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A century of trends in adult human height

NCD Risk Factor Collaboration (NCD-RisC)*

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Abstract

Being taller is associated with enhanced longevity, and higher education and earnings. We reanalysed 1472 population-based studies, with measurement of height on more than 18.6 million participants to estimate mean height for people born between 1896 and 1996 in 200 countries. The largest gain in adult height over the past century has occurred in South Korean women and Iranian men, who became 20.2 cm (95% credible interval 17.5–22.7) and 16.5 cm (13.3–19.7) taller, respectively. In contrast, there was little change in adult height in some sub-Saharan African countries and in South Asia over the century of analysis. The tallest people over these 100 years are men born in the Netherlands in the last quarter of 20th century, whose average heights surpassed 182.5 cm, and the shortest were women born in Guatemala in 1896 (140.3 cm; 135.8–144.8). The height differential between the tallest and shortest populations was 19-20 cm a century ago, and has remained the same for women and increased for men a century later despite substantial changes in the ranking of countries.

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People from different countries grow to different heights. This may be partly due to genetics, but most differences in height between countries have other causes. For example, children and adolescents who are malnourished, or who suffer from serious diseases, will generally be shorter as adults. This is important because taller people generally live longer, are less likely to suffer from heart disease and stroke, and taller women and their children are less likely to have complications during and after birth. Taller people may also earn more and be more successful at school. However, they are also more likely to develop some cancers.

The NCD Risk Factor Collaboration set out to find out how tall people are, on average, in every country in the world at the moment, and how this has changed over the past 100 years. The analysis revealed large differences in height between countries. The tallest men were born in the last part of the 20th century in the Netherlands, and were nearly 183 cm tall on average. The shortest women were born in 1896 in Guatemala, and were on average 140 cm tall. The difference between the shortest and tallest countries is about 20 cm for both men and women. This means there are large differences between countries in terms of nutrition and the risk of developing some diseases.

The way in which height has changed over the past 100 years also varies from country to country. Iranian men born in 1996 were around 17 cm taller than those born in 1896, and South Korean women were 20 cm taller. In other parts of the world, particularly in South Asia and parts of Africa, people are only slightly taller than 100 years ago, and in some countries people are shorter than they were 50 years ago.

There is a need to better understand why height has changed in different countries by different amounts, and use this information to improve nutrition and health across the world. It would also be valuable to understand how much becoming taller has been responsible for improved health and longevity throughout the world.

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Introduction

Being taller is associated with enhanced longevity, lower risk of adverse pregnancy outcomes and cardiovascular and respiratory diseases, and higher risk of some cancers (Paajanen et al., 2010; Emerging Risk Factors Collaboration, 2012; Green et al., 2011; Nelson et al., 2015; Batty et al., 2010; World Cancer Research Fund / American Institute for Cancer Research, 2007; 2010; 2011; 2012; 2014a; 2014b; Nüesch et al., 2015; Davies et al., 2015; Zhang et al., 2015; Kozuki et al., 2015; Black et al., 2008). There is also evidence that taller people on average have higher education, earnings, and possibly even social position (Adair et al., 2013; Stulp et al., 2015; Barker et al., 2005; Strauss and Thomas, 1998; Chen and Zhou, 2007; Case and Paxson, 2008).

Although height is one of the most heritable human traits (Fisher, 1919; Lettre, 2011), cross-population differences are believed to be related to non-genetic, environmental factors. Of these, foetal growth (itself related to maternal size, nutrition and environmental exposures), and nutrition and infections during childhood and adolescence are particularly important determinants of height during adulthood (Cole, 2000; Silventoinen et al., 2000; Dubois et al., 2012; Haeffner et al., 2002; Sørensen et al., 1999; Victora et al., 2008; Eveleth and Tanner, 1990; Tanner, 1962; Tanner, 1992; Bogin, 2013). Information on height, and its trends, can therefore help understand the health impacts of childhood and adolescent nutrition and environment, and of their social, economic, and political determinants, on both non-communicable diseases (NCDs) and on neonatal health and survival in the next generation (Cole, 2000; Tanner, 1992; Tanner, 1987).

Trends in men's height have been analysed in Europe, the USA, and Japan for up to 250 years, using data on conscripts, voluntary military personnel, convicts, or slaves (Cole, 2000; Floud et al., 1990; Fogel et al., 1983; Schmidt et al., 1995; Floud et al., 2011; Tanner et al., 1982; Hatton and Bray, 2010; Tanner, 1981;

Facchini and Gualdi-Russo, 1982). There are fewer historical data for women, and for other regions where focus has largely been on children and where adult data tend to be reported at one point in time or over short periods (Subramanian et al., 2011; Grasgruber et al., 2014; Baten and Blum, 2012; Deaton, 2007; Mamidi et al., 2011; van Zanden et al., 2014). In this paper, we pooled worldwide population-based data to estimate height in adulthood for men and women born over a whole century throughout the world.

Results

We estimated that people born in 1896 were shortest in Asia and in Central and Andean Latin America (Figure 1 and Figure 2). The 1896 male birth cohort on average measured only 152.9 cm (credible interval 147.9–157.9) in Laos, which is the same as a well-nourished 12.5-year boy according to international growth standards (de Onis et al., 2007), followed by Timor-Leste and Guatemala. Women born in the same year in Guatemala were on average 140.3 cm (135.8–144.8), the same as a well-nourished 10-year girl. El Salvador, Peru, Bangladesh, South Korea and Japan had the next shortest women. The tallest populations a century ago lived in Central and Northern Europe, North America and some Pacific islands. The height of men born in Sweden, Norway and the USA surpassed 171 cm, ~18–19 cm taller than men in Laos. Swedish women, with average adult height of 160.3 cm (158.2–162.4), were the tallest a century ago and 20 cm taller than women in Guatemala. Women were also taller than 158 cm in Norway, Iceland, the USA and American Samoa.

Changes in adult height over the century of analysis varied drastically across countries. Notably, although the large increases in European men's heights in the 19th and 20th century have been highlighted, we found that the largest gains since the 1896 birth cohort occurred in South Korean women and Iranian men, who became 20.2 cm (17.5–22.7) and 16.5 cm (13.3–19.7) taller, respectively (Figure 3, Figure 4 and Figure 5). As a result, South Korean women moved from the fifth shortest to the top tertile of tallest women in the world over the course of a century. Men in South Korea also had large gains relative to other countries, by 15.2 cm (12.3–18.1). There were also large gains in height in Japan, Greenland, some countries in Southern Europe (e.g., Greece) and Central Europe (e.g., Serbia and Poland, and for women Czech Republic). In contrast, there was little gain in height in many countries in sub-Saharan Africa and South Asia.

The pace of growth in height has not been uniform over the past century. The impressive rise in height in Japan stopped in people born after the early 1960s (Figure 6). In South Korea, the flattening began in the cohorts born in the 1980s for men and it may have just begun in women. As a result, South Korean men and women are now taller than their Japanese counterparts. The rise is continuing in other East and Southeast Asian countries like China and Thailand, with Chinese men and women having surpassed the Japanese (but not yet as tall as South Koreans). The rise in adult height also seems to have plateaued in South Asian countries like Bangladesh and India at much lower levels than in East Asia, e.g., 5–10 cm shorter than it did in Japan and South Korea.

There were also variations in the time course of height change across high-income western countries, with height increase having plateaued in Northern European countries like Finland and in English-speaking countries like the UK for 2–3 decades (Larnkaer et al., 2006; Schönbeck et al., 2013), followed by Eastern Europe (Figure 7). The earliest of these occurred in the USA, which was one of the tallest nations a century ago but has now fallen behind its European counterparts after having had the smallest gain in height of any high-income country (Tanner, 1981; Komlos and Lauderdale, 2007; Komlos and Baur, 2004; Sokoloff and Villaflor, 1982). In contrast, height is still increasing in some Southern European countries (e.g., Spain), and in many countries in Latin America.

As an exception to the steady gains in most countries, adult height decreased or at best remained the same in many countries in sub-Saharan Africa for cohorts born after the early 1960s, by around 5 cm from its peak in some countries (see for example Niger, Rwanda, Sierra Leone, and Uganda in Figure 8). More recently, the same seems to have happened for men, but not women, in some countries in Central Asia (e.g., Azerbaijan and Uzbekistan) and Middle East and North Africa (e.g., Egypt and Yemen), whereas in others (e.g., Iran) both sexes continue to grow taller.

Men born in 1996 surpass average heights of 181 cm in the Netherlands, Belgium, Estonia, Latvia and Denmark, with Dutch men, at 182.5 cm (180.6–184.5), the tallest people on the planet. The gap with the shortest countries – Timor-Leste, Yemen and Laos, where men are only ~160 cm tall – is 22–23 cm, an increase of ~4 cm on the global gap in the 1896 birth cohort. Australia was the only non-European country where men born in 1996 were among the 25 tallest in the world. Women born in 1996 are shortest in Guatemala, with an average height of 149.4 cm (148.0–150.8), and are shorter than 151 cm in the Philippines, Bangladesh and Nepal. The tallest women live in Latvia, the Netherlands, Estonia and Czech Republic, with average height surpassing 168 cm, creating a 20 cm global gap in women's height (Figure 5).

Male and female heights were correlated across countries in 1896 as well as in 1996. Men were taller than women in every country, on average by ~11 cm in the 1896 birth cohort and ~12 cm in the 1996 birth cohort (Figure 9). In the 1896 birth cohort, the male-female height gap in countries where average height was low was slightly larger than in taller nations. In other words, at the turn of the 20th century, men seem to have had a relative advantage over women in undernourished compared to better-nourished populations. A century later, the male-female height gap is about the same throughout the height range. Changes in male and female heights over the century of analysis were also correlated, which is in contrast to low correlation between changes in male and female BMIs as reported elsewhere (NCD Risk Factor Collaboration, 2016).

Change in population mean height was not correlated with change in mean BMI (NCD Risk Factor Collaboration, 2016) across countries for men (correlation coefficient = −0.016) and was weakly inversely correlated for women (correlation coefficient = −0.28) (Figure 10). Countries like Japan, Singapore and France had larger-than-median gains in height but little change in BMI, in contrast to places like the USA and Kiribati where height has increased less than the worldwide median while BMI has increased a great deal.

Discussion

We found that over the past century adult height has changed substantially and unevenly in the world's countries, with no indication of convergence across countries. The height differential between the tallest and shortest populations was ~19 cm for men and ~20 cm for women a century ago, and has remained about the same for women and increased for men a century later despite substantial changes in the ranking of countries in terms of adult height.

Data from military conscripts and personnel have allowed reconstructing long-term trends in height in some European countries and the USA, albeit largely for men, and treating it as a 'mirror' to social and environmental conditions that affect nutrition, health and economic prosperity, in each generation and across generations (Tanner, 1987; Fogel, 2004; Komlos, 2009; Martins et al., 2014; Martorell, 1995). Our results on the large gains in continental European countries, and that they have overtaken English-speaking countries like the USA, are consistent with these earlier studies although these earlier analyses covered fewer countries in Eastern and Southern Europe, and used some self-reported data with simple adjustments that cannot fully correct for their bias (Hatton and Bray, 2010; Facchini and Gualdi-Russo, 1982; Baten and Blum, 2012).

Less has been known about trends in women's height, and those in non-English-speaking/non-European parts of the world. We found that some of the most important changes in height have happened in these under-investigated populations. In particular, South Korean and Japanese men and women, and Iranian men, have had larger gains than European men, and similar trends are now happening in China and Thailand. These gains may partially account for the fact that women in Japan and South Korea have achieved the first and fourth highest life expectancy in the world (see also below). In contrast to East Asia's impressive gains, the rise in height seems to have stopped early in South Asia and reversed in Africa, reversing or diminishing Africa's earlier advantage over Asia. Prior studies have documented a rise in stunting in children in sub-Saharan Africa which continued to the mid-1990s (Stevens et al., 2012). Our results indicate that such childhood adversity may have carried forward to adulthood and be affecting health in the region. The early African advantage over Asia may also have been partly due to having a more diverse diet compared to the vegetable and cereal diet in Asia, partly facilitated by lower population density (Deaton, 2007; Moradi, 2010). Rising population, coupled with worsening economic status during structural adjustment, may have undermined earlier dietary advantage (Stevens et al., 2012; Pongou et al., 2006; Weil et al., 1990; Sundberg, 2009).

The main strengths of our study are its novel scope of estimating a century of trends in adult height for all countries in the world and for both sexes. Our population-based results complement the individual-level studies on the genetic and environmental determinants of within-population variation in height, and will help develop and test hypotheses about the determinants of adult height, and its health consequences. We achieved this by using a large number of population-based data sources from all regions of the world. We put particular emphasis on data quality and used only population-based data that had measured height, which avoids bias in self-reported height. Data were analysed according to a common protocol before being pooled, and characteristics and quality of data sources were verified through repeated checks by Collaborating Group members. Finally, we pooled data using a statistical model that could characterize non-linear trends and that used all available data while giving more weight to national data than to subnational and community surveys.

Although we have gathered an unprecedentedly comprehensive database of human height and growth, and have applied a statistical model that maximally utilizes the information in these sources, data in some countries were rather limited or were from community or sub-national studies. This is reflected in larger uncertainty of the estimated height in these countries. To overcome this, surveillance of growth, which has focused largely on children, should also systematically monitor adolescents and adults given the increasingly abundant evidence on their effects on adult health and human capital. Even measured height data can be subject to measurement error depending on how closely study protocols are followed. Finally, we did not have separate data on leg and trunk lengths, which may differ in their determinants, especially in relation to age at menarche and pre- vs. post-pubertal growth and nutrition, and health effects (Tanner et al., 1982; Frisch and Revelle, 1971).

Greater height in adulthood is both beneficially (cardiovascular and respiratory diseases) and harmfully (colorectal, postmenopausal breast and ovarian cancers, and possibly pancreatic, prostate and premenopausal breast cancers) associated with several diseases, independently of its inverse correlation with BMI (Paajanen et al., 2010; Emerging Risk Factors Collaboration, 2012; Green et al., 2011; Nelson et al., 2015; Batty et al., 2010; World Cancer Research Fund / American Institute for Cancer Research, 2007; 2010; 2011; 2012; 2014a; 2014b; Nüesch et al., 2015; Davies et al., 2015; Zhang et al., 2015). If the associations in epidemiological studies are causal, which is supported by the more recent evidence from Mendelian randomisation studies (Green et al., 2011; Nüesch et al., 2015; Davies et al., 2015; Zhang et al., 2015), the ~20 cm height range in the world is associated with a 17% lower risk of cardiovascular mortality and 20–40% higher risk of various site-specific cancers, in tall versus short countries. Consistent with individual-level evidence on the association between taller height and lower all-cause mortality in adult ages (Emerging Risk Factors Collaboration, 2012), gains in mean population height in successive cohorts are associated with lower mortality in middle and older ages in countries with reliable mortality data (correlation coefficient = −0.58 for men and −0.68 for women) (Figure 11), demonstrating the large impacts of height gain on population health and longevity. Further, short maternal stature increases the risk of small-for-gestational-age and preterm births, both risk factors for neonatal mortality, and of pregnancy complications (Kozuki et al., 2015; Black et al., 2008). Therefore, improvements vs. stagnation in women's height can influence trends in infant and maternal mortality.

Our study also shows the potential for using height in early adulthood as an indicator that integrates across different dimensions of sustainable human development. Adult height signifies not only foetal and early childhood nutrition, which was included in the Millennium Development Goals, but also that of adolescents (Lancet, 2014). Further, adult height is a link between these early-life experiences and NCDs, longevity, education and earnings. It can easily be measured in health surveys and can be used to investigate differences across countries and trends over time, as done in our work, as well as within-country inequalities. Therefore, height in early adulthood, which varies substantially across countries and over time, provides a measurable indicator for sustainable development, with links to health and longevity, nutrition, education and economic productivity.

Materials and methods

Overview

We estimated trends in mean height for adults born from 1896 to 1996 (i.e., people who had reached their 18th birthday from 1914 to 2014) in 200 countries and territories. Countries were organized into 20 regions, mostly based on a combination of geography and national income (Supplementary file 1). Our study had two steps, described below. First, we identified, accessed, and re-analysed population-based measurement studies of human anthropometry. We then used a statistical model to estimate trends for all countries and territories.

Data sources

We used data sources that were representative of a national, subnational, or community population and had measured height. We did not use self-reported height because it is subject to systematic bias that varies by geography, time, age, sex, and socioeconomic characteristics like education and ethnicity (Engstrom et al., 2003; Connor Gorber et al., 2007; Wetmore and Mokdad, 2012; Schenker et al., 2010; Ezzati et al., 2006; Clarke et al., 2014; Hayes et al., 2011).

Data sources were included in the NCD-RisC database if:

- measured data on height, weight, waist circumference, or hip circumference were available;
- study participants were five years of age and older;
- data were collected using a probabilistic sampling method with a defined sampling frame;
- data were representative of the general population at the national, subnational, or community level;
- data were from the countries and territories listed in Supplementary file 1.

We excluded data sources on population subgroups whose anthropometric status may differ systematically from the general population, including:

- studies that had included or excluded people based on their health status or cardiovascular risk;
- ethnic minorities;
- specific educational, occupational, or socioeconomic subgroups of the population; and
- those recruited through health facilities, with the exception noted below.

We used school-based data in countries where secondary school enrolment was 70% or higher, and used data whose sampling frame was health insurance schemes in countries where at least 80% of the population were insured. We used data collected through general practice and primary care clinics in high-income countries with universal insurance, because contact with the primary care systems tends to be at least as good as response rates for population-based surveys. No studies were excluded based on the level of height.

We used multiple routes for identifying and accessing data. We accessed publicly available population-based multi-country and national measurement surveys (e.g., Demographic and Health Surveys, and surveys identified via the Inter-University Consortium for Political and Social Research and European Health Interview & Health Examination Surveys Database) as well as the World Health Organization (WHO) STEPwise approach to Surveillance (STEPS) surveys. We requested identification and access to population-based data sources from ministries of health and other national health agencies, via WHO and its regional offices. Requests were also sent via the World Heart Federation to its national partners. We made a similar request to the NCD Risk Factor Collaboration (NCD-RisC; www.ncdrisc.org), a worldwide network of health researchers and practitioners working on NCD risk factors.

To identify major sources not accessed through the above routes, we searched and reviewed published studies. Specifically, we searched Medline (via PubMed) for articles published between 1st January 1950 and 12th March 2013 using the search terms 'body size'[mh:noexp] OR 'body height'[mh:noexp] OR 'body weight'[mh:noexp] OR 'birth weight'[mh:noexp] OR 'overweight'[mh:noexp] OR 'obesity'[mh] OR 'thinness'[mh:noexp] OR 'Waist-Hip Ratio'[mh:noexp] or 'Waist Circumference'[mh:noexp] or 'body mass index' [mh:noexp]) AND ('Humans'[mh]) AND('1950'[PDAT]: '2013'[PDAT]) AND ('Health Surveys'[mh] OR 'Epidemiological Monitoring'[mh] OR 'Prevalence'[mh]) NOT Comment[ptyp] NOT Case Reports[ptyp].

Articles were screened according to the inclusion and exclusion criteria described above. The number of articles identified and retained is summarised in Supplementary file 2. As described above, we contacted the corresponding authors of all eligible studies and invited them to join NCD-RisC. We did similar searches for other cardio-metabolic risk factors including blood pressure, serum cholesterol, and blood glucose. All eligible studies were invited to join NCD-RisC and were requested to analyse data on all cardio-metabolic risk factors.

Anonymised individual record data from sources included in NCD-RisC were re-analysed by the Pooled

Analysis and Writing Group or by data holders according to a common protocol. All re-analysed data sources included mean height in standard age groups (18 years, 19 years, 20–29 years, followed by 10 year age groups and 80+ years), as well as sample sizes and standard errors. All analyses incorporated appropriate sample weights and complex survey design when applicable. To ensure summaries were prepared according to the study protocol, the Pooled Analysis and Writing Group provided computer code to NCD-RisC members who requested assistance. We also recorded information about the study population, period of measurement and sampling approach. This information was used to establish that each data source was population-based, and to assess whether it covered the whole country, multiple subnational regions, or one or a small number of communities, and whether it was rural, urban, or combined. All submitted data were checked by at least two independent members of the Pooled Analysis and Writing Group to ensure that their sample selection met the inclusion criteria and that height was measured and not self-reported. Questions and clarifications about sample design and measurement method were discussed with the Collaborating Group members and resolved before data were incorporated in the database. We also extracted data from additional national health surveys, one subnational STEPS survey, and six MONICA sites from published reports.

We identified duplicate data sources by comparing studies from the same country and year. Additionally, NCD-RisC members received the list of all data sources in the database and were asked to ensure that the included data from their country met the inclusion criteria and that there were no duplicates. Data sources used in our analysis are listed in Supplementary file 3.

In this paper, we used data on height in adulthood (18 years of age and older) from the NCD-RisC database for participants born between 1896 and 1996. We used 1472 population-based data sources with measurements on over 18.6 million adults born between 1896 and 1996 whose height had been measured. We did not use data from the 1860–1895 cohorts because data on these early cohorts were available for only six countries (American Samoa, India, Japan, Norway, Switzerland and USA). We had data for 179 of the 200 countries for which estimates were made; these 179 countries covered 97% of the world’s population. All countries had some data on people born after 1946 (second half of analysis period); 134 had data on people born between 1921 and 1945; and 72 had data on people born in 1920 or earlier. Across regions, there were between an average of 2.0 data sources per country in the Caribbean to 34 sources per country in high-income Asia Pacific. 1108 sources had data on men as well as women, 153 only on men, and 211 only on women.

Statistical methods

The statistical method is described in detail elsewhere (Danaei et al., 2011; Finucane et al., 2014). In summary, the model had a hierarchical structure in which estimates of mean height for each country and year were nested in regional levels and trends, which were in turn nested in those of super-regions and worldwide. In this structure, estimates of mean height for each country and year were informed by its own data, if available, and by data from other years in the same country and in other countries, especially those in the same region with data for similar time periods. The hierarchical structure shares information to a greater degree when data are non-existent or weakly informative (e.g., because they have a small sample size), and to a lesser extent in data-rich countries and regions.

We used birth cohort as the time scale of analysis. We calculated the birth cohort for each observation by subtracting the mid-age of its age group from the year in which data were collected. We modelled trends in height by birth cohort as a combination of linear and non-linear trends, both with a hierarchical structure;

the non-linear trend was specified using a second-order random walk (Rue and Held, 2005). The model also included a term that allowed each birth cohort's height to change as it aged, e.g., because there is gradual loss of height during ageing and because as a cohort ages those who survive may be taller. The model described by Finucane et al (Finucane et al., 2014) had used a cubic spline for age associations of risk factor levels. In practice, the estimated change in population mean height over age was linear with a small slope of over 0.2 cm shorter for men and 0.3 cm shorter for women with each decade of older age. Therefore, we used a linear specification for computational efficiency.

While all our data were from samples of the general population, 796 (54%) of data sources represented national populations, another 199 (14%) major sub-national regions (e.g., one or more provinces or regions of a country), and the remaining 477 (32%) one or a small number of communities. The model accounted for the fact that sub-national and community studies, while informative, might systematically differ from nationally representative ones, and also have larger variation relative to the true values than national studies (e.g., see data from China, India, Japan and the UK in Figure 6 and Figure 7).

We fitted the Bayesian model with the Markov chain Monte Carlo (MCMC) algorithm. We monitored mixing and convergence using trace plots and Brooks–Gelman–Rubin diagnostics (Brooks and Gelman, 1998). We obtained 5000 post burn-in samples from the posterior distribution of model parameters, used to obtain the posterior distribution of mean height. The reported credible intervals represent the 2.5th–97.5th percentiles of the posterior distribution. We report mean height at age 18 years for each birth cohort; heights at other ages are available from the authors. All analyses were done separately by sex because height and its trends over time may differ between men and women.

We tested how well our statistical model predicts missing values by removing data from 10% of countries with data (i.e., created the appearance of countries with no data where we actually had data). The countries whose data were withheld were randomly selected from the following three groups: data-rich (more than 25 cohorts of data, with at least five cohorts after 1960), data-poor (up to and including 12 cohorts of data for women and 8 cohorts for men), and average data availability (13 to 25 cohorts for women, 9 to 25 cohorts for men, or more than 25 cohorts in total with fewer than five after 1960). In total, there were 64 data-rich countries for women and 51 for men; 57 data-poor countries for women and 58 for men; and 56 countries for women and 60 for men that had average data availability. We fitted the model to the data from the remaining 90% of countries and made estimates of the held-out observations. We repeated the test five times, holding out a different subset of data in each repetition. We calculated the differences between the held-out data and the estimates. We also checked the 95% credible intervals of the estimates; in a model with good external predictive validity, 95% of held-out values would be included in the 95% credible intervals.

Our model performed extremely well; specifically, the estimates of mean height were unbiased as evidenced with median errors that were very close to zero globally, and less than ±0.2 cm in every subset of withheld data (Supplementary file 4). Even the 25th and 75th percentiles of errors rarely exceeded ±1 cm. Median absolute error was only about 0.5 cm, and did not exceed 1.0 cm in subsets of withheld data. The 95% credible intervals of estimated mean heights covered 97% of true data for both men and women, which implies good estimation of uncertainty; among subgroups of data, coverage was never < 90%.

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Competing interests

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Author contributions

NCDRFC(NCD-RisC), collectively contributed to the research and manuscript. Members of the Country and Regional Data Group collected and reanalysed data, and checked pooled data for accuracy of information about their study and other studies in their country. MDC led data collection and JB led the statistical analysis and prepared results. Members of the Pooled Analysis and Writing Group collated data, checked all data sources in consultation with the Country and Regional Data Group, analysed pooled data, and prepared results. ME designed the study, oversaw research, and wrote the first draft of the report with input from other members of Pooled Analysis and Writing Group. Members of Country and Regional Data Group commented on draft report.

Additional files

Supplementary file 1.

Regions used for the Bayesian hierarchical model such that information was shared among countries within each region, among regions in a super-region, and among super-regions in the world.

Numbers in brackets show number of countries in each region or super-region.

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Supplementary file 2.

Flowchart of secondary search for data sources.

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Supplementary file 3.

Data sources used in the study, by country.

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Supplementary file 4.

Results of model validation.

The validation procedure is described in the main text.

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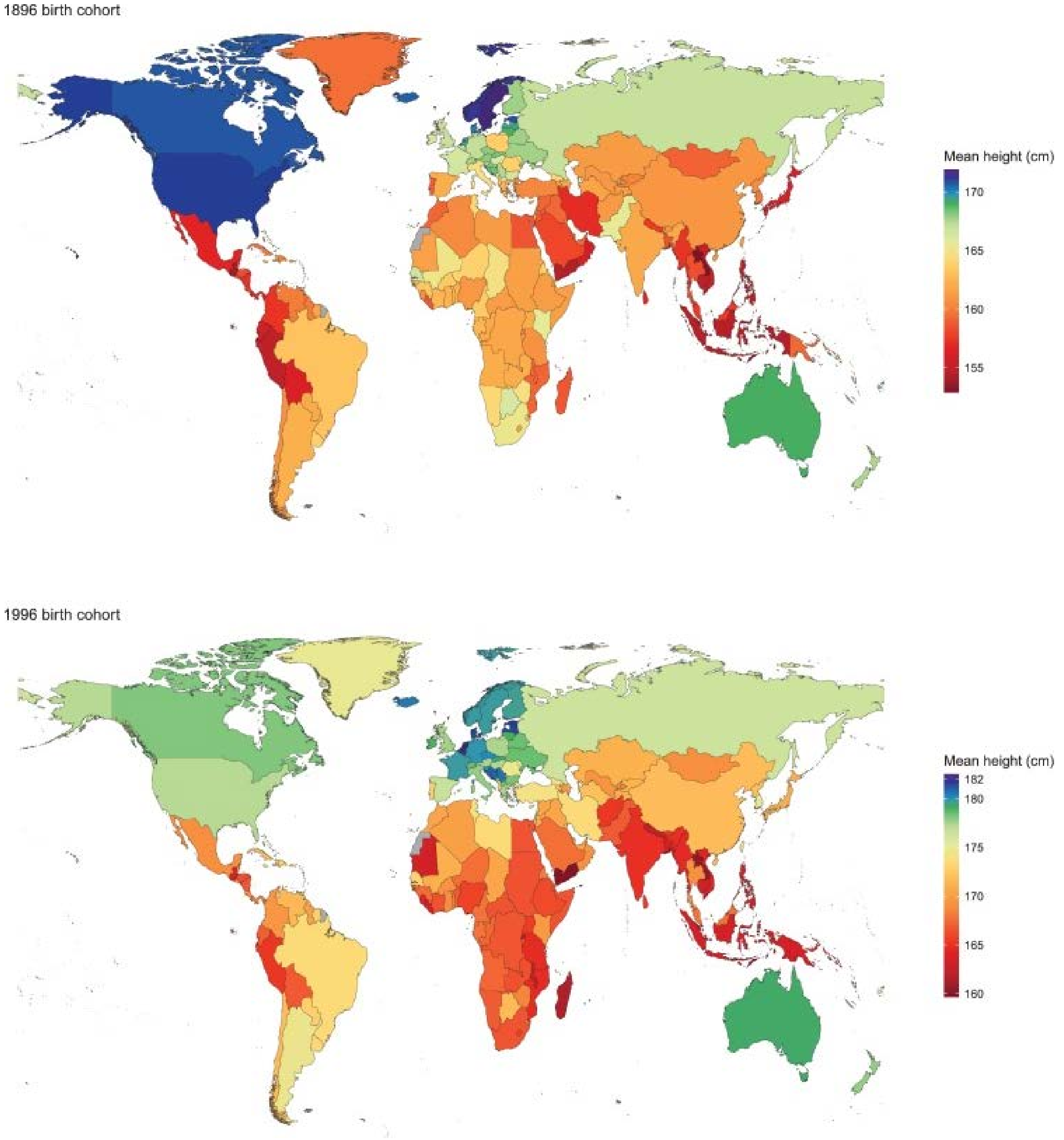
Figures and Tables

Figure 1.



Adult height for the 1896 and 1996 birth cohorts for men.

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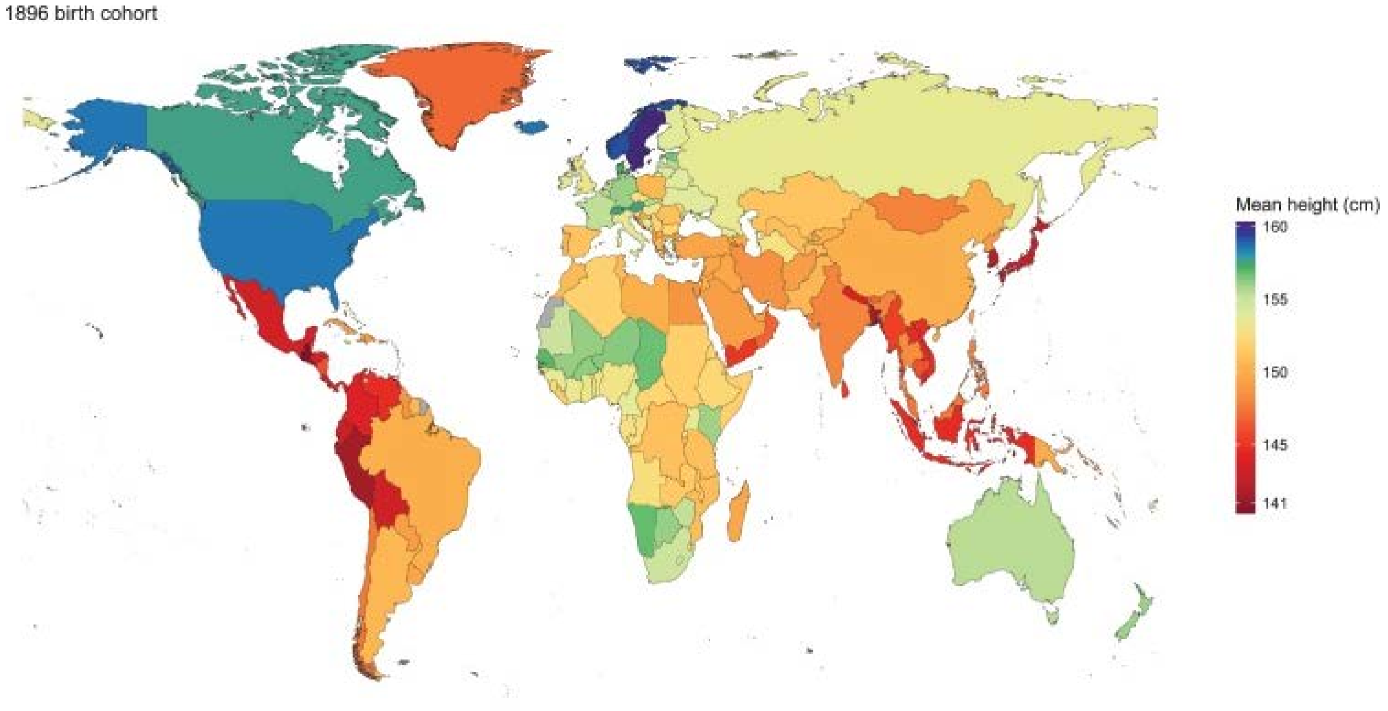
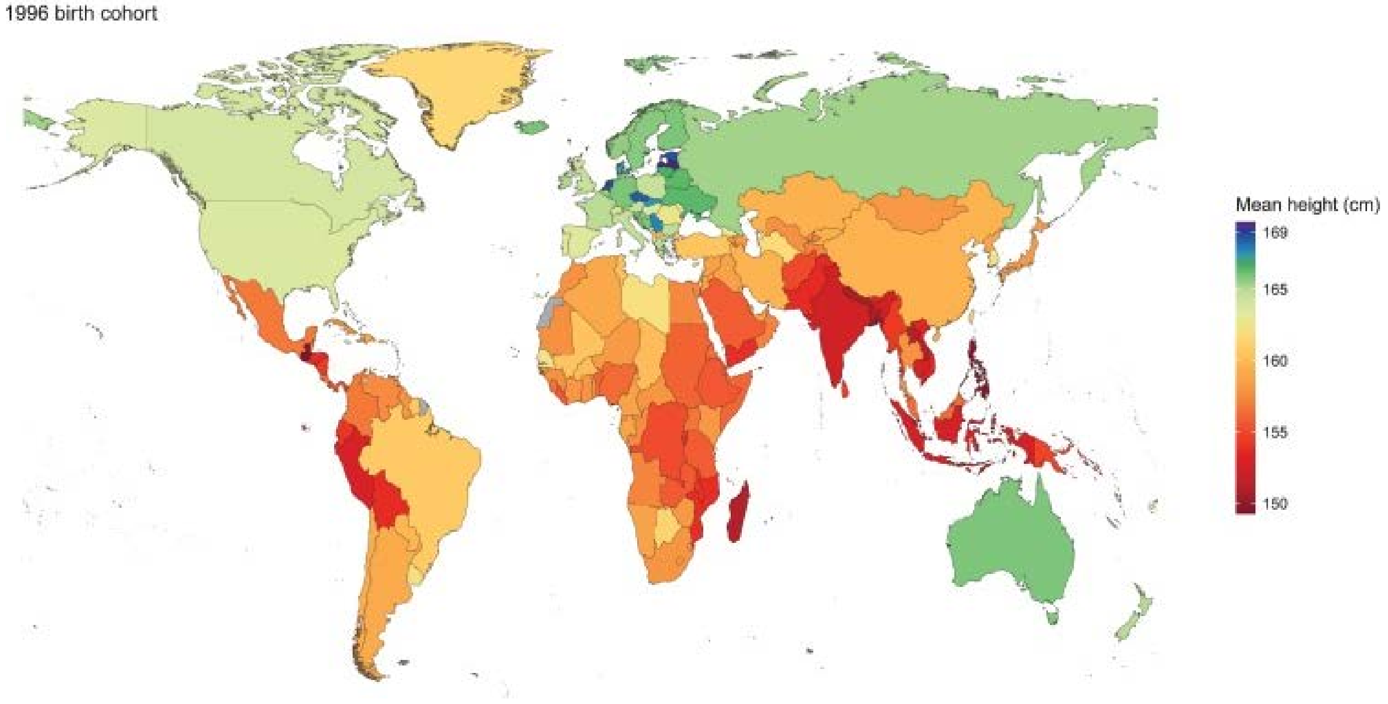
Figure 2.





Adult height for the 1896 and 1996 birth cohorts for women.

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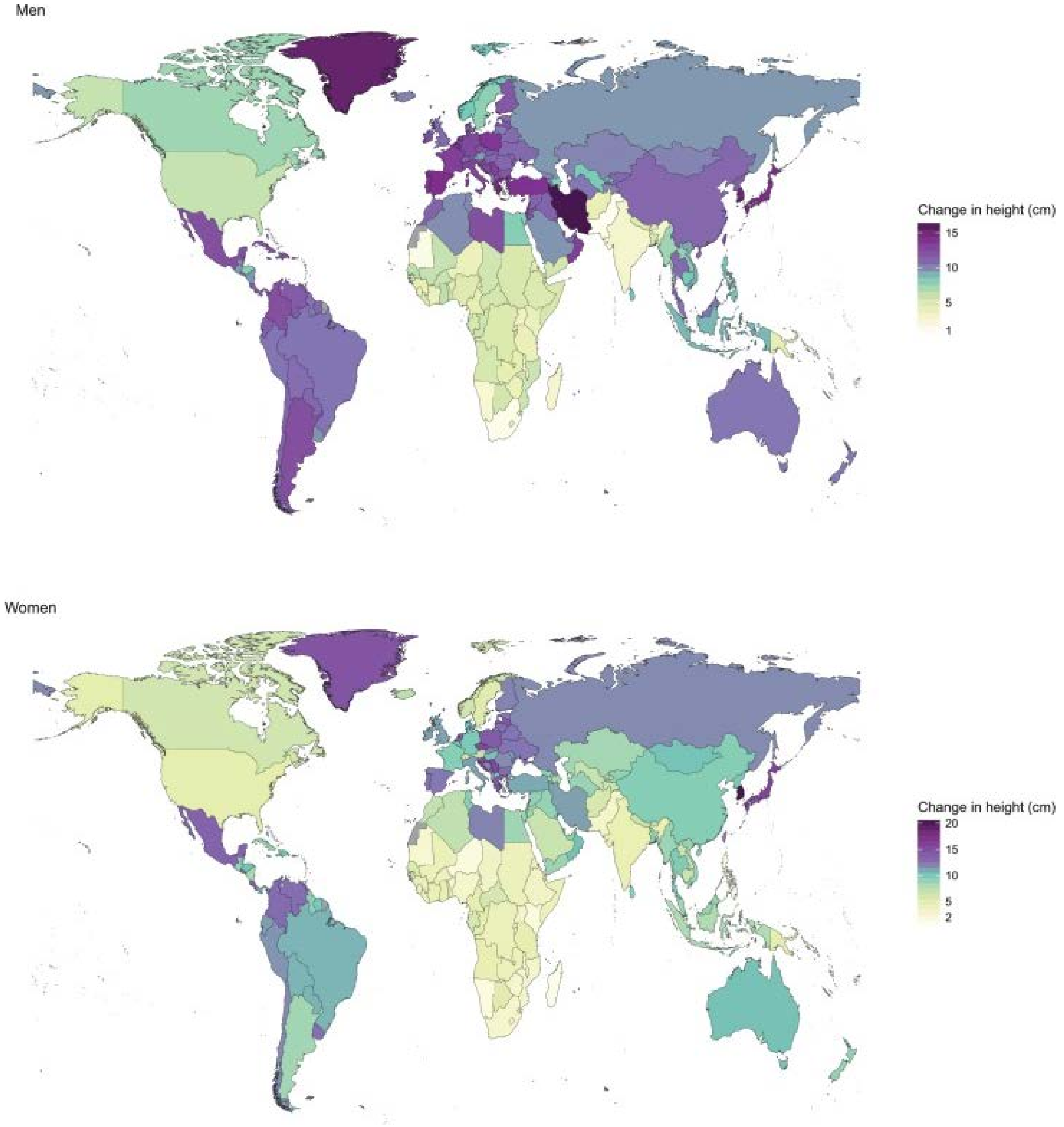
Figure 3.



Change in adult height between the 1896 and 1996 birth cohorts.

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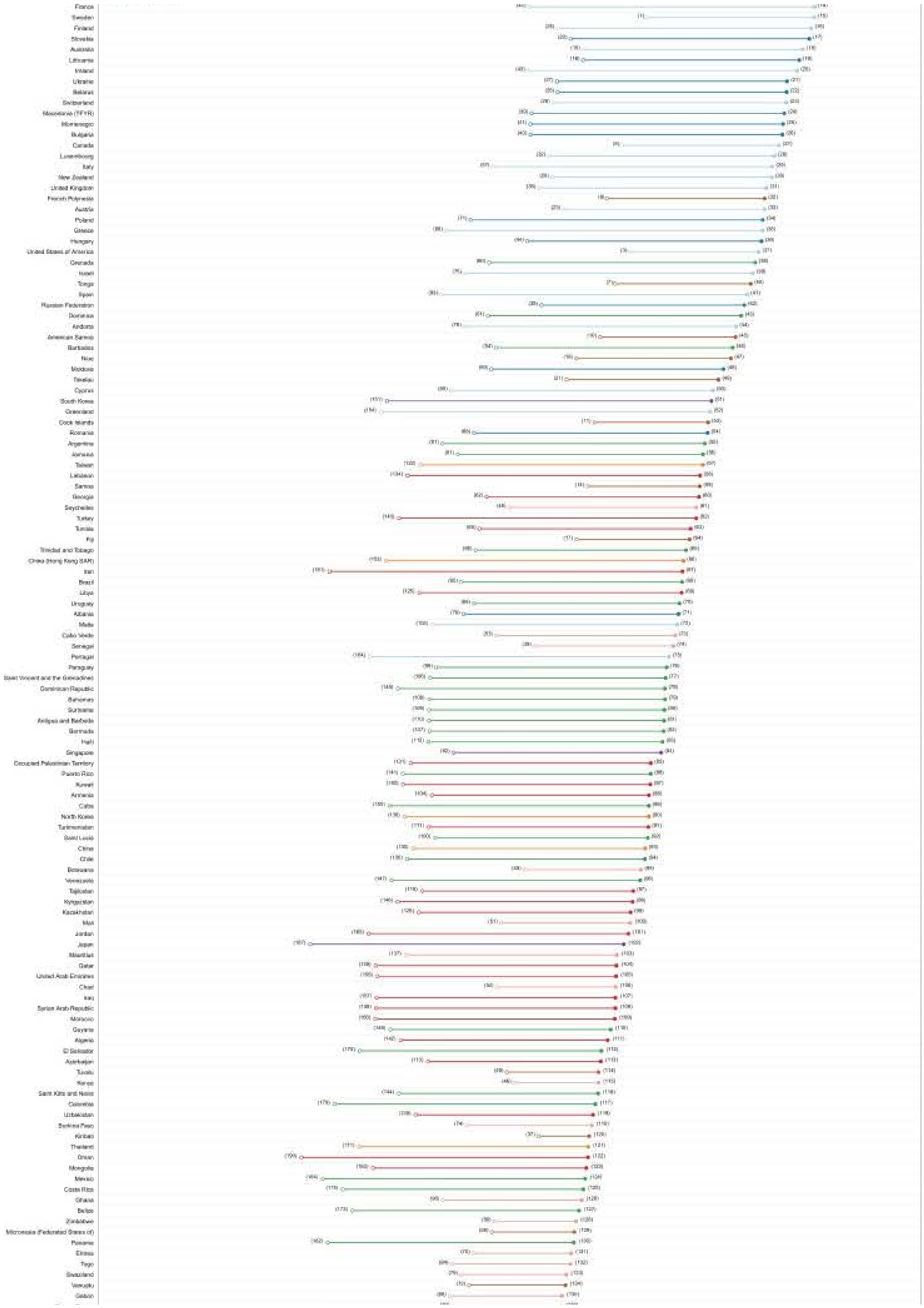
Figure 4.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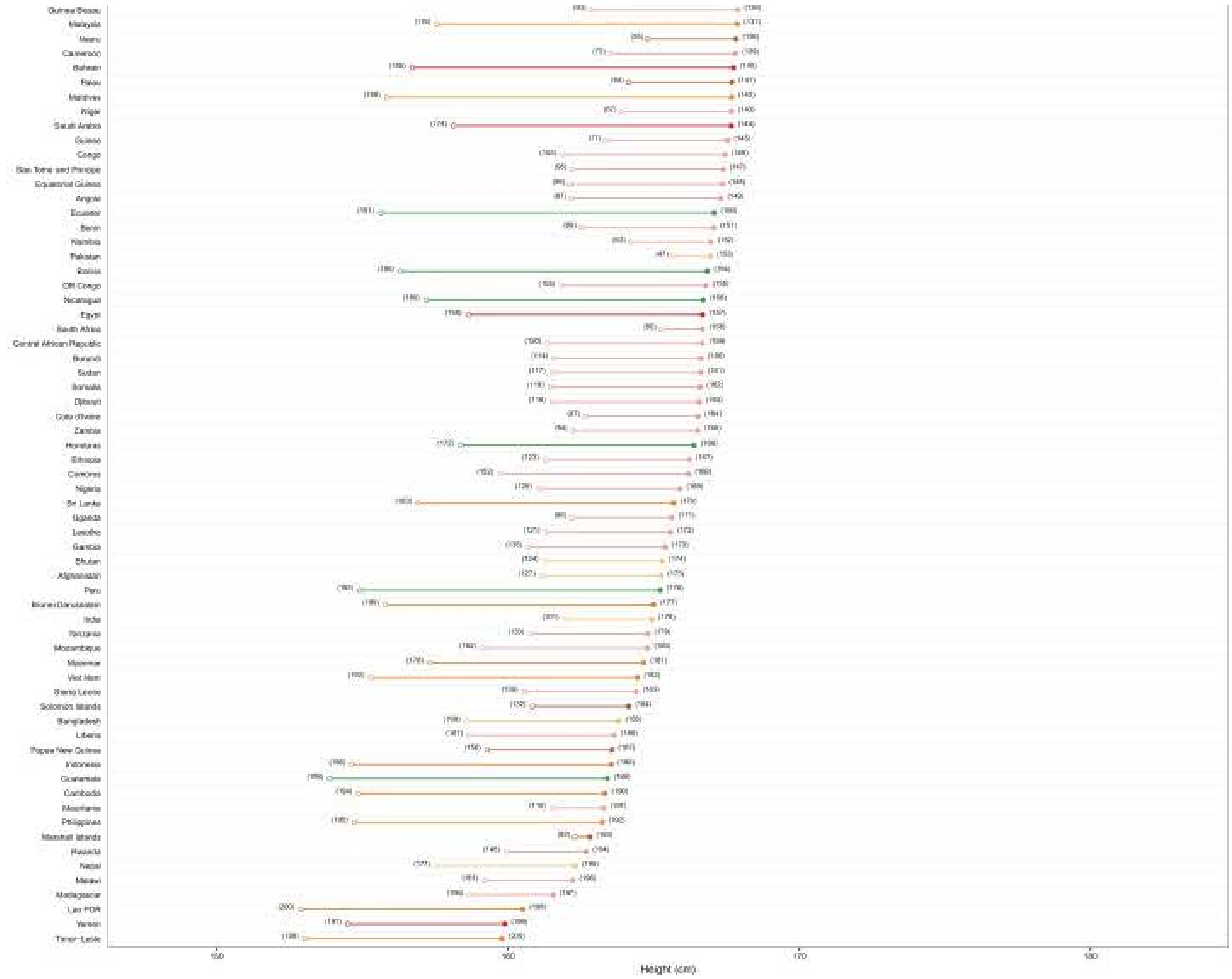
Grenada
Israel
Tonga
Spain
Russian Federation
Dominica
Andorra
American Samoa
Barbados
Niue
Moldova
Tokelau
Cyprus
South Korea
Greenland
Cook Islands
Romania
Argentina
Jamaica
Taiwan
Lebanon
Samoa
Georgia
Seychelles
Turkey
Tunisia
Fiji
Trinidad and Tobago
China (Hong Kong SAR)
Iran
Brazil
Libya
Uruguay
Albania
Malta
Cabo Verde
Senegal
Portugal
Paraguay
Saint Vincent and the Grenadines
Dominican Republic
Bahamas
Suriname
Antigua and Barbuda
Bermuda
Haiti
Singapore
Occupied Palestinian Territory
Puerto Rico
Kuwait
Armenia
Cuba
North Korea
Turkmenistan
Saint Lucia
China
Chile
Botswana
Venezuela
Tajikistan
Kyrgyzstan
Kazakhstan
Mali
Jordan
Japan
Mauritius
Qatar
United Arab Emirates
Chad
Iraq
Syrian Arab Republic
Morocco
Guyana
Algeria
El Salvador
Azerbaijan
Tuvalu
Kenya
Saint Kitts and Nevis
Colombia
Uzbekistan
Burkina Faso
Kiribati
Thailand
Oman
Mongolia
Mexico
Costa Rica
Ghana
Belize
Zimbabwe
Micronesia (Federated States of)
Panama
Eritrea
Togo
Swaziland
Vanuatu
Gabon

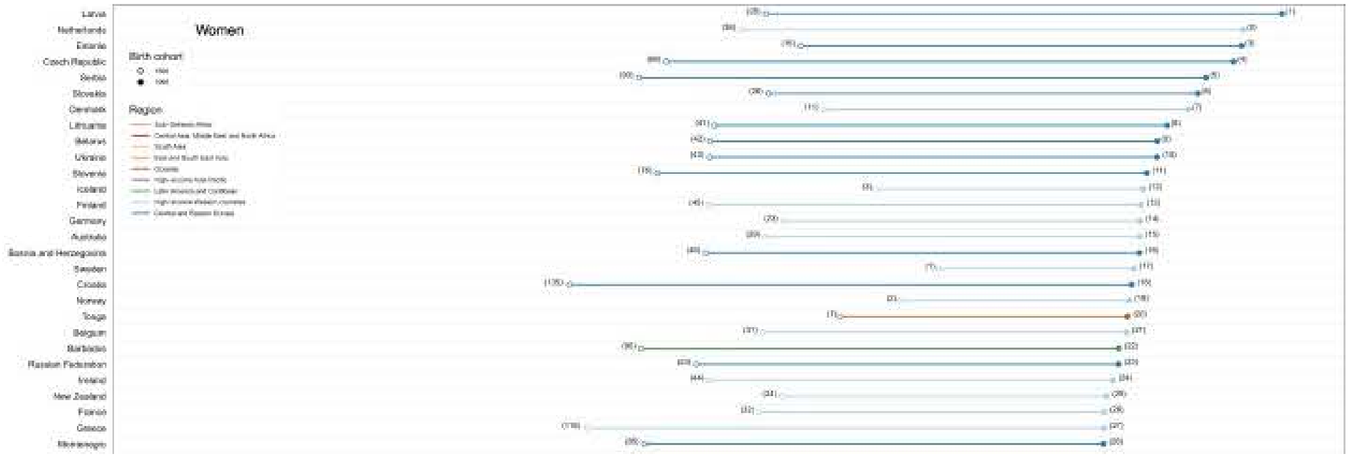


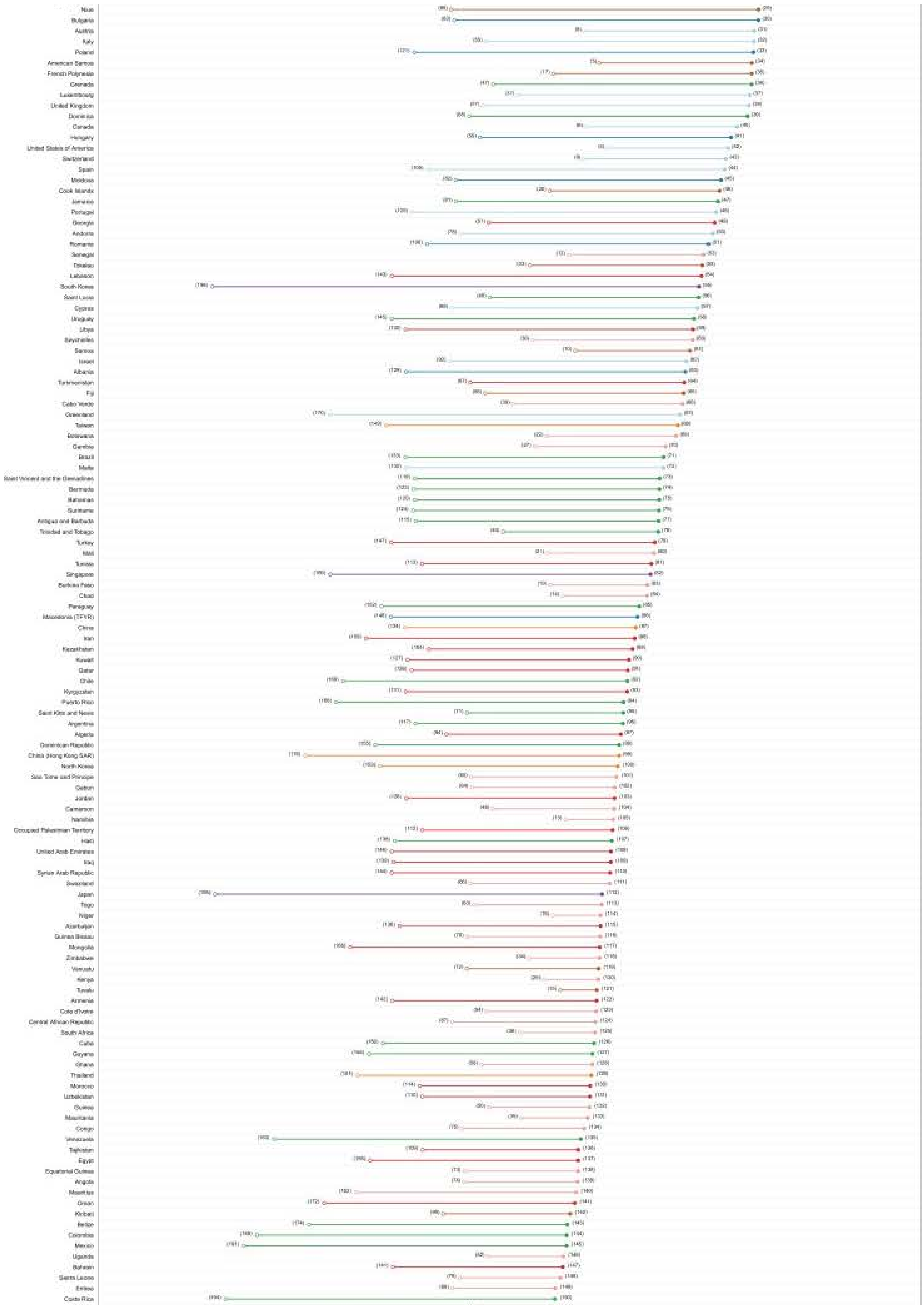
Height in adulthood for the 1896 and 1996 birth cohorts for men.

The open circle shows the adult height attained by the 1896 birth cohort and the filled circle that of the 1996 birth cohort; the length of the connecting line represents the change in height over the century of analysis. The numbers next to each circle show the country's rank in terms of adult height for the corresponding cohort. See www.ncdrisc.org for interactive version.

DOI: http://dx.doi.org/10.7554/eLife.13410.006

Figure 5.




Nauru
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Austria
Italy
Poland
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French Polynesia
Grenada
Luxembourg
United Kingdom
Dominica
Canada
Hungary
United States of America
Switzerland
Spain
Moldova
Cook Islands
Jamaica
Portugal
Georgia
Andorra
Romania
Senegal
Tokelau
Lebanon
South Korea
Saint Lucia
Cyprus
Uruguay
Libya
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Antigua and Barbuda
Trinidad and Tobago
Turkey
Mali
Tunisia
Singapore
Burkina Faso
Chad
Paraguay
Macedonia (TFYR)
China
Iran
Kazakhstan
Kuwait
Qatar
Chile
Kyrgyzstan
Puerto Rico
Saint Kitts and Nevis
Argentina
Algeria
Dominican Republic
China (Hong Kong SAR)
North Korea
Sao Tome and Principe
Gabon
Jordan
Cameroon
Namibia
Occupied Palestinian Territory
Haiti
United Arab Emirates
Iraq
Syrian Arab Republic
Swaziland
Japan
Togo
Niger
Azerbaijan
Guinea Bissau
Mongolia
Zimbabwe
Vanuatu
Kenya
Tuvalu
Armenia
Cote d'Ivoire
Central African Republic
South Africa
Cuba
Guyana
Ghana
Thailand
Morocco
Uzbekistan
Guinea
Mauritania
Congo
Venezuela
Tajikistan
Egypt
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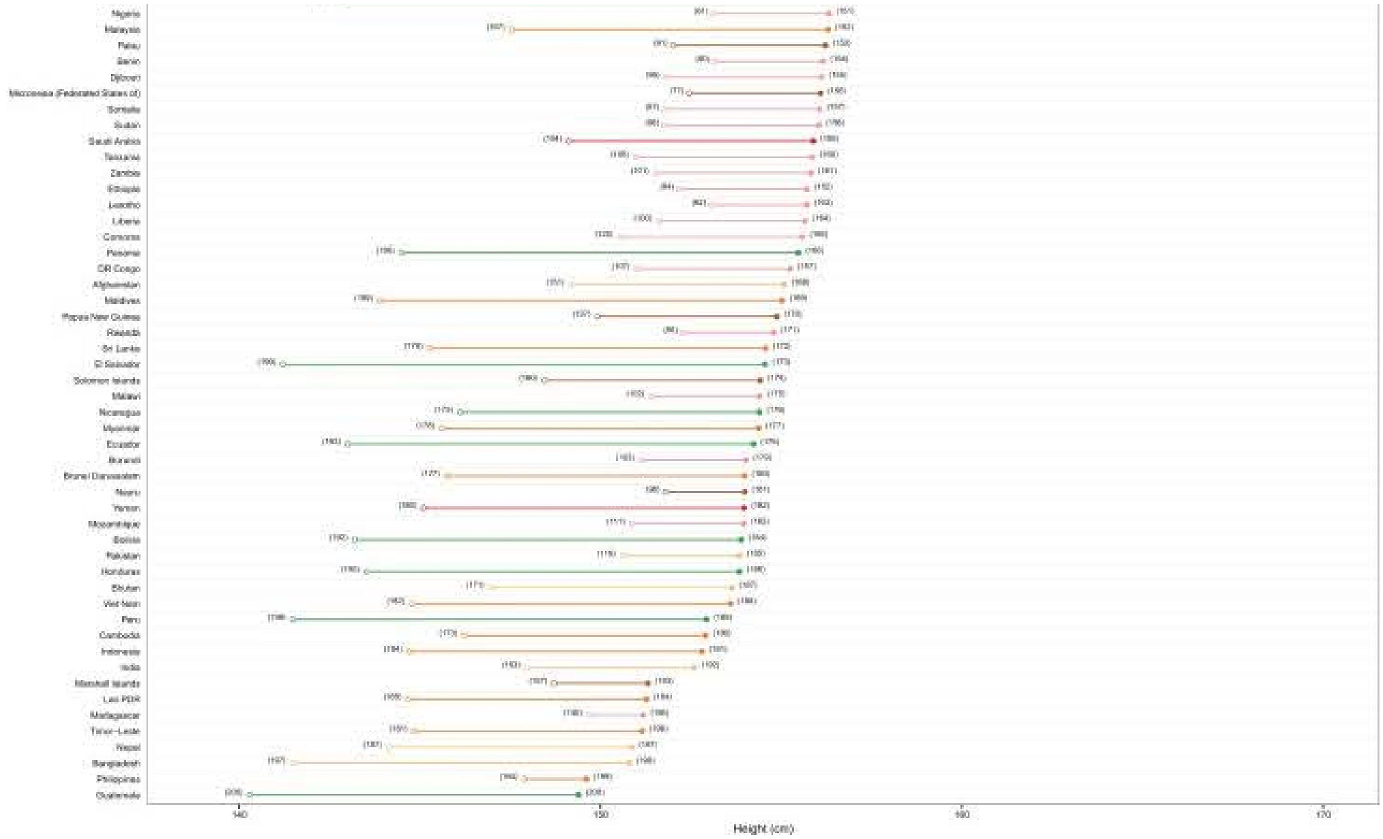
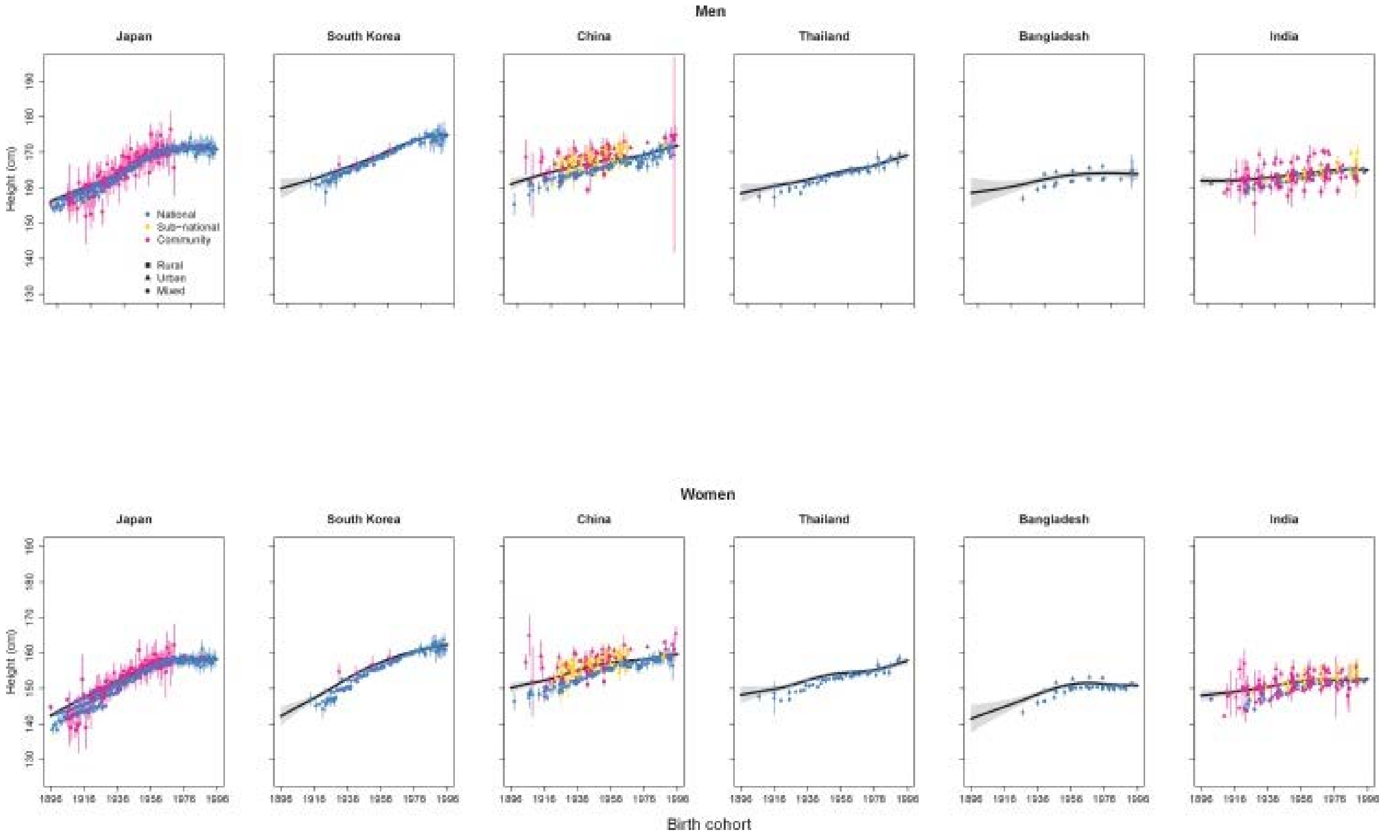


Height in adulthood for the 1896 and 1996 birth cohorts for women.

The open circle shows the adult height attained by the 1896 birth cohort and the filled circle that of the 1996 birth cohort; the length of the connecting line represents the change in height over the century of analysis. The numbers next to each circle show the country's rank in terms of adult height for the corresponding cohort. See www.ncdrisc.org for interactive version.

DOI: http://dx.doi.org/10.7554/eLife.13410.007

Figure 6.

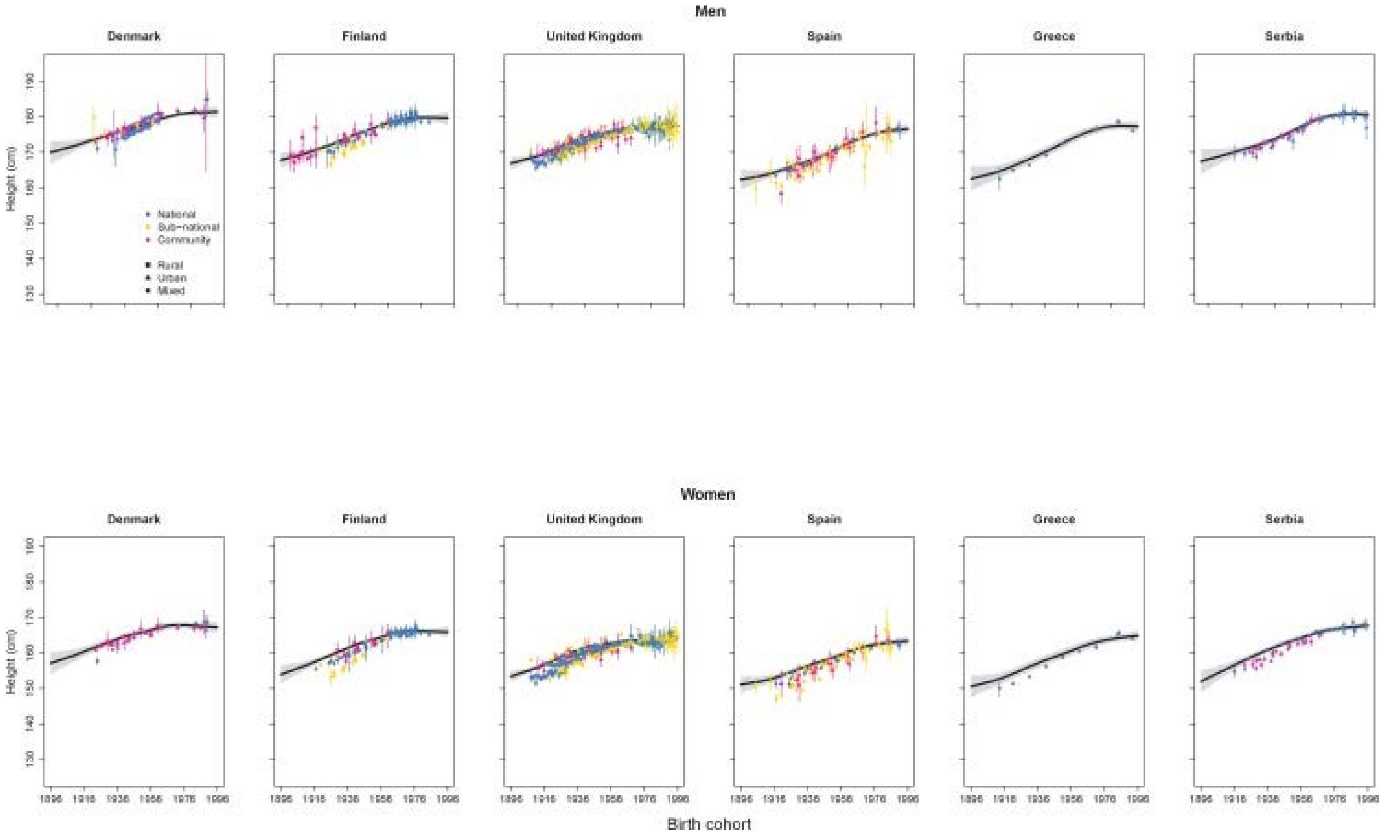


Trends in height for the adult populations of selected countries in Asia.

The solid line represents the posterior mean and the shaded area the 95% credible interval of the estimates. The points show the actual data from each country, together with its 95% confidence interval due to sampling. The solid line and shaded area show estimated height at 18 years of age, while the data points show height at the actual age of measurement. The divergence between estimates and data for earlier birth cohorts is because participants from these birth cohorts were generally older when their heights were measured.

DOI: http://dx.doi.org/10.7554/eLife.13410.008

Figure 7.

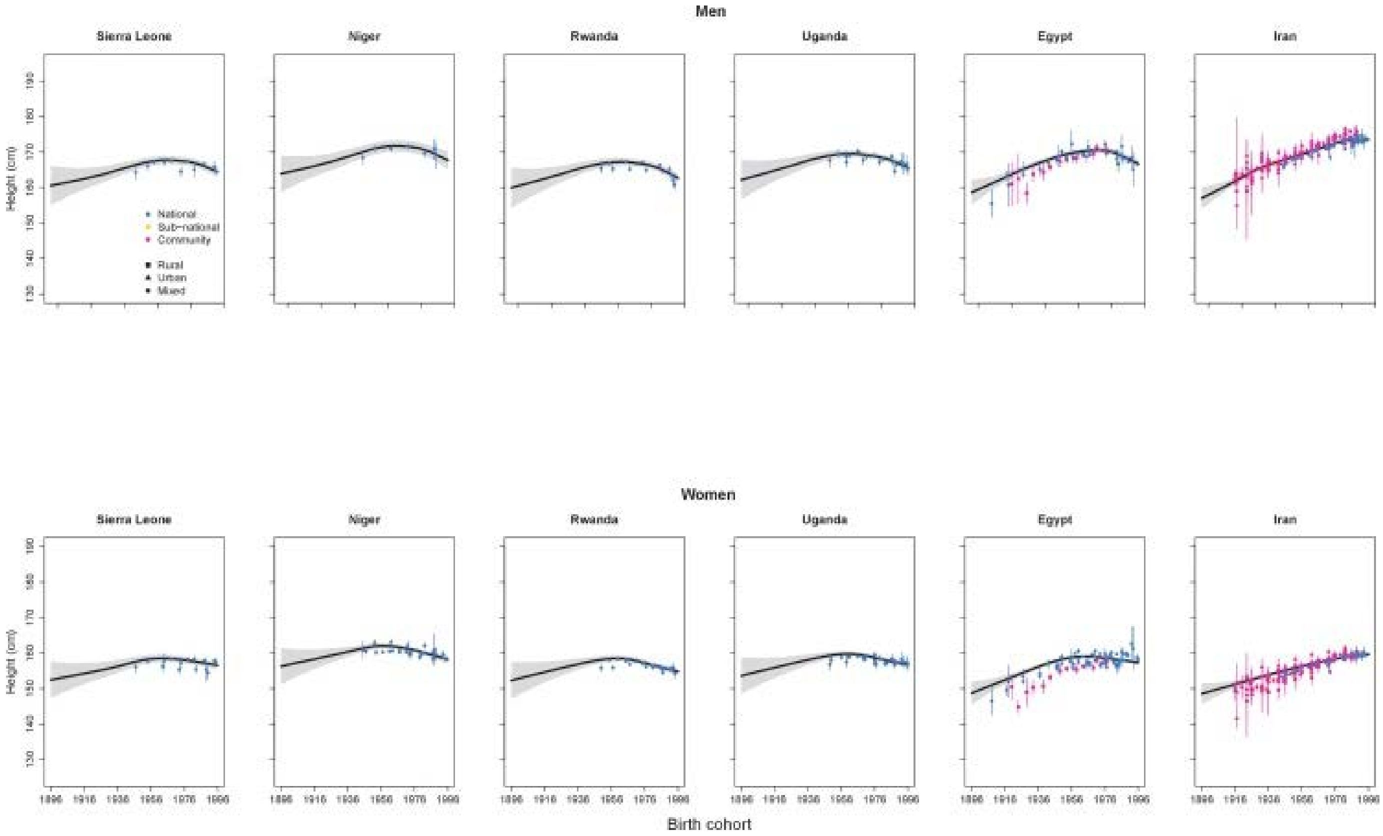


Trends in height for the adult populations of selected countries in Europe.

The solid line represents the posterior mean and the shaded area the 95% credible interval of the estimates. The points show the actual data from each country, together with its 95% confidence interval due to sampling. The solid line and shaded area show estimated height at 18 years of age, while the data points show height at the actual age of measurement. The divergence between estimates and data for earlier birth cohorts is because participants from these birth cohorts were generally older when their heights were measured.

DOI: http://dx.doi.org/10.7554/eLife.13410.009

Figure 8.

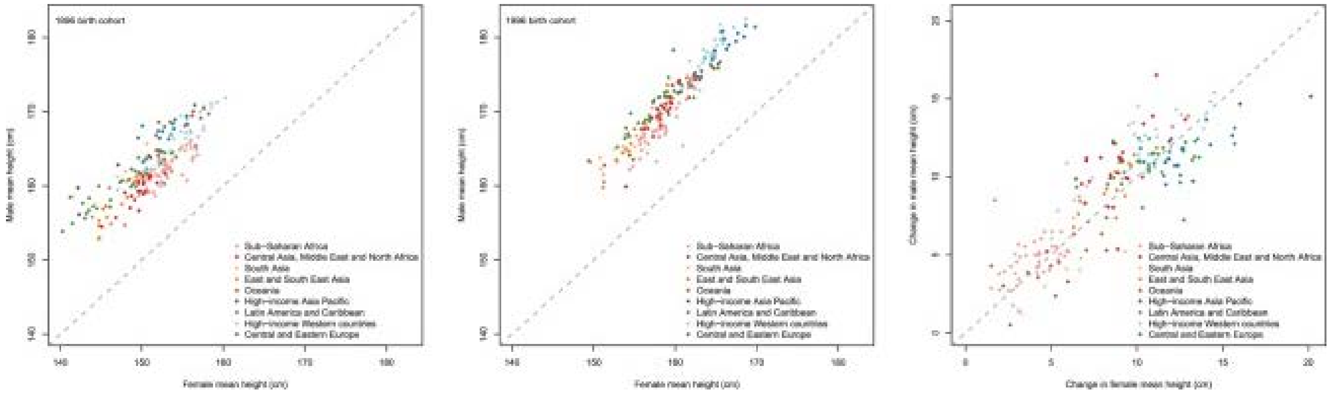


Trends in height for the adult populations of selected countries in the Middle East, North Africa, and sub-Saharan Africa.

The solid line represents the posterior mean and the shaded area the 95% credible interval of the estimates. The points show the actual data from each country, together with its 95% confidence interval due to sampling. The solid line and shaded area show estimated height at 18 years of age, while the data points show height at the actual age of measurement. The divergence between estimates and data for earlier birth cohorts is because participants from these birth cohorts were generally older when their heights were measured.

DOI: http://dx.doi.org/10.7554/eLife.13410.010

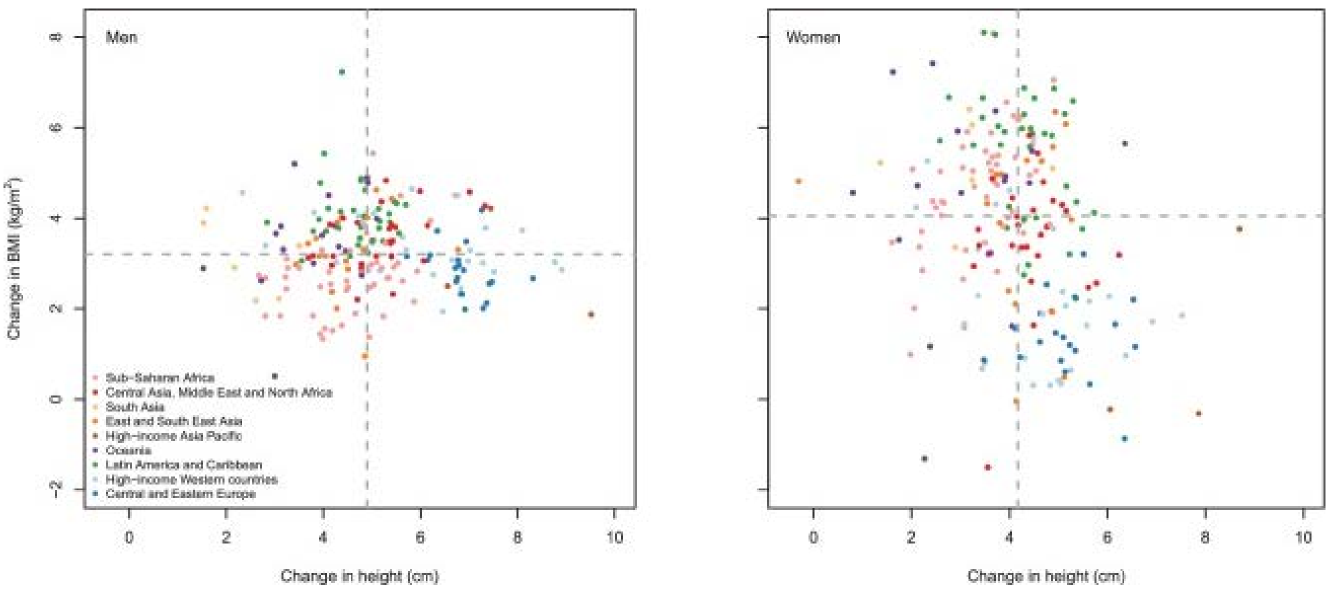
Figure 9.



Height in adulthood for men vs. women for the 1896 and 1996 birth cohorts, and change in men's vs. women's heights from 1896 to 1996.

DOI: http://dx.doi.org/10.7554/eLife.13410.011

Figure 10.

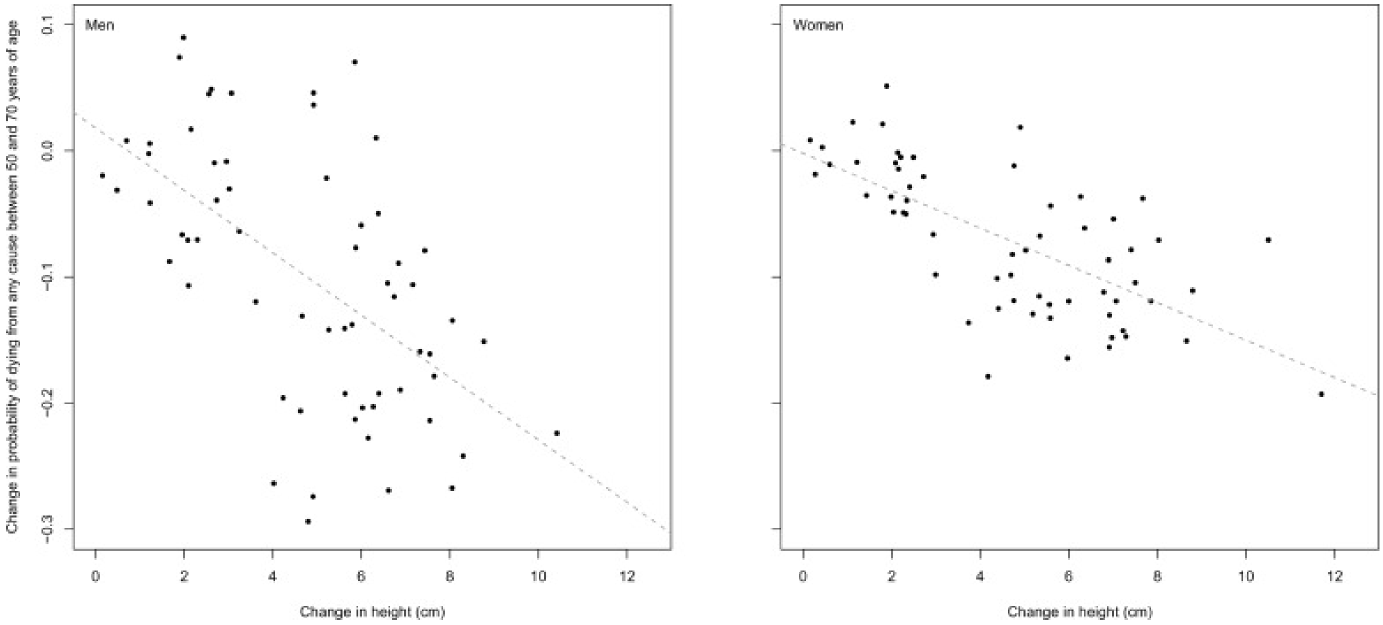


Change, over the 1928–1967 birth cohorts, in mean BMI vs. in mean height.

Each point shows one country. BMI change was calculated for mean BMI at 45–49 years of age – an age when diseases associated with excess weight become common but weight loss due to pre-existing disease is still uncommon. BMI data were available for 1975–2014 (NCD Risk Factor Collaboration, 2016); 45–49 year olds in these years correspond to 1928–1967 birth cohorts. BMI data were from a pooled analysis of 1698 population-based measurement studies with 19.2 million participants, with details reported elsewhere (NCD Risk Factor Collaboration, 2016).

DOI: http://dx.doi.org/10.7554/eLife.13410.012

Figure 11.



Association between change in probability of dying from any cause between 50 and 70 years of age and change in adult height by country for cohorts born between 1898 and 1946.

Probability of death was calculated using a cohort life table. Mortality data were available for 1950 to 2013. The 1898 birth cohort is the first cohort whose mortality experience at 50–54 years of age was seen in the data, and the 1946 birth cohort the last cohort whose mortality experience at 65–69 years of age was seen in the data. The dotted line shows the linear association. The 62 countries included have vital registration that is >80% complete and have data on all-cause mortality for at least 30 cohorts. The countries are Argentina, Australia, Austria, Azerbaijan, Belarus, Belgium, Belize, Brazil, Bulgaria, Canada, Chile, China (Hong Kong SAR), Colombia, Costa Rica, Croatia, Cuba, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Guatemala, Hungary, Iceland, Ireland, Israel, Italy, Japan, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Luxembourg, Macedonia (TFYR), Malta, Mauritius, Mexico, Moldova, Netherlands, New Zealand, Norway, Poland, Portugal, Puerto Rico, Romania, Russian Federation, Slovakia, Slovenia, South Korea, Spain, Sweden, Switzerland, Trinidad and Tobago, Turkmenistan, Ukraine, United Kingdom, United States of America, Uruguay, Uzbekistan and Venezuela.

DOI: http://dx.doi.org/10.7554/eLife.13410.013

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eLife. 2016; 5: e13410. » Decision letter

2016; 5: e13410.

Decision letter

Eduardo Franco, Reviewing editor
Eduardo Franco, McGill University, Canada;

In the interests of transparency, eLife includes the editorial decision letter and accompanying author responses. A lightly edited version of the letter sent to the authors after peer review is shown, indicating the most substantive concerns; minor comments are not usually included.

Thank you for submitting your work entitled "The height of the world – A century of trends in adult human height" for consideration by *eLife*. Your article has been reviewed by two peer reviewers, and the evaluation has been overseen by Eduardo Franco, as a Reviewing Editor, and Prabhat Jha, as the Senior Editor. M Dawn Teare, a Member of *eLife*'s Board of Reviewing Editors served as one of the reviewers and agreed to reveal her identity.

The reviewers have discussed the reviews with one another and the Reviewing Editor has drafted this decision to help you prepare a revised submission.

Summary:

This paper is a substantial and impressive report submitted on behalf of the NCD Risk Factor Collaboration. It represents a huge and extremely valuable new assemblage of data, including adult height measurements for around 15.4 million individuals born between 1896 and 1996 from 178 countries around the globe. Never before has such comprehensive data on stature been brought together, bearing on trends and differentials across the globe in health, nutrition, economy, and anthropometry. This collaborative group has published several papers now using this methodology, tackling a different health outcome in each paper. Here the health outcome is adult height and the team has systematically collected adult height measurements from 1450 studies from 178 countries for adults born between 1896 and 1996 and used a hierarchical Bayesian model to analyse trends over 100 years. Adult height lends itself nicely to this sort of analysis as the assumption is that height is pretty constant after 18, whereas weight (and hence BMI) is a much less stable measurement.

Essential revisions:

Structure and Organization:

The paper is difficult to read and some investment in visualisation tools would greatly enhance its value. The maps after the References section are very nice and easy to fit into the article in a pdf form. However, the country by gender plots need to be made a bit more accessible as these are the more interesting results summarizing the trends.

Please revise the Abstract and Introduction with due attention to providing factual material only. As they stand, the findings listed in the Abstract and Introduction would hardly justify publication. They are tidbits, engaging the curiosity of readers and showing off the scope of the assembled data, but not settling open questions of theoretical interest. Everyone knows that nutritional status across the world has not converged to some common level. Finding “no indication of convergence across countries” in mean adult heights is hardly news.

The paper has a number of strengths that do not come across in the Abstract. They have systematically searched for sampled measured data rather than self-reports; they have collected a large amount of data on women and have data from 178 countries. This means that the work is a substantial step up from other studies of trends in height. I think the paper is too short. Please explain the BMI analysis referred to in Figure 6.

The main text and figures are valuable. The 165 pages of Supplementary Information, in contrast, do not belong in the publication. The lists of NCD Risk Factor Collaborators and the long table of data sources belong on a Project Website with hyperlink pointers in the article, or perhaps as a separate appendix hosted in the journal. Some details of the validation study might reasonably belong an appendix, but the validation study as it stands is not entirely convincing. The uncertainties of importance relate to the out-of-sample-range extrapolations to timeframes and countries without datasets, whereas the cross-validation mainly measures success at within-sample-range interpolations within sets of times and cases where relevant datasets are available.

Data Analysis:

What is the specification of the Bayesian model in use here for filling in missing data and extrapolating back into the past and outward to nations with limited sets of direct measurements? The paper directs readers to Danaei et al., 2011 and Finucane et al., 2014 for details of the model, but the Bayesian models in those references pertain to systolic blood pressure and to health status, not to heights. Heights pose many different issues, particularly when only 70 of the 178 countries have data for cohorts born before 1920 and 22 of 200 countries for which estimates are generated have no data at all. Presumably, the model here incorporates features needed for application to heights, but nothing is spelled out. Toward the end of this review is a list of some of the model features that would seem important to describe.

In what form and under what arrangements are these data to be made available to the wider community of researchers? Is the creation of a data resource for heights along the lines of the Human Mortality Database and the Human Fertility Database underway? This question arises not only with regard to compliance with data-sharing requirements of *eLife* and other top journals, but also with regard to the wide range of scientific questions that could be addressed with these data. What is already treated in this paper hardly scratches the surface.

Please provide details on the Bayesian model regarding the following:

A) growth curves by age;

B) the "linear and non-linear" trends in mean age over time;

C) non-normality at younger and older ages;

D) variability in standard deviations and its relationship to the homogeneity or heterogeneity of each measured population;

E) smoothing (B-splines?);

F) covariance structures within region by age and time;

G) sample information with regard to measurement scales in centimeters or inches, with or without shoes (or unknown), degree of rounding, etc.

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eLife. 2016; 5: e13410. » Author response

2016; 5: e13410.

doi: 10.7554/eLife.13410.019

Author response

Essential revisions:

Structure and Organization:

The paper is difficult to read and some investment in visualisation tools would greatly enhance its value. The maps after the References section are very nice and easy to fit into the article in a pdf form. However, the country by gender plots need to be made a bit more accessible as these are the more interesting results summarizing the trends.

We take this comment to refer to old Figure 3 (new Figures 4 and 5), the long "ladder" plot of all countries. As the reviewer has correctly pointed out, with 200 countries, this figure would be best suited to a dynamic visualisation. We have developed the needed technology (see http://www.ncdrisc.org/ranking-bmi.html for what it looks likes for BMI) and will release similar graphs for height upon the paper's publication. If *eLife* system allows, the current static figure can be replaced with an embedded dynamic one on the Journal's website while the static one appears in the PDF. We would be happy to finalise the specifics with the Editors and the production team.

Please revise the Abstract and Introduction with due attention to providing factual material only. As they stand, the findings listed in the Abstract and Introduction would hardly justify publication. They are tidbits, engaging the curiosity of readers and showing off the scope of the assembled data, but not settling open questions of theoretical interest. Everyone knows that nutritional status across the world has not converged to some common level. Finding "no indication of convergence across countries" in mean adult heights is hardly news.

We have done as suggested for Abstract. The Introduction contains only a concise summary of current literature in the field, and the contribution of the paper; to the best of our ability, it is entirely factual.

The paper has a number of strengths that do not come across in the Abstract. They have systematically searched for sampled measured data rather than self-reports; they have collected a large amount of data on women and have data from 178 countries. This means that the work is a substantial step up from other studies of trends in height. I think the paper is too short. Please explain the BMI analysis referred to in Figure 6.

We understand that the Abstract is restricted to ~150 words. With this constraint in mind, we have stated that the data used in the paper were from "reanalysis" of "population-based studies with measurement of height" and have stated the number of studies and participants.

The paper that presents the BMI analysis is now published and has been cited (NCD Risk Factor Collaboration, 2016), together with a concise statement on its scope. We would be happy to provide more information in this paper if it is deemed informative to repeat the materials here.

The main text and figures are valuable. The 165 pages of Supplementary Information, in contrast, do not belong in the publication. The lists of NCD Risk Factor Collaborators and the long table of data sources belong on a Project Website with hyperlink pointers in the article, or perhaps as a separate appendix hosted in the journal. Some details of the validation study might reasonably belong an appendix, but the validation study as it stands is not entirely convincing. The uncertainties of importance relate to the out-of-sample-range extrapolations to timeframes and countries without datasets, whereas the cross-validation mainly measures success at within-sample-range interpolations within sets of times and cases where relevant datasets are available.

We request to keep the list of data sources because it is increasingly the norm in presenting global health estimates to state the data sources used in the analysis (soon to become a part of reporting guidelines). We have removed the country-specific graphs as suggested, and will show these on NCD-RisC website upon the paper's publication.

Our data use agreement with our collaborators requires listing all of the authors, which has been done even in print journals (see for example http://www.thelancet.com/journals/lancet/article/PIIS0140-6736(16)30054-X/fulltext and http://www.thelancet.com/journals/lancet/article/PIIS0140-6736(16)00618-8/fulltext; see http://www.ncbi.nlm.nih.gov/pubmed/26109024 for how this appears in PubMed). Therefore, we request to be allowed to include the full list of authors especially given that *eLife* is published online.

The validation analysis is entirely out of sample validation. We removed data for specific countries (i.e. they are no longer in the sample of countries with data) and tested how well the model predicts the known-but-withheld/removed data. We have attempted to clarify this procedure in the revised paper (subsection “Author contributions”).

Data Analysis:

What is the specification of the Bayesian model in use here for filling in missing data and extrapolating back into the past and outward to nations with limited sets of direct measurements? The paper directs readers to Danaei et al., 2011 and Finucane et al., 2014 for details of the model, but the Bayesian models in those references pertain to systolic blood pressure and to health status, not to heights. Heights pose many different issues, particularly when only 70 of the 178 countries have data for cohorts born before 1920 and 22 of 200 countries for which estimates are generated have no data at all. Presumably, the model here incorporates features needed for application to heights, but nothing is spelled out. Toward the end of this review is a list of some of the model features that would seem important to describe.

One of the two papers cited is a methodological paper that lays out the Bayesian model used here; the appendix of the other has full model specification even if the paper’s substance involves its application to blood pressure. Nonetheless, as suggested below, we have added additional details regarding the model (subsection “Statistical methods”, fourth paragraph).

In what form and under what arrangements are these data to be made available to the wider community of researchers? Is the creation of a data resource for heights along the lines of the Human Mortality Database and the Human Fertility Database underway? This question arises not only with regard to compliance with data-sharing requirements of eLife and other top journals, but also with regard to the wide range of scientific questions that could be addressed with these data. What is already treated in this paper hardly scratches the surface.

NCD-RisC is a data pooling analysis that uses secondary data. Some of our data are from public sources and we would be happy to point others to the relevant sites for these sources, or provide the data. Other sources are provided either by specific scientists or national health agencies. For these, we will be happy to provide contact information of the data provider for requests to be made.

Please provide details on the Bayesian model regarding the following:

A) growth curves by age;

We have specified the age component of the model (subsection “Statistical methods”, fourth paragraph), noting that we model population mean height over age from age 18, so it is not growth at the individual level.

B) the “linear and non-linear” trends in mean age over time;

Done (subsection “Statistical methods”, fourth paragraph).

C) non-normality at younger and older ages;

We do not model individual height, for which non-normality may be an issue. Rather our analysis models mean height of the population, and its distribution across countries and health surveys. We rely on standard central limit theorem as justification for treating *mean height* as normally distributed across countries/surveys (Finucane et al., 2014) with error around the true population mean, which is the quantity of interest. We also considered (and have used elsewhere (Stevens et al, 2012; Finucane et al., 2015) a t distribution which, by having heavier tails, allows for outlier studies. The results of the current analysis were not sensitive to choice, confirming that the normal prior appropriately described the distribution of mean height.

D) variability in standard deviations and its relationship to the homogeneity or heterogeneity of each measured population;

As mentioned above, the analysis and modelling are of the mean height, so the only relevant standard deviation is the standard error of the sample means. Standard errors were computed together with sample means when NCD-RisC members re-analysed each data source. The standard deviations of each data source study are reflected in the standard errors used in specifying the distribution of the sample means.

E) smoothing (B-splines?);

The smoothing of time trends is done using a 2nd order conditional auto-regressive model (also known as random walk), specified in the revised paper with appropriate citation (subsection “Statistical methods”, second paragraph).

F) covariance structures within region by age and time;

The covariance between different birth cohorts (i.e., the time scale in our model) is induced by the conditional auto-regressive structure. Formally, the auto-regressive model induces a particular precision (inverse covariance) structure for cohorts within a country and the induced covariance is therefore the inverse of that. The linear and non-linear components of this auto-regressive structure, as well as its intercept, are modelled hierarchically so the effects for each country borrow from the region to the extent that the data suggest that countries within a region have similar levels and trends across cohort. This induces covariance between countries within a region, even if not modelled explicitly. Such hierarchical structure is a standard strategy for accounting for dependence in statistical modelling. With regard to age, as stated in the revised paper, population mean adult height declined by only a small amount as the birth cohort ages (subsection “Statistical methods”, second paragraph). Nonetheless, the use of an age model introduces dependence in height over age.

G) sample information with regard to measurement scales in centimeters or inches, with or without shoes (or unknown), degree of rounding, etc.

A few data sources were in inches or meters and were converted to centimetres, which is of course an entirely deterministic calculation. To our knowledge, self-report is the single most important source of bias in adult height data. A major strength of our paper is the exclusive use of measured data and the exclusion of self-reported height. Removal of shoes is a part of the standard protocol of health and nutrition surveys (Madden et al, 2016). Our sources are high-quality health/nutrition surveys and epidemiological studies, and we expect removing shoes to be a part of their protocol. We have nonetheless stated measurement error as a potential limitation of population-based data (Discussion, sixth paragraph).

References

Finucane MM, Paciorek CJ, Stevens GA, Ezzati M. Semiparametric Bayesian density estimation with disparate data sources: a meta-analysis of global childhood undernutrition. J Am Stat Assoc 2015; 110(511): 889-901.

Madden AM, Smith S. Body composition and morphological assessment of nutritional status in adults: a review of anthropometric variables. J Hum Nutr Diet 2016; 29(1): 7-25.
