Lead Article

Adult height, nutrition, and population health

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In this review, the potential causes and consequences of adult height, a measure of cumulative net nutrition, in modern populations are summarized. The mechanisms linking adult height and health are examined, with a focus on the role of potential confounders. Evidence across studies indicates that short adult height (reflecting growth retardation) in low- and middle-income countries is driven by environmental conditions, especially net nutrition during early years. Some of the associations of height with health and social outcomes potentially reflect the association between these environmental factors and such outcomes. These conditions are manifested in the substantial differences in adult height that exist between and within countries and over time. This review suggests that adult height is a useful marker of variation in cumulative net nutrition, biological deprivation, and standard of living between and within populations and should be routinely measured. Linkages between adult height and health, within and across generations, suggest that adult height may be a potential tool for monitoring health conditions and that programs focused on offspring outcomes may consider maternal height as a potentially important influence.

INTRODUCTION

Human anthropometric history as it relates to standards of living has long been a focus of research in a range of social science disciplines.[1–35] Indeed, an abundance of studies describe relationships between child and adult height, nutrition, socioeconomic status, and health and show links between secular increases in height and key indicators of development and population health, with a recent review examining variation in height from an evolutionary perspective.[36] Given that average adult height has significantly increased in a short period of time in high-income countries, the pace of change cannot be attributable to changes in the gene pool.[37] Previous studies suggest that overall improvements in access to food, dietary diversification, sanitation, water, living standards, and decreasing exposure to disease are responsible for the secular increases in height occurring in the 19th and 20th centuries across many developed countries.[19,38,39] Notably, these factors are also related to nutrition and, ultimately, to mortality. Thus, adult height may be a potential marker for tracking cumulative net nutrition and population health over time.

Despite the large volume of published information on modern adult height, there has been little integration of the epidemiological and the population health perspectives on modern adult height. Here, modern adult height refers to height of humans over approximately

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the last 100 years. This lack of a conceptual map clouds understanding of the potential role of adult height in population health and development, and hinders the argument for including adult height as a key indicator of cumulative net nutrition and other exposure-related improvements. Therefore, a review of results across studies on modern adult height (as both an outcome and an explanatory factor) would help clarify the role of adult height in tracking nutritional improvements, biological deprivation, and population health. Building on previous articles exploring some of the pathways linking height and health,[12,40,41] an integrated discussion is presented on the set of potential mechanisms and pathways by which various factors affect adult height and by which height affects health, including intergenerational linkages. Specifically, several aims were established for this review: (1) Summarize the patterns, determinants, and health and development consequences of modern adult height as described in studies identified as salient to this review; (2) Outline known mechanisms linking modern adult height to nutrition, socioeconomic status, health, and intergenerational outcomes; (3) Identify challenges for causal inference when examining the consequences of height; and (4) Examine the relevance of adult height to the tracking of nutrition and population health improvements.

Before addressing these aims, the growth periods related to stature, which will reflect attained adult height via cumulative net nutrition, will be reviewed. This information provides a foundation from which to understand the discussions that follow regarding determinants and consequences of adult height as well as the basis on which using adult height and its distribution as potential measures of cumulative health capital at the population level is suggested.

AUXOLOGY: THE STUDY OF LINEAR PHYSICAL GROWTH AMONG HUMANS

Two growth periods are important for determining adult height: growth occurring from conception to 2 years of age, and growth occurring during adolescence before the onset of puberty. Adult height is primarily established during the first growth period in early childhood,[42] when nutritional requirements are greater than at any subsequent time and when infections, particularly diarrheal diseases, occur most frequently. The second growth period presents an opportunity for "catch-up growth," defined as body growth that is more rapid than normal for age and follows a period of growth inhibition.[2,43] The principal mechanism of catch-up growth appears to be delayed onset of puberty and therefore a longer period of growth in individuals with previous growth retardation. The timing and duration of catch-up growth may vary. Although there is debate as to the extent to which catch-up growth can occur after 2 years of age,[44,45] it appears that catch-up growth is not sufficient to fully make up for deficiencies in the first growth period and achieve full growth potential.[45–49] In terms of gender differences, age at menarche is linked with adult height in girls and has shown large changes over time,[50,51] which may explain diverging male–female height ratios,[52] although girls generally start growing earlier, attain adult height earlier and are shorter than boys.[53] Growth trajectories are similar across countries during the first few months of an infant's life, lag behind during the postweaning period in low- and middle-income countries, and are again similar after the age of 2 years.[54]

In sum, adult height represents the balance between nutritional intake and losses over time (particularly during the growth periods), including losses due to physical activity, psychological stress, and disease from conception to maturity.[55] As such, adult height is the product of cumulative net nutrition during the two growth periods (as well as genetics) and is relatively fixed as compared with child or youth height (which may not yet fully represent any effects of catch-up growth). Moreover, adult height, as a measure of *cumulative* net nutrition, differs from body mass index or weight-for-height, which is a measure of *current* net nutrition and is reflective of the immediate environment.

IDENTIFYING ARTICLES ON THE EPIDEMIOLOGY OF HEIGHT

Articles cited in this review were found through a search of the PubMed and ISI Web of Knowledge databases, using the terms "height," "stature," "body height," and "anthropometry" as keywords. Papers deemed relevant to a narrative review specifically addressing modern adult height were selected and included systematic reviews and meta-analyses, where available, in favor of individual papers discussing the same relationships. Emphasis was placed on publications from the past 25 years and included seminal papers, regardless of publication date. Additionally, searches for conference presentations and book chapters were performed, and reference lists of publications and reports identified by this search strategy also were reviewed. Articles on nonhuman height and those related to specific stature disorders were excluded.

While height is generally defined as the distance from the bottom of the foot to the top of the head when standing erect, adult height was measured in different ways across publications, and the biases associated with each method can lead to incomparability of recordings of adult height between sources and across time. For example, although recumbent or free-standing height is considered the gold standard, biases may arise due to behavior of the person taking the measurement, lack of precision and standardization of measurement instruments, diurnal variation (loss of about 1% of overall height during the day), subject behavior, change in instruments used, and the wearing of shoes (or not) during measurement. Finally, although self-reported height data is the easiest to collect, reports are upwardly biased in older individuals, shorter men, and heavier women, and in general there is greater bias in men than in women.[56–58]

PATTERNS OF MODERN ADULT HEIGHT

Secular increases

Since the Industrial Revolution, records of adult stature have shown unprecedented increases in average adult heights.[19,38,39] There is evidence, however, that average modern adult heights have been stagnating or actually declining, particularly in Africa and when considered relative to Western European countries.[17,59–61] Using data from the World Health Surveys (2002–2004)[62] to assess these claims, the correlation between mean adult self-reported height and increasing birth cohort (1934–1948; 1949–1963; 1964–1978) representing decreasing age cohorts (55–69, 40–54, and 25–39 years) was calculated. The smallest increases in adult height during this time period occurred in Africa (correlation = 0.01), and the greatest increases in adult height occurred in Europe (correlation = 0.25) (Figure 1). The four other regions defined by the World Health Organization had correlations ranging from 0.11 to 0.15 across the three age cohorts. With data from the World Bank included, a regression analysis of adult height on year of birth was conducted while adjusting for wealth quintile and country fixed effects and stratifying by sex and World Bank income classification. It was estimated that the largest gains in average adult height occurred for people born from 1930 to 1980 in the wealthiest countries, while height gains in the poorest countries stagnated, on average, during the same period (Figure 2).

Given its association with economic development, the average adult height of a population may be a useful indicator of access to nutrition and exposure to disease environments, representing a "biological standard of living."[12] A recent study found that between 43% and 68% of increases in adult height in Brazil between 1950 and 1980 were associated with increases in gross domestic product per capita.[63] In addition, adult height may be a better indicator of overall population health and development than some traditional measures, such as infant mortality. A study of trends in height, health,

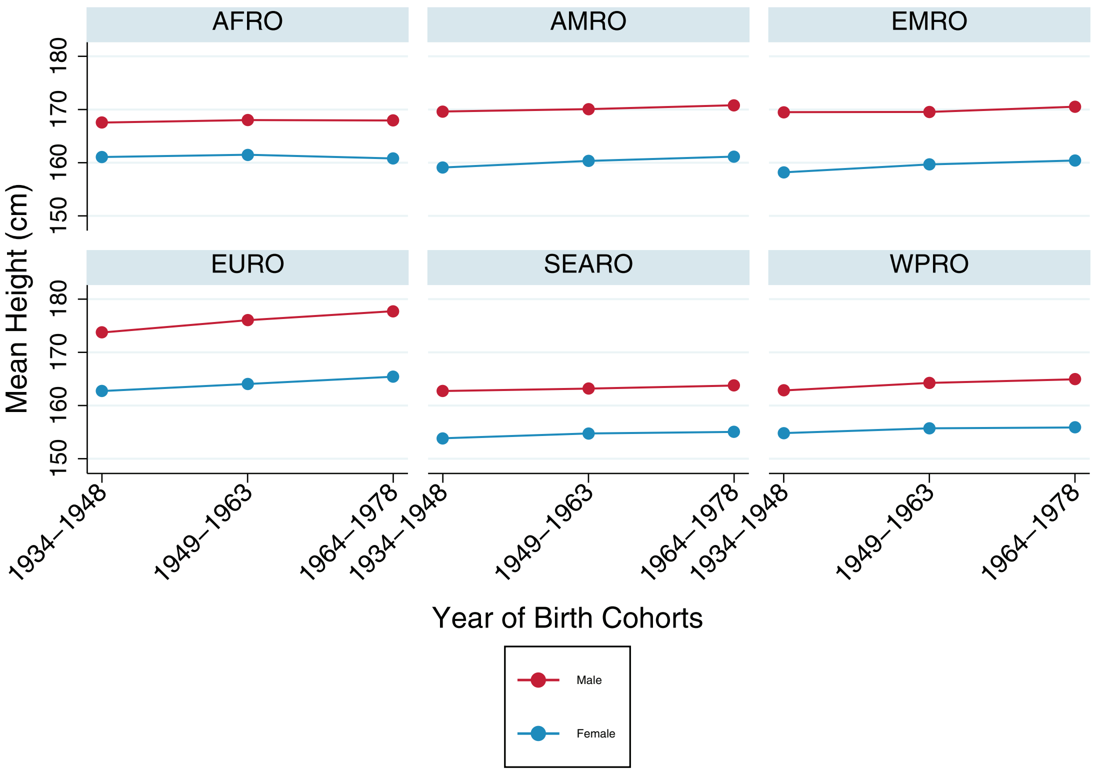

Figure 1 **Average height (in cm) of adult men and women by year of birth category and World Health Organization (WHO) region.** Data are from the 2003 World Health Surveys. The correlation of height with age group (represented by birth cohorts) for each WHO region is as follows: Africa (AFRO), 0.01; South-East Asia (SEARO), 0.10; the Americas (AMRO), 0.13; the Eastern Mediterranean (EMRO), 0.13; the Western Pacific (WPRO), 0.15; and Europe (EURO), 0.23.

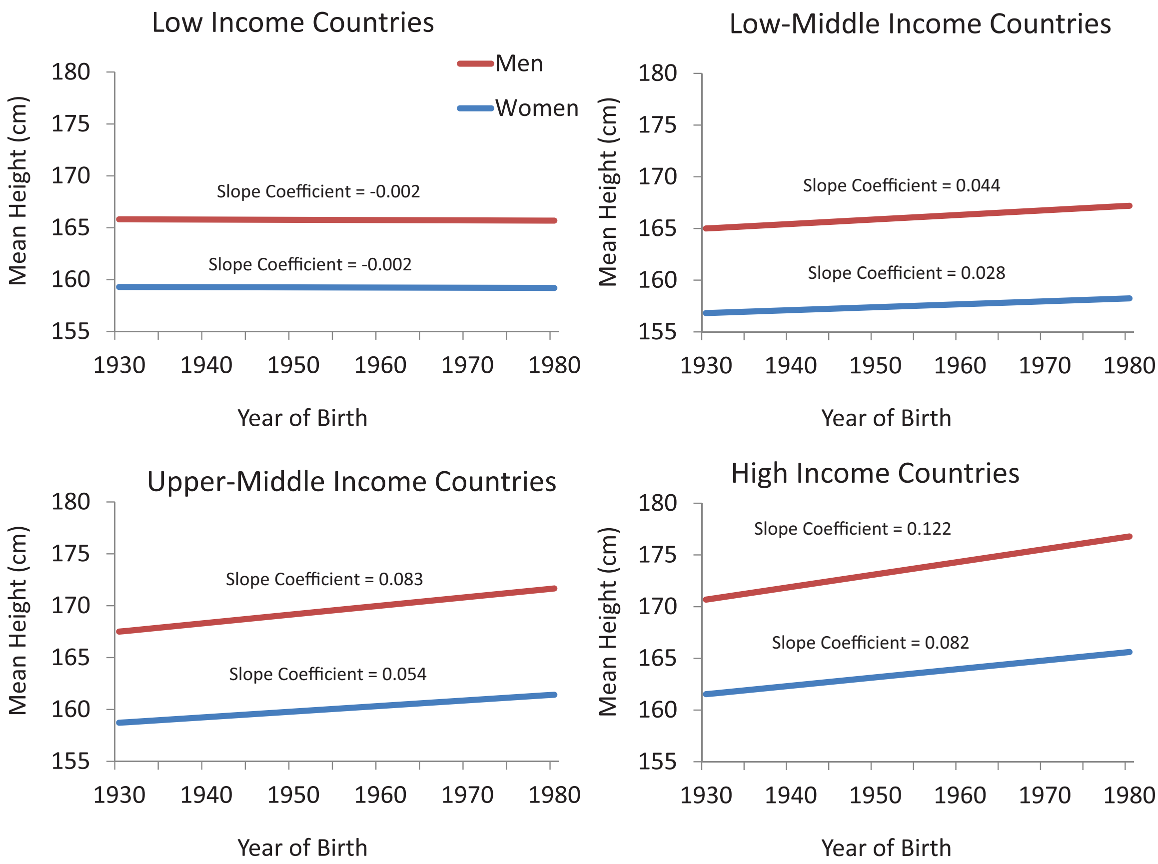

Figure 2 **Predicted association between height and year of birth by sex and World Bank income classification.** Data are from the 2003 World Health Surveys and the World Bank. Models were adjusted for wealth quintile (derived from an asset index) and country fixed effects, and estimates were calculated using robust standard errors, taking into account clustering by primary sampling units.

and infant mortality in sub-Saharan Africa showed that, although infant mortality had improved since 1961, average adult heights had not increased.[64]

Between- vs within-country variation in adult height

According to country-average adult heights calculated from self-reported data obtained through the World Health Surveys, there is large variation in height globally, even within high-income countries (Figure 3). The tallest countries are in Western Europe, whereas the shortest are concentrated in sub-Saharan Africa and Southeast Asia. The biggest gender differences are in the tallest countries (the correlation between average height and the gender gap is 0.7), suggesting that sexual dimorphism is more pronounced where undernutrition and childhood disease are mitigated. However, within-country variance dominates differences between countries, and country averages mask group differences within countries, particularly between socioeconomic and ethnic groups.[59] There are strong positive associations between adult height and household wealth and education across many countries (and within-country, the urban–rural differences in height appearing to depend largely on socioeconomic circumstances).[11,59,65,66] Moreover, trends in the relation between socioeconomic status and adult height may not have changed much in recent decades, indicating persistent social inequalities in height.[67] It is possible, however, that the link may be nonlinear and weaker for women.[68]

Notably, social and environmental differences both within and between countries dominate any genetic variation between groups in determining average adult heights.[59] This is exemplified by the greater height of children of Mayan immigrants in the United States as compared with Mayan children in Guatemala[69] or in the difference in height between the Koreas, where South Koreans, on average, are 13 cm taller than North Koreans.[70] There may, however, be a genetic component to some cross-country differences, with adaptation of height to different environments, most notably for Pygmy populations in isolated rainforests.[71]

DETERMINANTS OF ADULT HEIGHT

This section reviews the etiology of adult height in modern populations, extending previous work on the

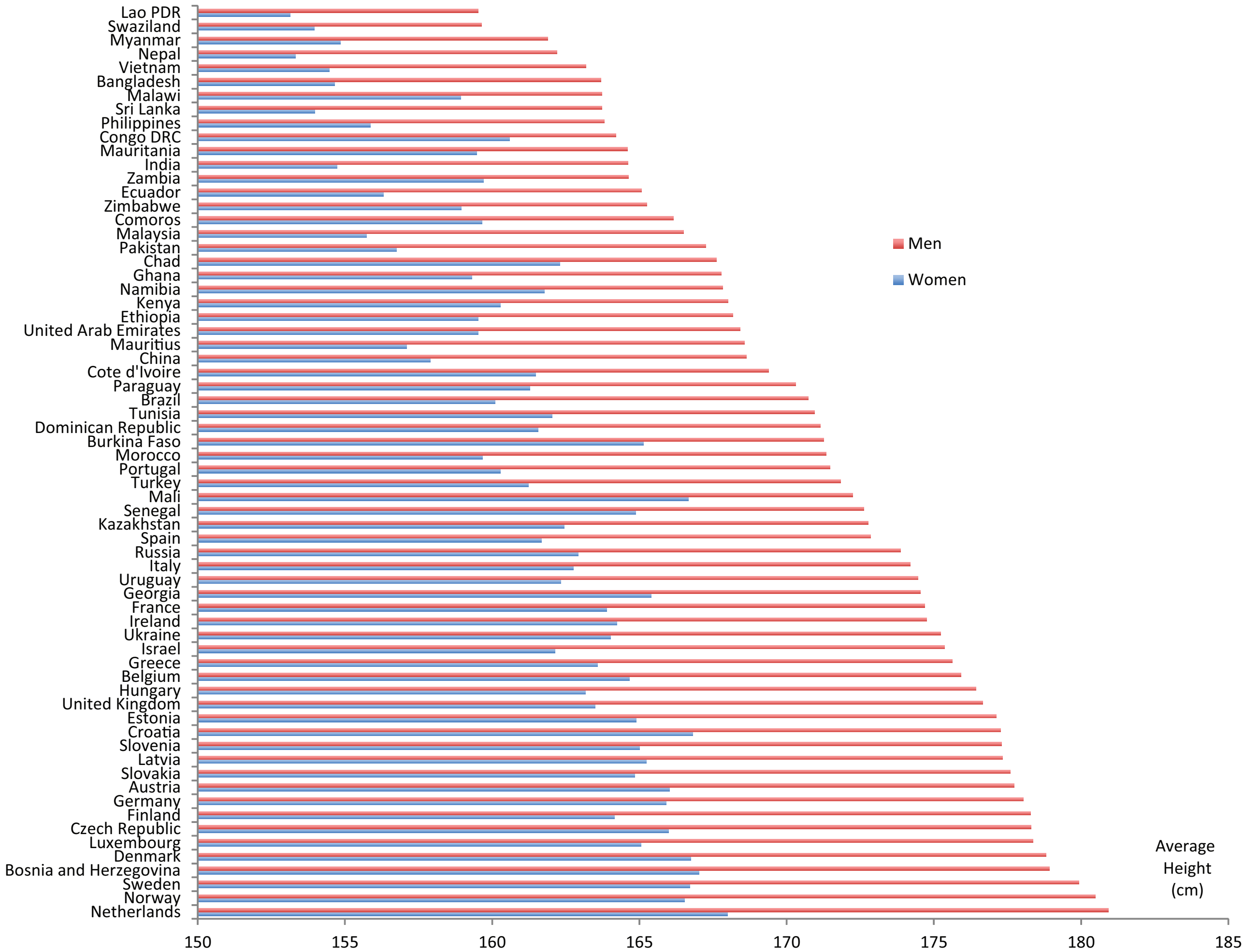

Figure 3 **Mean height (in cm) of adult men and women across countries.** The 2003 World Health Surveys measure self-reported heights for de facto populations, although surveys in India and China were not nationally representative. Mean heights for countries, calculated by the authors, are sample-weighted and age standardized by sex to the average World Health Surveys population.

determinants of modern adult height.[14] It first focuses on the key proximal roles of nutrition and disease, then describes genetic factors, and finally discusses the critical distal role of socioeconomic status.

Nutrition

Nutrition is the most important external factor affecting linear growth.[72] Growth retardation is often a response to a limited supply of nutrition at the cellular level, whereby maintenance of basic metabolic functions takes precedence and resources are diverted from growth.[42] Critically, different nutritional components received during both the in utero and the postnatal periods are linked to adult height.[73] For example, nutritional factors during pregnancy are associated with intrauterine growth retardation, premature birth, and low birth weight.[74–77] In turn, these consequences are associated with adult height. A recent study found that birth weight was inversely associated with adult height across five low- and middle-income countries after adjusting for several confounders.[78] In addition, being small for gestational age (a condition in which the weight and the crown-heel length of infants are less than 2 standard deviations below reference[48]) is related to adult height.[79] Maternal supplementation with micronutrients, iodine, iron, folate, and calcium, has been found to reduce the risk of small-for-gestational-age births.[80]

Nutrition affects growth more in the postnatal period than in the prenatal period.[73] In general, protein is the most essential single nutrient, followed by minerals and vitamins A and D.[73] A study of geographic differences in stature among young men from 45 countries of European origin demonstrated that nutrition level explained most of the differences in adult height, particularly the consumption of high-quality proteins from milk, pork, fish, and wheat.[81] Similarly, milk consumption was positively associated with adult height among a nationally representative sample from the United States.[82] In particular, increased consumption of cow's milk is associated with linear growth,[83] although there may be something specific to milk itself besides milk protein. One trial in India showed that children born within a community-based intervention offering nutrition supplementation during pregnancy and early childhood were 14 mm taller than the control group and had a reduced risk of cardiovascular disease upon reaching adolescence.[84] However, evidence of an impact of postnatal nutrition interventions on adult height remains weak overall. A small trial from Guatemala indicated that maternal and childhood nutritional protein supplementation had no effect on later young adult blood pressure and no attributable impact on adult height.[85] Another study from the Gambia demonstrated no difference in late adolescent height following supplementary maternal feeding during pregnancy and maternal supplementation during lactation.[86]

Disease

Nutrition and disease are synergetic, with decreased nutrient intake making infections more likely. In turn, disease can affect growth by hindering food intake, absorption, and nutrient transport to tissues, causing direct nutrient loss, increasing metabolic requirements, or affecting bone growth or density.[73] Indeed, in addition to poor nutrient intake, diarrheal diseases are the other main reason for growth failure in early childhood. Infections (most notably those causing diarrhea), hookworms, and intestinal parasites can affect stature, while fevers and respiratory tract infections can sap nutrients and inflammatory diseases can hinder growth of long bones.[73,87,88] In addition, asthma has also been associated with reduced stature in high-income countries, as has the incidence of any major disease in childhood.[73,89,90] Moreover, treatments for some diseases may themselves retard growth.[91,92]

Genetics

Height is one of the earliest human traits for which the concept we now term heritability—the component of phenotypic variance within a population that is attributable to genetic variation—was discussed and investigated.[93,94] According to twin studies in high-income countries, estimates of the genetic component of the variation of height are about 80%, with lower estimates for women than for men.[95–97] The underlying assumptions for heritability estimates based on twin studies, however, can be problematic.[98] In recent years, genome-wide association studies have allowed the contribution of identified common genetic variants (single-nucleotide polymorphisms) to the proportion of variation in height that is attributable to them to be estimated.[99] Several of these studies showed that confirmed and identified variants account for a relatively small proportion of the variance in height (around 20%).[100–102] However, studies using a conglomeration of common single-nucleotide polymorphism variants, but not specific genetic loci, and studies using genome-wide complex trait analysis, which combines information from all common, rare, and imputed single-nucleotide polymorphism variants that exist in principle, find that the those variants, all together, are associated with about 60% of the variation in height that is attributable to genetics.[103–106] These modern methods show, however, that known genetic loci only account for a small proportion of the estimated heritability of height.[107]

In general, genome-wide association studies have shown that height is a polygenetic trait controlled by many genes, each with a small effect. Notwithstanding the contribution of genetics to explaining variation in height between individuals, genetics is unlikely to be a major contributor to explaining mean differences in height across populations and changes in height over time. Furthermore, height heritability estimates may be lower in low- and middle-income countries because of the increased importance of height determinants such as nutrition, disease, and socioeconomic conditions during the critical periods of growth. Indeed, several twin studies have demonstrated lower estimates of heritability for people in low- and middle-income countries.[108,109]

Socioeconomic status

Parental social class, poor socioeconomic conditions (as indexed by income, education, and occupation, for example), and maternal education are all important predictors of adult height because these characteristics represent access to resources, exposure to risk factors, and health behaviors of the mother.[73,87] Indeed, they are critically intertwined with nutrition and disease during the two critical periods of growth. Challenges to growth include overcrowding, reduced access to healthcare, poor infant feeding practices, poor nature of local diet, and contamination of foods/liquids, all of which impact net nutrition. Environmental exposures in poor socioeconomic areas, such as the consumption of aflatoxin, may also retard growth.[110,111]

The dependence of height on socioeconomic circumstances, however, may lessen as populations become wealthier. For example, the socioeconomic gradient in adult height, though still existing, decreased (by about 2 cm) among Swedish men from 1818 to 1968.[112] A similar trend was found among men born in Spain from 1859 to 1967.[113] The social gradient of adult height in young adults in a UK birth cohort appears to be entirely dependent on the height of the parents.[114] While discussing the relationship between income and height, it is important to note that the relationship between average adult height and income is nonlinear and that average population height can be dependent on socioeconomic distribution; transferring income to poor families would increase average height because, while children from poor families would grow, children from wealthy families would not lose any part of their cumulative net nutrition (as they already have more than enough).

In sum, variation in modern adult height substantially reflects differences in environmental conditions, which ultimately affect cumulative net nutrition. Environmental conditions refers to all factors within a context that affect availability of, access to, and use of resources, as well as exposure to health risks. Such factors include appropriate nutrition, socioeconomic status of individuals, characteristics of households or places, access to and quality of health services, and exposure to certain diseases and climates. Importantly, these factors do not operate in isolation or in sequential order; conditions may be relevant at multiple time points, operate across multiple levels, and exhibit substantial effect modification. The level of exposure to factors negatively affecting net nutrition remains high in many low- and middle-income countries experiencing minimal nutritional, sanitation, and water-supply related improvements in recent decades. These exposures can lead to undernutrition, child stunting, and ultimately to a failure to reach one's genetic adult height potential. While there is variation at the individual level, average adult height in low-resource contexts is lower than genetically possible. By comparing average adult height across populations, the extent of variation in exposures affecting cumulative net nutrition for cohorts, particularly during the first growth period, can be determined. Indeed, modern adult height may offer an important window into understanding improvements in population health, nutrition, and development over time.

CONSEQUENCES OF HEIGHT

In this section, the role of adult height as a determinant of adult health, access to resources, and the health of future generations is examined. To do so, evidence of the relationship between adult height and various manifestations of morbidity and causes of mortality is presented. Then, evidence that links adult height to socioeconomic status, education, well-being, and the health and height of offspring is provided.

Mortality and morbidity

In general, the association between adult height and cause-specific mortality is heterogeneous.[115] However, some disease-specific associations are strong enough that the use of height as a variable in screening for these conditions may be explored. The strongest negative associations between adult height and cause-specific mortality (and morbidity) are found for respiratory and cardiovascular diseases across different populations.[115–119] A review of 52 studies on coronary heart disease concluded there was enough evidence to indicate a relationship between adult height and coronary heart disease–related morbidity and mortality; shorter adults had about a 50% greater risk than taller adults.[117] In addition, a recent study found a positive relationship between sudden cardiac arrest and adult height.[120] Yet, in a prospective study of men and women in Japan, Honjo et al.[121] found no relationship between height and coronary heart disease after adjusting for education, although height was inversely associated with total risk of hemorrhagic or ischemic stroke. In contrast, adult height is positively associated with risk of pulmonary and aortic aneurysms,[115] coronary artery calcium,[122] weight gain and obesity,[123] and venous thromboembolism in men.[124] A recent study found that tallness was associated with lower risk of ischemic heart disease and premature death but was associated with increased risk of atrial fibrillation.[125] In that study, stature was not associated with stroke or venous thromboembolism in men. Another study also found that, independent of gender, adult height was positively associated with risk of atrial fibrillation.[126] Separately, tallness may confer protection against glucose intolerance[127] and high cholesterol.[128]

Several studies have found a positive association between adult height and various types of cancer, including malignancies of the colorectum, breast, head and neck, ovaries, skin, endometrium, central nervous system, blood, liver, thyroid, brain (gliomas), and lymphatic system.[115,116,129–138] Conversely, tallness may confer protection from neoplasms of the stomach,[116] esophagus, and mouth, although discrepant findings have been reported.[131,132,139] No consistent differences in associations between sex, regions, or populations have been found.[132]

Despite mixed findings on the relationship between adult height and cause-specific mortality and morbidity, the historical epidemiological literature indicates a strong inverse relationship between adult height and all-cause mortality.[6,140,141] Moreover, the increase in life expectancy in the 19th and 20th centuries has been attributed to key determinants of stature (i.e., improved nutrition and lowered rates of infection and trauma),[142] and the risk of mortality has been shown to increase with decreasing height.[73,129,143] Subpopulation differences are less clear across studies, even though a dose–response relationship between height and all-cause mortality has been suggested for men and a threshold effect for women.[143] A recent study of the association between adult height and health in later life found that height was positively associated with lung function, grip function, good self-reported health, and no difficulties with activities of daily living or instrumental activities of daily living across six low- and middle-income countries.[144]

Socioeconomic status and education

Adult height is strongly associated with both higher income and higher level of education in modern populations and is a predictor of economic productivity, with taller people earning more and being more likely to be in the workforce,[145] even after controlling for education[146,147] and productivity.[148] Taller people have also been shown to be more socially upwardly mobile,[73] which will perpetuate the socioeconomic gradient in height. For example, in the Philippines, higher length-for-age at age 2 years was associated with a 40% increase in likelihood of formal work as an adult.[149] In addition, data from the United States showed that comparing women and men of below-average height with those of above-average height corresponded to an 18% increase in family income for women and a 24% increase for men.[150] While part of this association may reflect the positive correlation between height and intelligence,[151,152] it is not possible to reliably separate socioenvironmental from genetic contributions to this correlation.

Finally, within populations, some studies have found that adult height is positively correlated with cognitive functions, such as memory and numeracy.[153,154] A recent study found that height among adults aged 50 years or older was positively associated with cognitive ability (measured as a summary score of memory, numeracy, and verbal fluency) even after adjustment for an extensive set of controls.[155] This study also provided some evidence of an association between height and cognitive ability across countries for pre-1950 birth cohort respondents; moreover, taller height was associated with smaller decreases in age-related cognitive function. Another study in the urban elderly in Latin America and the Caribbean found a positive association between height and later-life cognition, and this association was stronger among women than among men.[156] Separately, stunting has been noted as a marker for poor psychological performance[157] and as being associated with lower school attainment resulting from late school entry, more grade repetition, and increased likelihood of early dropout.[158] Supporting these findings, a review of height in low- and middle-income countries reported that height-for-age at 2 years was the best predictor of human capital.[159] While some twin studies have shown that the taller twin completed more education and earned higher wages,[160] one twin study suggested that genetic factors explained the association of adult height and intelligence or could interact with environmental factors to explain the association.[161]

Well-being

Overall, taller individuals consistently report better health and less illness[162] and better results on various well-being measures, including enjoyment, happiness, sadness, physical pain, and social activity.[150,163] Tall people, however, are also more likely to report stress and anger and, for women, worry.[150] Most of the associations between stature and these measures may be accounted for by income and education.[150] Yet, even when controlling for socioeconomic position, adult height is inversely associated with lowered risk of depression and suicide[164] and demonstrates a positive association with psychological well-being,[165] although there may be gender differences in this association.[166] Adult height is positively correlated with higher IQ[167] and higher achievement in cognitive testing.[168] Although these associations are evident in modern societies, they may not appear in traditional ones.[169]

Offspring health

Maternal height is strongly associated with reproductive success.[170,171] For example, several studies have shown inverse associations between maternal adult height and risk of congenital malformations,[172] poor fetal growth,[173] preterm births,[174] premature labor,[75] low birth weight,[175] stillbirths,[176] assisted delivery,[177] and cesarean deliveries.[178] One study in women from different countries found that maternal height was associated with child height during all periods of development (intrauterine, birth to age 2 years, age 2 years to mid-childhood, and mid-childhood to adulthood).[179] In addition, lower maternal height may be a risk factor for child mortality, underweight, and stunting across low- and middle-income countries.[180,181] Moreover, parental height (and, in particular, maternal height) may also be inversely associated with offspring coronary heart disease,[182] although evidence on the particular effect of maternal height is mixed,[183] and maternal childhood growth may be linked to offspring growth.[184] Indeed, maternal adult height is an exemplary intergenerational factor. Intergenerational factors are defined as "those factors, conditions, exposures, and environments experienced by one generation that relate to the health, growth and development of the next generation."[185]

In summary, adult height is associated with a myriad of health and well-being outcomes, relationships that often remain even when adjusting for potential confounders. Moreover, height may affect multiple outcomes, which may, in turn, affect each other. Given the potential for shorter maternal height to produce intergenerational consequences at the individual level, which can, in aggregate, lead to continued high levels of child stunting at the population level, particularly in contexts of limited nutrition,[186] average adult height, if tracked over time, can be an important indicator of changes, or lack thereof, in health, well-being, and socioeconomic inequalities in populations. Further research on maternal height, in particular in the context of studies that can compare the influence of maternal and paternal height on offspring outcomes, is required.

MECHANISMS LINKING ADULT HEIGHT TO HEALTH AND SOCIOECONOMIC STATUS

This review of potential determinants and consequences suggests that adult height is both affected by, and affects, health, nutrition, and socioeconomic status, and that these environmental conditions are critical to the height and health of future generations. Unfortunately, few studies examining height have a design that facilitates clear causal inference (e.g., determination of which factors are most relevant and in which order they are likely to affect each other). Discussing what may be behind these associations, however, will help to reveal both the usefulness of adult height as a screening criterion for biological deprivation, standard of living, and nutritional deprivation and the degree to which the causal factors potentially underlying the associations are amenable to intervention. Therefore, in the sections below, the mechanisms linking adult height to health, socioeconomic status, and intergenerational factors are analyzed, while allowing for the possibility that these relationships may be partially or entirely due to unobserved factors.

Mechanisms

There are at least four possible mechanisms that could underlie the associations between adult height and health, socioeconomic, and intergenerational outcomes.[187] (1) *Biomechanical*[42]: Height confers advantages and disadvantages related to body and organ size and function that have health and reproductive consequences; (2) *Biological*[14]: Height is an indicator of health capital, and growth, as well as rate of growth at different periods, has metabolic effects that translate into lifelong and intergenerational health consequences; (3) *Genetic*[104]: Factors that influence growth may be tied to risks for disease or ability, and their joint transmission creates associations between height and these outcomes; (4) *Psychosocial*[129]: Society places a premium on height, and those who are taller are conferred greater social status and exhibit greater confidence.

These mechanisms do not have distinct boundaries; some of them are likely to overlap, and all are likely to be functioning to some extent, and to variable extents, within and across generations. Given the essential interconnectedness of these mechanisms, the conventional approaches of observational epidemiology are not powered to distinguish between them. However, specific examples of how these mechanisms may link height to (1) health and well-being, (2) socioeconomic status, and (3) intergenerational outcomes are provided in Table 1.[188–198]

Confounding, effect modification, and mediation

Other factors associated with both modern adult height and health outcomes may play a role in creating the associations observed. Evidence from across studies included in this review suggests that income and education are positively correlated with both adult height and health and are thus potential confounders in the relationship between adult height and health. Indeed, there are several pathways linking height and socioeconomic status (Figure 4). However, the association between adult height and health remains robust in studies adjusting for adult income, education, and other measures of socioeconomic circumstances.[6,89,115,124,125,129,137,141,199,200] Yet, there certainly is a strong argument that childhood conditions may confound part of the association between adult income, education, and height and that socioeconomic conditions during childhood is linked to both adult height (through nutrition and disease) and to adult socioeconomic status. For example, wealthy and more educated parents are likely both to provide better nutrition and to invest more in their children's education. Finally, there may be effect modification of the role of height on health by socioeconomic status (e.g., shorter height was more strongly associated with coronary heart disease among men in high employment grades than among men in lower employment grades).[201]

Adult height is also associated with risk factors for health, which possibly confound the association between height and health outcomes. For example, taller people smoke less, have lower blood pressure, and better diets. Controlling for these factors, however, does not greatly diminish observed associations.[129] Other potential confounders between height and health outcomes include medical conditions, socioeconomic conditions, or nutritional conditions that lead to both shorter stature and lower cognitive ability (e.g., fetal alcohol syndrome, or brain volume)[202,203] or disease-related height loss and subsequent mortality and morbidity,[204,205] However, a study of son's height as an instrument to predict parental mortality suggested little confounding due to health-related shrinkage on the relationship between own height and mortality.[206] Finally,

Table 1 **Potential mechanisms linking height with health, socioeconomic status, and intergenerational outcomes**

Type of mechanism	Outcome		
	Health and well-being	Socioeconomic status	Intergenerational consequences
Biomechanical	Taller people have increased pulmonary function (protective against CHD and respiratory disorders), larger coronary vessel diameter (protective against CHD), and larger organs (higher risk for malignancies due to increased number of cells)	There may be a biomechanical component to the link between stature and economic productivity. Taller people are healthier and may be more physically capable and robust.	Taller women have wider pelves, allowing easier births and a reduced likelihood of fetopelvic disproportion,[187] obstructed labor, and cesarean delivery[188]
Biological	Childhood nutrition and disease have consequences that impact mortality and morbidity in adulthood. Specific hormones associated with growth are also associated with risk for disease (e.g., insulin-like growth factor 1). Early deprivation followed by catch-up growth, partly through delayed onset of puberty, may be linked to risk of diabetes and CHD (partially masking the link between early growth insults and stature). Overall energy intake is associated with both growth and, at the upper end, cancer risk[189]	Childhood malnourishment impacts both stature and health, including cognitive development, which in turn can lead to fewer years of schooling completed[159] and reduced capacity to work.[190] Higher rates of morbidity are associated with increased absenteeism and decreased attentiveness and capacity to learn.[149] Higher cognitive test scores of taller children have been proposed to explain the association between adult height and wages[168]	Maternal stature is related to low birth weight in offspring. Low birth weight is due to intrauterine growth restriction or prematurity (or both). Shorter mothers may have smaller organs, affecting pregnancy through a reduced nuclear/ cytoplasmic ratio and through a reduced cell number. Poor nutrition in early life may induce adaptations in organ function, organ size, or metabolism or may cause gene expression to adapt in order to raise survival probabilities through the early years, which may cause problems later in life.[6,191]
Genetic	Genetic factors influencing growth may be tied to mortality or risk of specific diseases through pleiotropic effects or because the variants controlling both height and disease may be transmitted together (i.e., are in linkage disequilibrium). For example, the association between short stature and increased LDL-C may be partly of genetic origin[192]; SNPs associated with adult height may also share an association with risk of testicular cancer[193]	As with health, height and cognitive abilities may be transmitted together, with height being related to social mobility and, thus, socioeconomic position. Taller parents in more favored socioeconomic circumstances will transmit both their genes and their social advantages to their children[114]	The association between maternal height and child health may be due to underlying genetic control of both, with short stature transmitted along with increased risk of mortality and disease from mother to child. Comparing associations of child outcomes with both maternal and paternal height allows for separation of transmitted germline genetic variants (balanced between mother and father) and other mechanisms of intergenerational transmission of phenotype[194]
Psychosocial	Height as a socially desirable trait may result in better self-care and preventive behaviors, and may also elicit responses from others that have beneficial consequences.	Tallness is a desired trait and is rewarded by society with higher conferred status and wages. This preference may have evolutionary roots; taller men may be both more attractive[195] and have higher marriage rates. They may also exhibit greater interpersonal dominance.[196] The wage–height premium may be due to taller people having higher self- esteem. Self-esteem and social skills that lead to human capital accumulation may be most important in adolescence. Height as a teen may explain the stature–wage association[197]	Confident and successful tall parents may raise more confident and healthier children

Abbreviations: CHD, coronary heart disease; LDL-C, low-density lipoprotein cholesterol; SNP, single-nucleotide polymorphism.

although humans shrink with age,[207,208] two factors counter this as a general confounding mechanism: (1) the robustness of the associations between adult height and outcomes across all ages before shrinkage occurs and (2) the differential association between how different components of height (e.g., leg length and trunk length) are linked to different stages of early growth and health outcomes.[209] Indeed, leg length and trunk length may give insight into the importance of different childhood conditions in adult disease. For example, the components of height are differentially associated with some cancers,[131] and leg length is linked to chronic heart disease[210] and diabetes.[211] Moreover, a recent study found little bias due to potential height loss in the estimates obtained from models using stature to predict health when controlling for age.[212]

Potential confounding should not be ignored in the observed association between mothers' adult height and the health of their children. If adult height is a surrogate for health, then healthier mothers may get more education (through better school attendance) or have better cognitive function.[213] Height is similarly related to socioeconomic status: taller mothers may earn more and be better off than shorter mothers. Indeed, there is evidence that healthier, more educated, and wealthier mothers have healthier children,[214] thus potentially confounding the relationship between maternal height and child health.

Figure 5 presents a conceptual diagram displaying links between these factors and outcomes, and demonstrates pathways for confounding and mediation, with potential mechanisms and interactions noted. The various relationships between determinants of height and health across generations, including the roles of environmental conditions and genetics, are depicted. These visual demonstrations of the complex interrelationships eventually affecting child health present a starting point for future research to elucidate these relationships and to assess the relevance of the various mechanistic processes occurring within these relationships, which in turn determine outcomes. This conceptualization may assist future studies to measure the role of confounders and determine how some outcomes themselves may impact adult height (reverse causality), and how adult height may be on the pathway between a third factor and outcomes of interest (mediation).

Utilization of the novel Mendelian randomization approach[215,216] provides stronger evidence regarding causal relationships than conventional observational studies. Two Mendelian randomisation studies[119,217] demonstrate that genetically-influenced greater height translates into a lower risk of coronary heart disease, to the extent anticipated on the basis of observational studies. Similar concordance has been shown with respect to the positive association between height and colorectal cancer risk.[218] These findings provide some support for the biomechanical interpretation, with differences in height having the same impact on disease risk whether or not they are generated by genetic or non-genetic factors. Other techniques to establish causation may include reliance on instrumental variables, regression discontinuity design, differences-in-differences estimation, panel data, vector autoregression, and the Granger–Sims causality test.

Finally, although it has been suggested that expression of genetic factors associated with height may change according to environmental factors experienced, there is currently little robust evidence on molecular epigenetic processes in relation to adult height.

DISCUSSION

This review identifies four salient observations summarized from reviewed studies regarding patterns, determinants, and consequences of adult height. First, substantial differences in modern adult height exist between and within countries, reflecting both past and current distribution of disease and nutrition in early life. Second, environmental conditions (representing nutrition, disease, access to resources, and socioeconomic status) play a critical role in establishing adult height, especially during the first 2 years of life and especially in low- and middle-income countries. Third, shorter height is associated with adverse consequences for mortality and morbidity, even when adjusting for education, occupation, and income. Finally, the strong intergenerational linkages observed between parental height and offspring stunting and subsequent short adult stature as well as offspring mortality in low- and middle-income countries, along with stagnation in the average adult height in many countries, suggest that future inequalities in health will persist and may even increase unless immediate steps are taken to improve nutritional (and socioeconomic) circumstances for children during critical growth periods.

In general, the high levels of short adult stature observed in many low- and middle-income countries strongly suggest that growth retardation is not primarily attributable to genetic factors. Rather, short stature reflects the cumulative net impact of nutrition and, therefore, the roles of disease and more distal environmental conditions, such as socioeconomic status, on height over time and across generations. That the two regions of the world with the lowest average adult heights are also the regions with the greatest prevalence of undernourishment (sub-Saharan Africa) and the greatest number of undernourished people (Southeast Asia)[219] supports this claim.

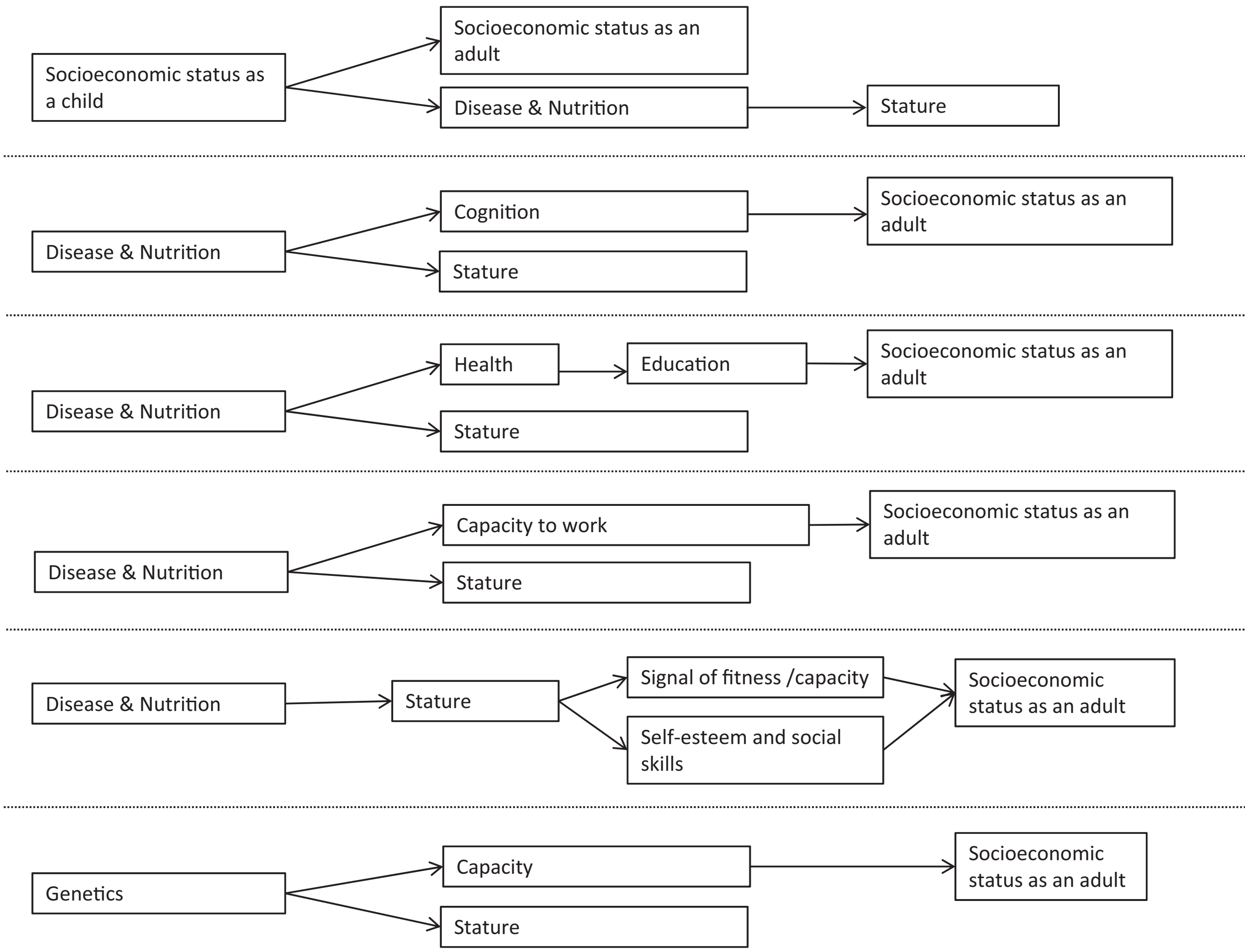

Figure 4 **Disaggregation of some of the pathways through which environmental factors (socioeconomic status, disease, and nutrition) and genetics determine stature, and through which stature determines socioeconomic status and other outcomes.**

Moreover, at the individual level, the relative roles of net nutrition and genetics appear to differ between the growth periods: the impact of nutrition (and other environmental factors) may be relatively stronger during the first period, while the genetic component may be relatively stronger during the second period.[220,221] Estimates of height heritability, however, may lead to confusion about the relative importance of genetic and environmental factors in determining adult height. To clarify, there is no inherent contradiction between the estimated heritability of height and the evidence of secular changes (usually increases) in adult height at rates too rapid to be associated with changes in the genetic structure of a population. Heritability relates to differences between individuals within a particular population at a particular time. Thus, when environmental factors are changing across the board within a population, these changes can lead to substantial, and entirely environmentally based, changes in population mean height, which are in no way incompatible with high heritability.[222] Nonetheless, it is important to distinguish short stature related to polygenic genetic influences from those related to environmental influences. Indeed, it is the processes leading to failure to meet genetic potential for height or "target height" that may be of most importance in linking height to some health and social outcomes.

Height is associated with improved social and economic development and has consequences for current and future population health and well-being. As such, adult stature is a measure that, at least partially, captures current human capital and human capability at the population level. There is strong evidence that adult height (and maternal height, in particular) is linked to offspring undernutrition, stunting, and mortality. Therefore, shorter average adult height of today can be viewed as a reflection of tomorrow's burden; on average, stunted children will not meet their full genetic potential for height (even after experiencing catch-up growth). Indeed, achieving national and global goals

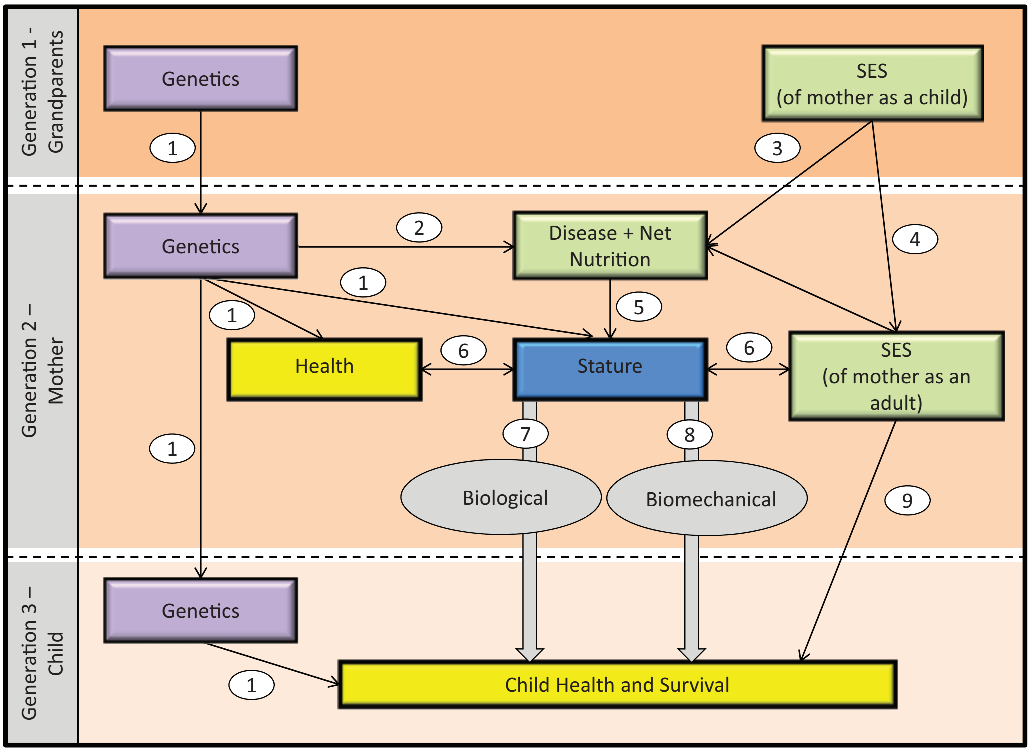

Figure 5 **Conceptual model exploring the mechanisms that may link socioeconomic status (SES), height, and health across generations.** Boxes are risk factors and outcomes, and ovals are mechanisms and interactions. The following points, which correspond to the numbers within the ovals, describe how determinants and consequences are related: (1) The additive endowment component affects maternal stature and health as well as child outcomes. (2) The multiplicative endowment component represents gene–environment interactions. (3) The socioeconomic conditions of the mother during childhood can mediate her exposure to disease and nutrition through a number of pathways, including food resources, access to medical care, and environmental sanitation. (4) Education and income can be transmitted intergenerationally through direct pathways (e.g., through inheritance for income or through transmission of skills for education). (5) The nutritional balance between intake and losses, including nutritional losses due to physical activity, psychological stress, and disease, directly affect growth. (6) There are potentially large interactions between stature, health, income, and education. (7) The biological pathways encapsulate factors that work through the viability of the uterine environment during pregnancy. (8) The biomechanical pathways indicate factors related to the relationship between stature and pelvic size. (9) Socioeconomic pathways through which the education of mothers (e.g. through health behaviors or autonomy of women to make health-related decisions for their children) and parental income affect childhood outcomes.

related to reducing child undernutrition and mortality, poverty, and inequality may require consideration of the strong intra-generational and intergenerational linkages in height.

CONCLUSION

From a biological/anthropological perspective, adult height is a relatively easy indicator to routinely collect. Evidence of the robust relationship between adult height and outcomes, as well as between determinants and adult height, even after controlling for potential confounders, points to the utility of adult height as a measure of population cumulative net nutrition, health, and development. At the same time, the remaining questions about causality and associated mechanisms point to the importance of continuing to investigate how nutrition and other environmental factors (particularly during early childhood years) are related to adult height, and how adult height in turn predicts subsequent outcomes. Notably, understanding the impact of adult height on future generations does not mean that continuous increases in average adult height are the ultimate goal. Rather, the summary provided in this review supports utilizing adult height as a key indicator for comparison of between- and within-country population-level improvements over time, particularly those that may be related to inequality in nutrition and environmental factors. From a macro perspective, average adult height can be considered a critical indicator of human capability and may reflect the quality of a nation's workforce. By at least partially representing past health, current health, and future health as well as the impact of environmental conditions over time on cumulative net nutrition, adult height can be used as a marker of long-term progress in global health and development.

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