JPA2 model, Jolicoeur et al., 1992), the Preece–Baines modeling was chosen on purpose for its robustness. The model offers five parameters that can be used to derive age and height at "take-off" (minimum in growth velocity at the end of the juvenile period); age and height at adolescent "peak height velocity "(age at maximum pubertal growth velocity); and it provides an estimate of final height. The model implies an adolescent growth spurt and fails in growth data that lack an apparent adolescent growth spurt. Adolescent growth is defined as that increase in height that takes place after the age at take-off. As Preece–Baines modeling identifies the age at which adolescents grow at peak height velocity, the model was used to characterize tempo differences between studies.

Thereafter, to characterize global factors Principal Component Analysis was applied to the mean values for each of the six reference combinations arising from combining gender with height, weight, and BMI, where each of the reference combinations contains S_r, $r = 1, \ldots, 6$ reference studies. Given this, mean values of reference combination r at time t where characterized as

$$m_r(t) = \iota_{S_r}\beta_r(t) + \alpha_r C_r(t) + e_r(t), \quad t = 1, \ldots, K,$$

where $m_r(t)$ denotes the $S_r \times 1$ vector of mean values for reference combination r at time t, ι_{S_r} denotes a $S_r \times 1$ vector of ones, $\beta_r(t)$ denotes the global mean value of the S_r studies in reference combination r at time t, α_r denotes the $S_r \times K$ matrix of loading parameters often also referred to as scores, $C_r(t)$ the $K \times 1$ vector of factor or component values at time t, and $e_r(t)$ is an $S_r \times 1$ vector of errors assumed to be normally, independently, and identically distributed with mean zero and covariance matrix $\Sigma_r = \mathrm{diag}(\sigma_r^2(t), \ldots, \sigma_r^2(t))$. The aim of the Principal Component Analysis is to obtain loadings of components that are uncorrelated. Analysis of the 23 age groups from birth to maturity results in $K = 23$ components, but the full spectrum of all 23 components was not needed. When restricting the maximum number of components K to five, we were still able to explain 98.4% of the between-study variance in mean height, 99.2% of this variance in mean weight, and 93% (females) and 94% (males) of this variance in mean BMI. The obtained global mean values for height, weight, and BMI, together with the five factors for each reference combination and the residual variances at each of the 23 time points, are displayed in Tables (2–4), respectively. Together with the global mean values for each reference combination, the components define a growth model that describes growth from birth to maturity.

Step 2: Characterizing the most likely growth curve for the population of interest.

The global factors of annual mean values for height, weight, and BMI and the information about the distribution of these factors can now be used to address a different goal. Given an arbitrary set of mean values for a particular new population of interest we ask: *How can we characterize the most likely growth curve for this group*? Given that the new population can be linked to one of the considered reference combinations, the true—but unknown—mean population growth curve for this new population takes the form

$$m_{\text{new}} = \beta_r + \alpha_{\text{new}}\ C_r + e_{\text{new}},$$

where m_{new} denotes the vector of mean values observed for this new population not necessarily covering all 23 considered time points, β_r the corresponding set of global means, α_{new} the population specific vector of loadings, and C_r the corresponding matrix of five factors matching the observed time points for this population. Further, the vector of errors e_{new} is assumed to be normally, independently, and identically distributed with mean zero and variance $\Sigma_{r,\text{new}}$. $\Sigma_{r,\text{new}}$ has diagonal structure and collects on the main diagonal all variances $\sigma_r^2(t)$ for the observed time points. A valid prediction for unobserved mean values for this population at time t can be based on

$$m_{\text{new}}^{\text{pred}}(t) = \beta_r(t) + \alpha_{\text{new}} C_r(t),$$

and thus requires knowledge of the population specific vector of loadings α_{new}. To obtain an estimate for α_{new}, we use a Bayesian rationale. As we assume that the new population is similar to those included in the pool of reference studies, we assume a multivariate normal prior distribution for α_{new} with expected value given as the mean of the loadings matrix α_r, which by properties of the loadings is zero, and empirical covariance matrix of the estimated loadings matrix $V_{\bar{\alpha}_r}$, that is, $V_{\bar{\alpha}_r} = \frac{1}{S_r}\sum_{p=1}^{S_r} \alpha_{p,r}' \alpha_{p,r}$, with $\alpha_{p,r}$ denoting a row vector of the loading matrix α_r, which by properties of the loadings has diagonal structure, see Table 5. This results in

$$\alpha_{\text{new}} \sim N(0, V_{\bar{\alpha}_r}).$$

As the likelihood for the mean values of the new population observed at grid of time points $\bar{t}$ denoted as $m_{\text{new}}(\bar{t})$ takes the form of a normal distribution, with the mean given as $\beta_r(\bar{t}) + \alpha_{\text{new}} C_r(\bar{t})$, where $\beta_r(\bar{t})$ denotes the vector of global mean values corresponding to observed time points $\bar{t}$, and the covariance given as $\Sigma_r(\bar{t})$, α_{new} has then a posteriori a normal distribution given as

$$\alpha_{\text{new}} \sim N\Bigg(\Bigg(\Big(C_r(\bar{t})'\Sigma_r(\bar{t})^{-1}C_r(\bar{t})\Big)^{-1} + V_{\bar{\alpha}_r}^{-1}\Bigg)^{-1}$$
$$\Big(C_r(\bar{t})'\Sigma_r(\bar{t})^{-1} m_{\text{new}}(\bar{t})\Big),\ \Bigg(\Big(C_r(\bar{t})'\Sigma_r(\bar{t})^{-1}C_r(\bar{t})\Big)^{-1} + V_{\bar{\alpha}_r}^{-1}\Bigg)^{-1}\Bigg).$$

Using the expected mean value of this distribution provides the best predictions incorporating both, knowledge

TABLE 2. Global means (cm), Principal Components (cm), and time-specific residual variances of height

Females

Age	Mean height	$C_1^{(1)}$	$C_1^{(2)}$	$C_1^{(3)}$	$C_1^{(4)}$	$C_1^{(5)}$	σ_1^2
0	49.99	0.18	0.25	−0.37	−0.14	−0.32	0.25
0.25	59.96	−0.11	0.50	0.03	−0.63	−0.44	0.46
0.5	66.31	0.34	0.57	−0.42	−0.48	−0.38	0.13
0.75	70.59	0.63	0.62	−0.56	−0.53	−0.28	0.15
1	74.26	0.98	0.83	−0.57	−0.66	−0.21	0.12
1.5	80.23	1.59	0.85	−0.65	−0.49	0.11	0.17
2	85.48	2.11	0.97	−0.78	−0.20	0.26	0.28
3	93.91	2.59	0.88	−0.78	0.33	0.45	0.43
4	101.29	2.87	1.13	−0.96	0.31	0.37	0.33
5	107.79	3.35	0.79	−0.49	0.45	−0.01	0.35
6	114.10	3.68	0.64	−0.22	0.65	−0.13	0.37
7	119.98	3.95	0.57	−0.08	0.45	−0.54	0.40
8	125.42	4.13	0.28	0.25	0.34	−0.33	0.29
9	130.72	4.39	0.27	0.47	0.21	−0.34	0.33
10	136.36	4.61	0.44	0.77	0.08	−0.29	0.33
11	142.33	5.03	0.67	0.99	−0.17	0.02	0.37
12	148.39	5.42	0.50	1.03	−0.32	0.20	0.23
13	153.65	5.50	−0.02	0.65	−0.35	0.45	0.26
14	157.31	5.18	−0.59	0.13	−0.34	0.37	0.26
15	159.35	4.87	−1.04	−0.29	−0.25	0.17	0.33
16	160.43	4.61	−1.35	−0.54	−0.13	−0.06	0.25
17	160.99	4.50	−1.46	−0.66	−0.05	−0.12	0.25
18	161.36	4.35	−1.60	−0.74	0.11	−0.28	0.27

Males

Age	Mean height	$C_2^{(1)}$	$C_2^{(2)}$	$C_2^{(3)}$	$C_2^{(4)}$	$C_2^{(5)}$	σ_2^2
0	50.46	0.34	0.39	−0.17	0.02	0.23	0.37
0.25	61.11	0.29	0.67	−0.03	0.79	0.58	0.33
0.5	67.60	0.81	0.98	−0.18	0.55	0.42	0.25
0.75	71.86	1.17	0.82	−0.25	0.31	0.36	0.14
1	75.52	1.35	1.02	−0.20	0.37	0.33	0.32
1.5	81.35	1.82	1.29	−0.18	0.42	0.11	0.30
2	86.42	2.25	1.47	−0.20	0.29	−0.04	0.40
3	94.98	2.62	1.39	−0.06	−0.26	−0.38	0.41
4	101.97	2.98	1.20	−0.21	−0.35	−0.46	0.43
5	108.53	3.27	1.07	−0.11	−0.49	−0.38	0.49
6	114.81	3.66	0.68	0.08	−0.78	−0.21	0.36
7	120.62	4.13	0.21	0.10	−0.86	0.16	0.44
8	126.10	4.52	0.00	0.15	−0.63	0.39	0.31
9	131.37	4.77	−0.07	0.21	−0.53	0.38	0.46
10	136.34	5.02	−0.17	0.27	−0.43	0.37	0.42
11	141.31	5.13	−0.27	0.41	−0.28	0.32	0.42
12	146.65	5.63	−0.34	0.74	0.01	0.22	0.42
13	152.91	6.20	−0.25	1.01	0.37	0.01	0.38
14	159.72	6.67	−0.33	1.03	0.70	−0.30	0.25
15	165.67	6.83	−0.34	0.18	0.77	−0.43	0.43
16	169.72	6.47	−0.48	−0.75	0.51	−0.35	0.29
17	171.92	6.09	−0.75	−1.32	0.14	−0.03	0.21
18	173.11	5.74	−0.85	−1.52	−0.13	0.21	0.39

The first five Principal Components explain 98.4% of the height variation in the females and 98.7% of the height variation in the males.

on study-specific partially observed mean values and knowledge on growth in the set of reference studies. These loading parameters then characterize the best, that is, a posteriori most likely, mean growth curves, which can be used to construct complete reference charts.

To result in LMS (refers to a statistical method (Cole and Green, 1992) to describe growth reference curves; M, stands for mean; S, stands for a scaling parameter; L, stands for the Box-Cox power) type reference, the above approach can be extended. It is then not only performed for mean values (M), but also for reported standard deviations (S) and reported skewness parameters (L). Having characterizations then on mean LMS parameters, these can be transformed via

$$z = \frac{\left(\frac{y}{M}\right)^L - 1}{LS}$$

into z-Scores and assuming normality into corresponding reference quantile charts (Hermanussen et al., 2012). Height can be considered normally distributed, but not weight and BMI. Yet very few studies report on weight and BMI skewness. As published earlier (Hermanussen et al., 2012), one can therefore utilize heuristic reasonable values for S and L in weight and BMI.

As the study is based on meta-analyzing published data on mean values of height, weight, and BMI, approval of an institutional ethics committee is not necessary.

TABLE 3. Global means (kg), Principal Components (kg), and time-specific residual variances of weight

Females							
Age	Mean weight	$C_3^{(1)}$	$C_3^{(2)}$	$C_3^{(3)}$	$C_3^{(4)}$	$C_3^{(5)}$	σ_3^2
0	3.25	0.09	−0.05	0.01	−0.05	0.00	0.01
0.25	5.71	−0.09	0.11	−0.02	0.01	0.03	0.05
0.5	7.39	0.08	0.01	−0.04	−0.06	−0.06	0.05
0.75	8.47	0.26	−0.06	0.01	−0.16	−0.05	0.03
1	9.33	0.48	−0.15	0.03	−0.23	−0.10	0.03
1.5	10.66	0.63	−0.17	0.01	−0.30	−0.16	0.03
2	11.82	0.71	−0.14	0.00	−0.32	−0.17	0.03
3	13.93	0.85	−0.11	−0.02	−0.36	−0.15	0.05
4	15.94	1.03	−0.07	−0.08	−0.36	−0.15	0.06
5	17.95	1.32	−0.01	−0.10	−0.37	−0.10	0.05
6	20.09	1.59	0.03	−0.18	−0.38	−0.03	0.04
7	22.54	1.87	0.05	−0.27	−0.34	0.07	0.06
8	25.16	2.22	0.20	−0.40	−0.22	0.19	0.06
9	28.03	2.60	0.37	−0.52	−0.05	0.14	0.11
10	31.37	3.03	0.64	−0.46	0.05	0.17	0.11
11	35.28	3.52	1.05	−0.37	0.19	0.11	0.07
12	40.00	4.10	1.22	0.05	0.34	−0.34	0.10
13	44.86	4.46	0.95	0.34	0.11	−0.24	0.04
14	48.86	4.54	0.38	0.48	−0.15	0.08	0.14
15	51.65	4.53	−0.34	0.61	−0.19	0.26	0.09
16	53.56	4.37	−0.89	0.33	0.08	0.18	0.11
17	54.68	4.17	−1.34	−0.11	0.27	−0.01	0.04
18	55.44	3.84	−1.76	−0.44	0.25	−0.24	0.12

Males							
Age	Mean weight	$C_4^{(1)}$	$C_4^{(2)}$	$C_4^{(3)}$	$C_4^{(4)}$	$C_4^{(5)}$	σ_4^2
0	3.37	0.09	−0.06	−0.01	−0.08	0.00	0.01
0.25	6.14	0.08	0.22	0.02	0.04	0.01	0.10
0.5	7.89	0.25	0.07	−0.05	−0.06	0.01	0.06
0.75	9.02	0.41	−0.07	−0.10	−0.13	0.02	0.07
1	9.89	0.56	−0.16	−0.11	−0.21	0.01	0.05
1.5	11.19	0.72	−0.23	−0.14	−0.29	−0.05	0.03
2	12.32	0.80	−0.27	−0.13	−0.33	−0.10	0.04
3	14.41	0.91	−0.18	−0.21	−0.38	−0.10	0.06
4	16.38	1.06	−0.20	−0.20	−0.39	−0.07	0.04
5	18.36	1.27	−0.18	−0.22	−0.37	−0.03	0.06
6	20.52	1.47	−0.13	−0.36	−0.31	0.03	0.05
7	22.96	1.81	−0.10	−0.50	−0.24	0.05	0.05
8	25.60	2.23	0.00	−0.55	−0.13	0.10	0.04
9	28.42	2.65	0.12	−0.60	−0.02	0.20	0.06
10	31.50	3.14	0.31	−0.60	0.09	0.17	0.05
11	34.79	3.64	0.69	−0.60	0.34	0.15	0.16
12	38.67	4.22	0.89	−0.43	0.23	−0.04	0.06
13	43.53	4.93	1.22	0.01	0.05	−0.15	0.12
14	49.14	5.74	1.22	0.50	−0.14	−0.43	0.06
15	54.69	6.22	0.41	0.67	−0.22	0.11	0.14
16	59.27	6.39	−0.52	0.65	−0.12	0.44	0.08
17	62.38	6.39	−1.15	0.22	0.23	0.23	0.08
18	64.51	6.06	−1.81	−0.25	0.30	−0.52	0.03

The first five Principal Components explain 99.2% of the weight variation in the females and 99.4% of the weight variation in the males.

RESULTS

Variability in growth studies

We found substantial differences between the studies. Figures 1 and 2 illustrate values for mean heights and mean BMIs of all studies. Mean height varies most around 15 years of age in males with a maximum between-study standard deviation of 7.52 cm, and around 12 and 13 years of age in females with a maximum between-study standard deviation of 6.06 cm.

Historic trends are more obvious when comparing studies from the same ethnic background. Figures 4 and 5 exemplify height of the German population in 15 male and 15 female studies since 1893 and height of the Japanese population in 12 male and 12 female studies since 1945. The figures depict the absolute differences in mean height between the national studies and the average global height curve. Historic cohorts are shorter and mature later than modern cohorts. This is particularly evident at mid-adolescence when the delay in tempo maximally contributes to the shortness observed in the historic cohorts. The figures indicate that also modern Japanese infants and young children tend to increase less in mean height than the average global curve suggests.

Preece–Baines modeling was used to highlight differences in developmental tempo, and appeared successful in most growth studies when applied for age 2–18 years. Modeling failed in female Australian aborigines (Table 1:

TABLE 4. Global means (kg/m^2), Principal Components (kg/m^2), and time-specific residual variances of BMI

Females

Age	Mean BMI	$C_5^{(1)}$	$C_5^{(2)}$	$C_5^{(3)}$	$C_5^{(4)}$	$C_5^{(5)}$	σ_5^2
0	13.03	0.13	−0.21	−0.01	0.02	−0.11	0.19
0.25	15.94	−0.23	0.04	0.77	0.02	0.07	0.03
0.5	16.85	−0.02	−0.22	0.42	−0.03	0.00	0.04
0.75	17.04	0.14	−0.38	0.22	−0.16	−0.14	0.03
1	16.94	0.38	−0.55	−0.02	−0.17	−0.18	0.04
1.5	16.55	0.35	−0.52	−0.10	−0.11	−0.04	0.04
2	16.18	0.25	−0.43	−0.06	−0.06	0.05	0.04
3	15.78	0.23	−0.29	−0.02	−0.03	0.08	0.08
4	15.52	0.29	−0.20	−0.03	−0.03	0.13	0.06
5	15.34	0.40	−0.15	−0.04	−0.02	0.13	0.05
6	15.33	0.48	−0.09	−0.01	−0.06	0.17	0.03
7	15.50	0.54	−0.04	0.00	−0.08	0.16	0.02
8	15.80	0.65	0.02	0.01	−0.09	0.19	0.03
9	16.17	0.74	0.06	0.00	−0.10	0.19	0.04
10	16.66	0.83	0.13	0.03	−0.13	0.10	0.03
11	17.20	0.85	0.23	0.05	−0.18	0.03	0.03
12	17.94	0.91	0.28	0.03	−0.17	−0.08	0.05
13	18.73	0.91	0.25	0.02	−0.12	−0.12	0.03
14	19.46	0.88	0.18	0.03	0.00	−0.19	0.03
15	20.05	0.85	0.06	0.06	0.10	−0.21	0.03
16	20.52	0.82	0.00	0.03	0.25	−0.14	0.02
17	20.85	0.78	−0.10	0.04	0.38	0.01	0.01
18	21.05	0.72	−0.20	0.00	0.45	0.14	0.03

Males

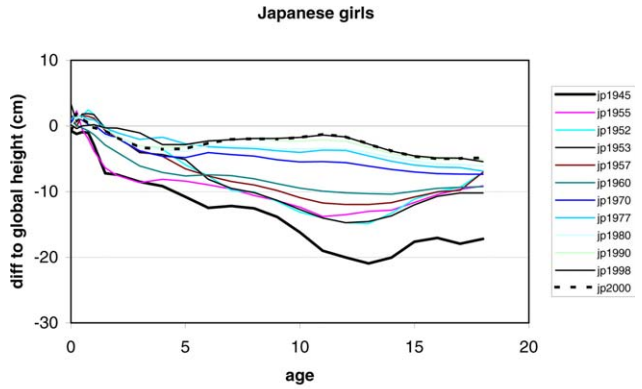
Age	Mean BMI	$C_6^{(1)}$	$C_6^{(2)}$	$C_6^{(3)}$	$C_6^{(4)}$	$C_6^{(5)}$	σ_6^2
0	13.23	0.07	−0.21	−0.00	−0.26	0.06	0.20
0.25	16.43	0.03	0.67	0.73	−0.11	−0.11	0.03
0.5	17.28	0.18	0.06	0.66	−0.04	−0.01	0.05
0.75	17.43	0.32	−0.23	0.52	−0.09	0.07	0.04
1	17.29	0.39	−0.46	0.25	−0.11	0.19	0.03
1.5	16.83	0.36	−0.54	0.13	−0.04	0.11	0.03
2	16.42	0.28	−0.45	0.11	0.01	−0.04	0.08
3	15.96	0.32	−0.31	0.13	0.03	−0.05	0.03
4	15.68	0.32	−0.22	0.12	0.08	−0.13	0.05
5	15.47	0.36	−0.21	0.10	0.09	−0.11	0.03
6	15.46	0.42	−0.14	0.10	0.14	−0.10	0.05
7	15.61	0.50	−0.09	0.12	0.17	−0.07	0.03
8	15.87	0.61	−0.06	0.07	0.17	−0.03	0.02
9	16.22	0.73	0.01	0.05	0.18	0.02	0.03
10	16.67	0.85	0.08	0.04	0.18	0.04	0.02
11	17.14	0.93	0.20	−0.01	0.16	0.10	0.03
12	17.68	0.96	0.19	−0.03	0.15	0.09	0.02
13	18.30	0.97	0.23	−0.05	0.00	0.14	0.03
14	18.96	0.99	0.19	−0.14	−0.13	0.16	0.04
15	19.63	0.98	0.16	−0.13	−0.16	0.01	0.03
16	20.29	1.00	0.05	−0.14	−0.22	−0.05	0.03
17	20.79	1.01	0.01	−0.18	−0.17	−0.14	0.04
18	21.22	1.00	−0.13	−0.14	−0.10	−0.29	0.07

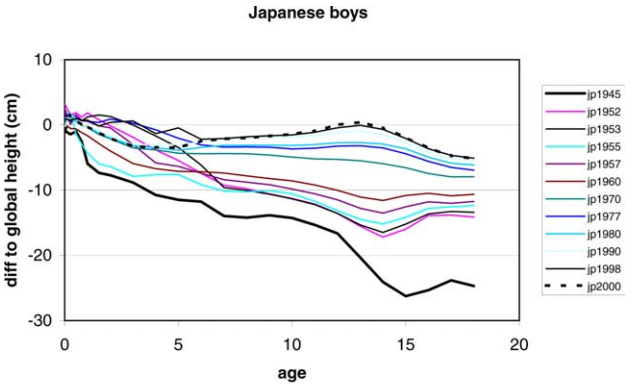
The first five Principal Components explain 92.8% of the BMI variation in the females and 94% of the BMI variation in the males.

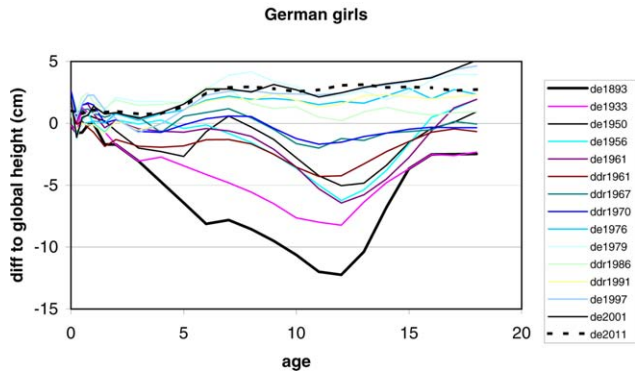
TABLE 5. Diagonal elements of empirical covariance of estimated loadings

	Female height	Male height	Female weight	Male weight	Female BMI	Male BMI
$C^{(1)}$	17.1222	17.9741	17.4873	18.6279	13.4400	14.2268
$C^{(2)}$	3.0430	2.2502	4.0340	1.5788	3.5117	3.3145
$C^{(3)}$	0.7302	0.8953	0.3312	1.0159	1.7850	2.0724
$C^{(4)}$	0.6681	0.8512	0.3107	0.3302	0.9198	0.9633
$C^{(5)}$	0.5646	0.2170	0.2256	0.2649	0.8113	0.7492

au1963), Punjabi girls and boys in 1992 (Table 1: in1992), a Tamil population in 2000 (Table 1: in2000), girls from Peru in 1966 (Table 1: pe1966), a war cohort of Slovenian girls from 1940 (Table 1: si1940), US females from 1864 (Table 1: usa1864), and a male study in 1870 from Belgium (Table 1: be1870) because it was unable to detect the adolescent growth spurt. We did not use these studies for analyzing developmental tempo. We also refrained from







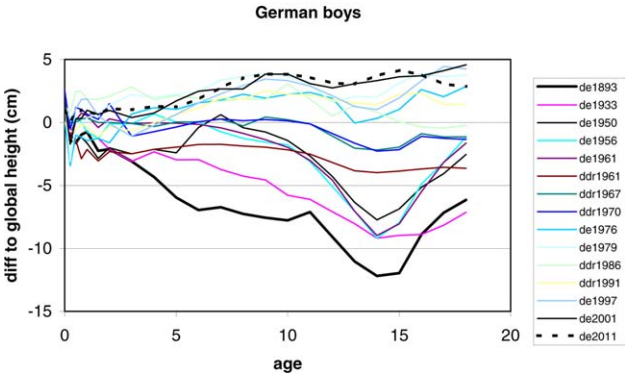


Fig. 4. Growth of Japanese and German girls. The figures depict the absolute differences in mean height between 12 Japanese growth studies since 1945 and 15 German growth studies since 1893, and the average global height curve.

Fig. 5. Growth of Japanese and German boys.

studies in whom modeled final height differed from measured final height by more than 3 cm, leaving 187 female and 187 male height studies for this analysis.

East Asians mature at faster tempo than Europeans, Mediterranean populations mature at a faster pace than Northern Europeans. To better quantify changes in developmental tempo, we correlated age at take-off and historic date in 12 male and 12 female national studies from Japan, 15 male and female national studies from Germany, and 13 male and female studies from the United States. In each of these three countries, the developmental tempo has increased throughout history. Male Japanese increased in tempo by approximately 1 week per year ($r = -0.63$, $P < 0.01$), so did the male Germans ($r = -0.59$, $P < 0.01$) and the male US Americans ($r = -0.74$, $P < 0.01$). Also, females increased in tempo by approximately 1 week per year in Japan ($r = -0.86$, $P < 0.01$), in Germany ($r = -0.67$, $P < 0.01$), and in the United States ($r = -0.60$, $P < 0.01$).

The difference between height at take-off and final height has increased too. In male Japanese, adolescent growth increased by 0.6 mm per year ($r = 0.58$, $P < 0.01$), in male Germans by 1.2 mm per year ($r = 0.77$, $P < 0.01$), and in male US Americans by 0.5 mm per year ($r = 0.54$, $P < 0.01$). Smaller increases in adolescent growth were observed in females, but due to smaller numbers this increase did not reach statistical significance in all cases. In males, adolescent growth contributed to some 60% of the secular trend in height ($P < 0.01$) in Germans, and to some 40–50% ($P < 0.01$) in Japanese and US Americans. This was similar in the females, although the trend reached significance only in Japanese and US American females ($P < 0.01$).

Similarity in growth studies

Human height, weight, and BMI curves show common traits that can be described by Principal Component Analysis. Tables (2–4) show the variation for each age cohort that is due to each of the five Principal Components. Table 6 summarizes the cumulative proportion of variance that is explained by the first five Principal Components. Five components explain 98.4% of the between-study variance in mean height, 99.2% of this variance in mean weight, and 93% (females) and 94% (males) of this variance in mean BMI. Note that Component 1 is characterized by an almost linear increase in height and weight up to mid-adolescence indicating that the main source of variance is simply tallness/shortness and heaviness/lightness at all age; that is, populations that are tall and heavy early in life will end up being tall and heavy, and vice versa. Components 2 and 3 explain variance that is located in early life and during adolescence. The contribution of all higher components is very small.

Also, the age-dependent patterns of the within-study standard deviations of height, weight, and BMI show common traits. Within-study standard deviations steadily increase from birth to mid-adolescence, and slightly

TABLE 6. Cumulative proportion (%) of explained variance of the first five Principal Components

		$C^{(1)}$	$C^{(2)}$	$C^{(3)}$	$C^{(4)}$	$C^{(5)}$
Females	Height	90.0	94.5	96.9	97.8	98.4
	Weight	91.7	97.1	98.1	98.9	99.2
	BMI	66.5	78.2	85.0	89.8	92.8
Males	Height	92.3	95.3	97.0	98.2	98.7
	Weight	94.2	97.5	98.6	99.1	99.4
	BMI	68.3	79.3	89.2	92.1	94.0

decrease thereafter. Yet, the within-study standard deviations, and also the within-study measures of skewness of weight and BMI, differ very little between the studies. We therefore decided to ignore between-study differences in variation and skewness, and for the further analysis, rather used heuristic *L* and heuristic *S* for height, weight, and BMI as published previously (Hermanussen, 2013) (data not shown in detail).

Figure 6 and Table 7 exemplify this approach. The upper part of Figure 6 depicts absolute differences in mean height in a very heterogeneous group of 14 male studies (WHO reference, three modern European, three modern Asian, three post-World-War II, two early 20th century, and two 19th century studies), and the average global height curve. The differences are large as the studies differ substantially. When assuming that height at certain age groups is known, we can generate synthetic growth curves for each of these studies. When starting with only two age groups (e.g., age 7 and 18), the differences in mean height between the 14 synthetic curves and the average global height curve already declines markedly (center part of Fig. 6) with average residuals of 0.92 cm. The residuals further shrink when more age groups are used. When using five age groups (e.g., at age 3, 7, 14, 16, and 18 years) the residuals decline to 0.45 cm. The table 7 also shows that the residuals in modern studies tend to be generally smaller than residuals in historic studies.

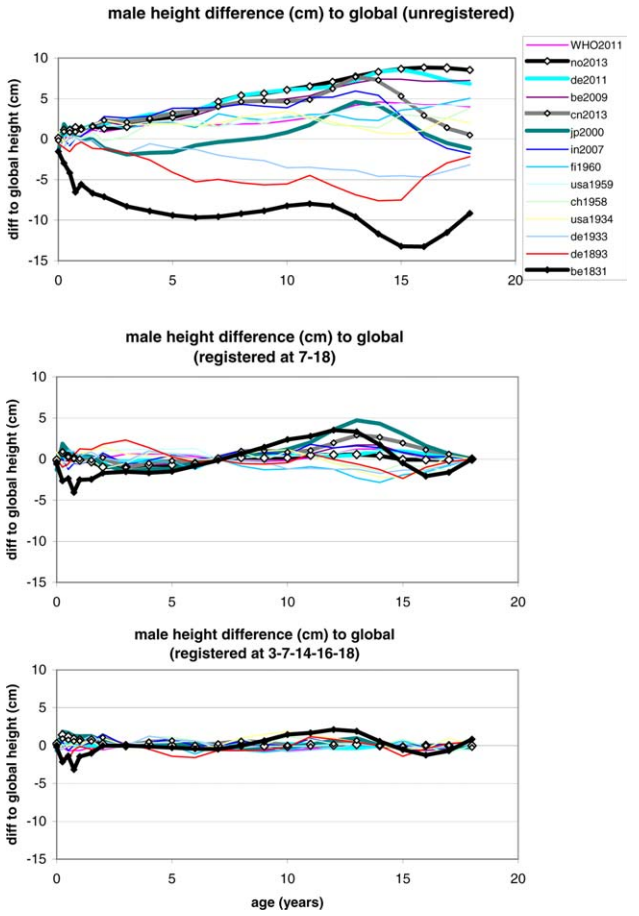


Fig. 6. Residuals in height (cm) in 14 male growth studies (WHO reference, three modern European, three modern Asian, three post-World-War II, two early 20th century, and two 19th century studies). Upper part: Absolute differences in height between the 14 studies and the average global height curve. Center part: Residuals in height of synthetic growth references when two age groups (at age 7 and 18) are known. Lower part: Residuals in height of synthetic growth references when five age groups (at age 3, 7, 14, 16, and 18) are known (Table 6).

DISCUSSION

The world-wide variation in human growth (Eveleth and Tanner, 1990) has scientifically been documented since the first half of the 19th century (Quetelet, 1869) and been attributed to genetic, nutritional, health-related, and socioeconomic circumstances (Hermanussen, 2013). Growth references are being published at irregular intervals in most developed countries. Trends in height, weight, and BMI have since been documented particularly in populations that undergo socioeconomic transition (Webb, 2008) indicating that growth references tend to be limited to specific populations within specific historic periods. Growth references should be renewed once every 10 years (Vignerová and Bláha, 1998).

We reanalyzed 197 male and 196 female historic and modern growth studies performed since 1831. All studies underwent Preece–Baines modeling for height (Preece and Baines, 1978). Preece–Baines modeling is particularly suitable for modeling age and height at take-off, age and height at peak height velocity, and thus for modeling the adolescent portion of the human growth curve. The model can be applied for individual series of longitudinal data and for population-derived cross-sectional data (Zemel and Johnston, 1994). The present data confirm current knowledge that developmental tempo differs between populations. East Asians mature at faster tempo than Europeans, Mediterranean populations mature faster than Northern Europeans. Modern populations tend to grow at a faster pace than historic populations and they show proportionally more adolescent growth (Hermanussen, 1997). The marked between-study variability in height and tempo has always led to significant uncertainty about which growth chart is the right chart to use (Radcliffe et al., 2007).

Yet, human growth shows common characteristics. We previously meta-analyzed body height, and the variation of body height in 40 male and 51 female growth studies, from 14 European countries and the United States, including the 1992 German birth cohort with more than 500,000 measurements of newborns, 10,000 measurements of 2-year old German children, more than 500,000 measurements of German school children, and six large growth

TABLE 7. Height residuals (cm) in synthetic references when derived from 2, 3, 4, or 5 known age groups, in 14 male growth studies

	(Two ages)	(Three ages)	(Four ages)	(Five ages)
	7 + 18 years	7 + 14 + 18 years	3 + 7 + 14 + 18 years	3 + 7 + 14 + 16 + 18 years
WHO2011	0.46	0.44	0.27	0.32
NO2013 Juliusson	0.47	0.35	0.10	0.10
DE2011 Schaffrath	0.45	0.27	0.22	0.22
BE2009 Roelant	0.76	0.31	0.32	0.25
CN2013 Zong	1.14	0.41	0.26	0.29
JP2000 Japan Ministry	1.96	0.78	0.34	0.35
IN2007 Khadilkar	0.68	0.47	0.39	0.33
FI1960 Bäckström	0.81	0.44	0.43	0.43
USA1959 Reed	0.50	0.61	0.35	0.29
CH1958 Heimendinger	0.80	0.63	0.61	0.60
USA1934 Meredith	1.06	0.62	0.76	0.74
DE1933 Schlesinger	0.82	0.46	0.49	0.51
DE1893 Camerer	1.06	0.83	0.88	0.81
BE1831 Quetelet	1.92	1.66	1.35	1.01
Average	0.92	0.59	0.48	0.45

surveys of Japan, and Czechoslovakia, with altogether more than 24,000,000 measurements (Hermanussen and Burmeister, 1999). We found a rigid pattern of cross-sectional body stature increment between birth and early adulthood that could be expressed by age-specific linear regression coefficients. We were able to use these linear regression coefficients for generating synthetic references for height, body weight, and BMI.

The method is still valid and currently used for harmonizing growth reference charts. Harmonizing references converts historic and/or incomplete local or national growth references into a unified interchangeable LMS format (Cole and Green, 1992). Harmonizing facilitates producing growth references "on demand," for limited regional purposes, for ethnically, socioeconomically or politically defined minorities such as German-born Turkish children and adolescents (Redlefsen et al., 2007), but also for matching geographically different groups of children and adolescents for international growth and registry studies (Hermanussen et al., 2012). Synthetic growth references generated by the previous technology are implicated into a large German medical competence network (Keller et al., 2000) and show excellent cost-benefit and a significantly better statistical agreement with the respective populations of interest than WHO references as recently exemplified by the national 2000–2002 Lithuanian reference (Hermanussen et al., 2010). Synthetic growth references can be used for plausibility checks in small datasets of populations for which height and weight references do not exist, for example, modern Maya (Bogin, personal communication, 2014), migrants, and ethnic minorities that have recently moved into the large urban centres of Europe (Kirchengast, personal communication, 2014).

Although the previous method is practical and has widely been used (Hermanussen et al., 2010; Keller et al., 2000), it lacks a proper definition of accuracy. We, therefore, decided to significantly extend the former set of data—we gathered a global set of 393 growth studies from 53 countries published since 1831—and to apply different statistical tools. We used imputation (Buuren, 2012) to fully utilize all information available in the global set of data, and instead of using linear correlations, we applied Principal Component Analysis (Bronstein and Semendjajew, 1991). Principal Component Analysis has been used in previous work describing individual growth (Hermanussen and Meigen, 2007) and has been found suitable not only to model growth, but also to assess a technical error of each of the modeled curves. We now combined Principal Component Analysis and a Bayesian rationale and instead of modeling individual growth, we now used this approach for modeling population growth.

The new methodology is applicable to any limited set of height and weight measurements of a given population; it generates a synthetic growth reference chart with LMS values from birth to maturity. Each synthetic chart is a compromise integrating (1) specific local information on height and weight and (2) the information about the global pattern of human growth provided by the Principal Components.

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LITERATURE CITED

Bogin BA. 1999. Patterns of human growth, 2nd ed. Cambridge: Cambridge Univ Press.
Bronstein IN, Semendjajew KA. 1991. Taschenbuch der Mathematik. Leipzig: Teubner.
Buuren SV. 2012. Flexible imputation of missing data. Boca Raton, FL: CRC Press, Taylor & Francis.
Cole TJ, Green PJ. 1992. Smoothing reference centile curves: the LMS method and penalized likelihood. Stat Med 11:1305–1319.
Eveleth PB, Tanner JM. 1990. Worldwide variation in human growth, 2nd ed. Cambridge: Cambridge University Press.
Fredriks AM, van Buuren S, Burgmeijer RJ, Meulmeester JF, Beuker RJ, Brugman E, Roede MJ, Verloove-Vanhorick SP, Wit JM. 2000. Continuing positive secular growth change in the Netherlands 1955-1997. Ped Res 47:316–323.
Hauspie RC, Molinari L. 2004. Parametric models for postnatal growth. In: Hauspie RC, Cameron N, Molinari L, editors. Method in human growth research. Cambridge: Cambridge University Press. p 205–233.
Hermanussen M. 1997. Plasticity of adolescent growth in boys. Am J Hum Biol 9:469–480.
Hermanussen M, editor. 2013. Auxology - studying human growth and development. Stuttgart: Schweizerbart.
Hermanussen M, Aßmann C, Tutkuviene J. 2010. Statistical agreement and cost-benefit: comparison of methods for constructing growth reference charts. Ann Hum Biol 37:57–69.
Hermanussen M, Aßmann C, Wöhling H, Zabransky M. 2012. Harmonizing national growth references for multi-centre surveys, drug monitoring, and international postmarketing surveillance. Acta Paediatr 101:78–84.
Hermanussen M, Burmeister J. 1999. Synthetic growth charts. Acta Paediatr Scand 88:809–814.
Hermanussen M, Meigen C. 2007. Phase variation in child and adolescent growth. Int J Biostat 3:1–16.
Jolicoeur P, Pontier J, Abidi H. 1992. Asymptotic models for the longitudinal growth of human stature. Am J Hum Biol 4:461–468.
Keller E, Burmeister J, Gausche R, Keller A, Hermanussen M, Kiess W. 2000. [Model program for the early detection and optimal treatment of disorders of growth and physical development using a medical competence network]. Z Arztl Fortbild Qualitatssich 94:695–698.
Khadilkar V, Khadilkar A. 2011. Growth charts: a diagnostic tool. Indian J Endocrinol Metab 15(Suppl 3):S166–S171.
Olsen EM. 2006. Failure to thrive: still a problem of definition. Clin Pediatr (Phila) 45:1–6.
Preece MA, Baines MJ. 1978. A new family of mathematical models describing the human growth curve. Ann Hum Biol 5:1–24.
Quetelet A. 1869. Physique sociale. Tome II. Bruxelles: Muquardt.

Radcliffe B, Payne JE, Porteous H, Johnston SG. 2007. "Failure to thrive" or failure to use the right growth chart? Med J Aust 186:660–661.

Redlefsen T, Commentz J, Meigen C, Hermanussen M. 2007. Reference values for height, weight and body mass index of German born Turkish children. Anthrop Anz 65:263–274.

Subramanyam MA, Ackerson LK, Subramanian SV. 2010. Patterning in birthweight in India: analysis of maternal recall and health card data. PLoS One 5:e11424.

Vignerová J, Bláha P. 1998. The growth of the Czech child during the past 40 years. In: Bodzsár BE, Susanne C, editors. Secular growth changes in Europe. Budapest: Eötvös University Press. p 93–107.

Walker R, Gurven M, Hill K, Migliano A, Chagnon, N, De Souza R, Djurovic G, Hames R, Hurtado AM, Kaplan H, Kramer K, Oliver WJ, Valeggia C, Yamauchi T. 2006. Growth rates and life histories in twenty-two small-scale societies. Am J Hum Biol. 18:295–311.

Webb EA, Kuh D, Pajak A, Kubinova R, Malyutina S, Bobak M. 2008. Estimation of secular trends in adult height, and childhood socioeconomic circumstances in three Eastern European populations. Econ Hum Biol 6:228–236.

Zemel BS, Johnston FE. 1994. Application of the Preece-Baines growth model to cross-sectional data: problems of validity and interpretation. Am J Hum Biol 6:563–570.