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How can two biological variables have opposing secular trends, yet be positively related? A demonstration using timing of puberty and adult height

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Abstract

Timing of puberty and adult height have opposing secular trends yet are positively associated in individuals. We demonstrate this using data from a single sample and discuss possible statistical and epidemiological reasons behind it. The sample comprised 365 females from Fels Longitudinal Study born 1929-1992. We used Super-Imposition by Translation and Rotation (SITAR) to estimate individual age at peak height velocity (PHV) and PHV from serial height data (8149 observations between 5-24 years). General linear regression was used to investigate the association between height and age at PHV, and secular trends in height, age at PHV and PHV. Although adult height increased 0.42 (95%CI 0.08, 0.77) cm per decade, and age at PHV decreased 1.14 (-3.74, 1.45) weeks per decade, adult height increased by 2.44 (1.78, 3.10) cm per year higher age at PHV. We found tentative evidence the positive association between age at PHV and adult height strengthened 0.25 (-0.09, 0.59) cm each decade. Secular trends in related variables may differ if the between-individual and between-cohort associations are different. To understand if a secular trend in one variable has contributed to a trend in another, each needs to be modelled over time, together with the changing association between them.

Keywords

secular trends; puberty; peak velocity; menarche; height;

Introduction

Human biologists sometimes face counterintuitive observations, where two variables thought to be positively correlated, display opposing secular trends (i.e., one variable has increased over time while the other has decreased). For example, over the last century many populations have experienced a decrease in timing of puberty and an increase in adult height (Cole, 2000; Eckert-Lind et al., 2020; Garenne, 2020; Hauspie et al., 1997; NCD-RisC, 2016), despite evidence showing that individuals who go through puberty earlier tend to become shorter adults (Hägg and Taranger 1991; Limony et al. 2015). Both population trends are believed to be due to improvements in environmental conditions, including better nutrition, sanitation, and health care (Bogin & Keep, 1999; Cole, 2003; Krzyżanowska, Mascie-Taylor et al., 2016; Tanner, 1986; Tanner, 1981). Knowledge of how and why pubertal timing and adult height have changed over time cannot, however, be used to infer how one variable is associated with the other. Similarly, knowledge of the association between two variables at the individual level does not necessarily help when inferring how a secular trend in one variable might be related to, or contribute to, the secular trend in the other. Obesity causes coronary heart disease (CHD), for example, but while obesity prevalence have increased over the last 30 years, incidence of CHD has seen a dramatic decrease worldwide (Bots et al. 2017; NCD-RisC 2017). Advances in, and more aggressive use, of pharmacotherapy is one explanation for this phenomenon (Herrington et al. 2016). Despite such examples, the mistake of assuming that a secular change in one variable has contributed to a secular change in another is often made in human population biology and epidemiology literature (Rodgers et al. 2018). Seeing the way these two phenomena change together may also be wrongly taken to imply an association at the individual level (the so-called ecological fallacy, e.g. it would be wrong to infer that obesity is protective against CHD because obesity has increased, and CHD has declined).

In the case of the present study, we hypothesise that a decrease in mean adult height due to earlier puberty could be overpowered and reversed by a positive association between pubertal timing and adult height strengthening over time, for example, due to a higher peak height velocity (PHV). This idea is conceptualised in Figure 1, where the first panel shows a hypothetical positive secular trend in height, and a negative secular trend in age at PHV. The third panel demonstrates a stronger positive association in these variables within individuals in a later vs. earlier birth year cohort. By modelling the change in the strength of the association between adult height and age at PHV over time, we should be able to estimate how much each of these two processes would have contributed to any cohort difference in height.

To illustrate this hypothetical model using a real-life sample, this short report uses data from females born between 1929 and 1992 in the Fels Longitudinal Study. We show opposing secular trends in, yet a positive association between, age at PHV and adult height. Results are confirmed with age at menarche. We further investigate whether the strength of the association between timing of puberty and adult height has changed over time, and whether there has been an increase in peak height velocity. In addition to explaining the possible biological reasons for the results, we discuss broader implications for research aiming to quantify the causes of an increase (or decrease) in the prevalence of some disease outcomes.

Methods

Sample

The Fels Longitudinal Study began in 1929 as a study of normative child growth and development and continued until recently as a study of the early-life antecedents of chronic diseases of ageing. Mother-infant dyads living in Yellow Springs and other towns in southwestern Ohio, USA were enrolled from 1929 onward, with the infants being followed-up across their lives (Roche 1992). The study had a family design with up to four generations of participants within a family actively followed.

The sample included in this analysis comprised 365 females born 1929-1992 who had at least five serial height measurements between 5-24 years of age, with one taken in adulthood (18-24 years). These females come from 106 nuclear and extended families. For a subsample of 264 females, age at menarche was also available.

All protocols and informed consent documents for the Fels Longitudinal Study were approved by the Wright State University Institutional Review Board. Parents provided written consent for their offspring's participation until 18 years of age, and children aged 7-18 years provided their additional assent, after which written consent was obtained in adulthood.

Data

Height was measured every six months between 5-18 years of age, and subsequently every two years (i.e., 20, 22, and 24 years), using standard anthropometric methods (Lohman et al. 1998). In total, there were 8,149 serial measurements and ~90% of the sample had more than 10 observations. The measurement closest to age 20 years was used to indicate height in adulthood (ages 18-24). This was done to maximise the data available to us (most individuals had data at age 20, fewer individuals had data at the later adult ages).

At each of the semi-annual visits, females aged 9 years and older responded to questions regarding whether they had started menstruating since their last visit (Demerath et al. 2004). If the answer was yes, the girls were asked to provide, if possible, an exact date. In most cases, girls report the onset of their menses at their first study examination after menarche. Eighty percent reported menarche within 6 months of its onset, and the remaining 20% reported menarche within 5 years of its onset, which limits the likelihood of recall error.

Statistical analysis

A Super-Imposition by Translation and Rotation (SITAR) model was fitted to the longitudinal height data in order to estimate the age (years) of PHV for each individual. Age at PHV is a core indicator of pubertal timing that does not rely on recall of biological events, and in females, occurs approximately one year before age at menarche (Tanner 1981; Simpkin et al. 2017). Briefly, SITAR works by fitting an average smooth curve to the data, using a natural cubic B-spline and, at the same time, estimating individual-level random effects for size, pubertal timing (corresponding to age at PHV), and pubertal intensity (correspond to magnitude of PHV) (Cole et al. 2010). PHV is the maximum growth velocity and can theoretically occur at any point across the age range. SITAR produces estimates of age at PHV for all individuals. The model fit improved after a log-transformation of age. Individual estimates of age at PHV and PHV were extracted for further analysis.

General linear regression was used to estimate the associations of adult height and age at PHV with birth year, thereby documenting the secular trends in each of the two variables. We also tested the association of age at menarche with birth year in the subsample. To display these results, a single figure was produced showing the three regression lines.

General linear regression was also used to investigate the individual-level association of age at PHV with adult height. To examine whether the strength of the association between age at PHV and adult height changed over time (effect modification) we incorporated an age at PHV-by-birth year interaction term. In order to visually display this interaction, we ran stratified analyses for three birth year cohorts: the lowest 25% of birth years (1929-1947, N=94), the middle 50% of birth years (1948-1977, N=186), and the highest 25% of birth years (1978-1992, N=85). A figure was produced showing the regression lines for each of these birth year cohorts. Another useful way of visualising an interaction effect between two continuous variables is a 3D surface plot. We provide an example of this in the supplementary materials, where the association of the age at PHV-by-birth year effect on adult height is shown as a ‘warped surface’. To create the plot, we attained linear predictions of adult

height as a function of the age at PHV and birth year interaction for an equidistant 60 by 60 datapoint grid of age at PHV (between ages 10-15 years) and birth year (between 1929-1992) values. These grid estimates were used to create a 3D scatterplot where the y-axis was adult height, x-axis was age at PHV, and the z-axis was birth year.

A further general linear regression model was used to investigate the associations of PHV and birth year, to examine whether there was any increase or decrease in the magnitude of PHV over time.

All models where height was the outcome were developed to incorporate a random intercept for family to account for clustering within the data. This was necessary because, using a variance components model, ~30% of the variation in adult height was due to differences between families (as opposed to differences between individuals). This was not necessary for age at PHV, age at menarche or PHV, because between-family variation in these measures was much smaller. The adult height predictions used for the 3D image were unadjusted for the family-level clustering.

Finally, to show the process hypothesised in Figure 1, a Blinder–Oaxaca decomposition analysis was performed using data from the earliest (1929-1947) and latest (1978-1992) birth year cohorts. This method works by regressing adult height on age at PHV for each cohort and computing the difference in the mean linear predictions (i.e., estimated adult height). The change in estimated adult height is then computed under two scenarios. First, if the earlier birth year cohort had the same age at PHV values as the later cohort. This computation shows how the process described in the second panel of Figure 1, might have contributed to the process shown in the first panel. Second, if the regression coefficients for the later cohort were applied to the age at PHV values of the earlier cohort. This second computation shows how the process shown in the third panel, might have contributed to the process shown in the first panel.

The SITAR modelling was performed in R using the SITAR package (Cole et al. 2010), and the 3D image was created in R using the *plotly* package (Sievert 2020). Stata 15 (StataCorp, Texas) was used for all other analyses.

Results

The sample had a mean adult height of 165.2 cm (SD 6.2), age at PHV of 11.6 (SD 0.9) years and PHV of 7.9 (SD 0.8) cm/year. In the subsample, mean age at menarche was 12.8 (SD 1.1) years.

As shown in Figure 2, adult height increased by 0.42 (95%CI 0.07, 0.77) cm per decade and age at PHV decreased by 1.14 (-3.74, 1.45) weeks per decade. In the sub-sample, age at menarche also demonstrated a negative secular trend, declining by 3.65 (-7.74, 0.433) weeks per decade. As expected, the line for age at menarche is ~1 year after age at PHV. Despite these opposing trends, adult height and age at PHV had a strong positive association; adult height was estimated to be 2.44 (1.78, 3.10) cm greater for each year increase in age at PHV. Similarly, in the subsample, adult height was estimated to be 1.12 (0.55, 1.70) cm greater for each year increase in age at menarche.

We found tentative evidence that birth year modified the association of age at PHV with adult height. The age at PHV-by-birth year interaction showed that the positive association between age at PHV and adult height strengthened by 0.25 (-0.09, 0.59) cm each decade. Figure 3 shows this effect modification using models stratified by birth year cohort, and Supplementary Figure 1 shows the interaction effect in 3D space. The increase in adult height for each unit (year) increase in age at PHV was 2.25 (1.03, 3.46) cm for females born 1929-1947, 2.60 (1.61, 3.59) cm for females born 1948-1977, and 3.58 (2.07, 5.10) cm for females born 1978-1992. The magnitude of PHV increased by 0.06 (0.02, 0.11) cm/year per decade.

The results of the decomposition analysis indicated that the predicted mean adult height was 0.95 (-0.94, 2.85) cm higher for the latest birth year cohort (1978-1992) compared to the earliest birth year cohort (1929-1947). It was estimated that adult height in the 1929-1947 cohort would have been:

- -0.26 (-0.79, 0.27) cm lower if this cohort had the same age at PHV values as the 1978-1992 cohort.
- +1.43 (-0.34, 3.21) cm higher if the regression coefficients for the 1978-1992 cohort were applied to the age at PHV values from the 1929-1947 cohort.

Discussion

Using data from a cohort-sequential study which started in 1929 and continued until recently, this short report demonstrates how two biological variables can have opposing secular trends yet be positively related in individuals. While this finding might seem counterintuitive to some researchers, other people likely do not view this as a conundrum. This issue has not, however, been previously discussed in a single paper, including its relevance and application to secular trend epidemiology. Instead, assumptions of how a given variable may contribute to the secular trend observed in another continue to be made without explicitly modelling their association. For instance, factors known to be related to obesity risk, such as motivation to exercise, healthy food choices, or genetic predisposition are commonly used to explain the rapid increase in obesity prevalence in the US from late-1970s,

without explicitly showing through statistical modelling that e.g. physical activity has declined, and contributed to increase in obesity (Rodgers et al. 2018).

In the present study, we observed that adult height has increased over time despite age at PHV decreasing. Importantly, the association between age at puberty and adult height takes place between individuals, whereas the comparisons with birth year take place between cohorts. As such, there is no requirement for the two sets of correlations to be consistent with each other, as the between-subject associations can change over time in a way that is independent of the between-cohort time trends. We hypothesised that one reason for the differing time trends could relate to changes in the magnitude of PHV over time, and indeed, we found that PHV showed a small increase over time. Another explanation could be that children born more recently might have better foetal, infant, and childhood growth and thus enter puberty at a greater height than those born less recently.

Individuals who go through puberty earlier tend to have a reduced total growth period and thus end up as shorter adults. In the present study, age at PHV explained only about 12% of the variance in adult height, and this is unadjusted for potential covariates. No genetic study has specifically set out to test the causality of the effect of pubertal timing on final height, but there is evidence of a small, positive association between timing of puberty and adult height from Mendelian Randomization studies that incorporate adult height as a positive control (Bonilla et al. 2016; Magnus et al. 2020). This means there might be some rationale for assuming that the secular trend toward earlier puberty would contribute to a secular decline in adult height. But as the strength of the association is small, the many other factors at play (e.g. changes in nutritional, disease etc. environment) could have overpowered the effect and caused adult height to increase over time.

A small negative secular trend in adult height due to earlier puberty could also be overpowered and reversed by the strength of the positive association between pubertal timing and adult height increasing over time. This is what we hypothesised and show through the decomposition analysis (and Figure 3). Theoretically, the earlier age at PHV in the latest birth year cohort (1978-1992) could have a small negative effect on the predicted adult height of the earliest birth year cohort (1929-1947). However, the positive effect we see due to the strengthened association between adult height and age at PHV is much larger and would lead to an overall increase in adult height. The reason why we observe a strengthening association between height and timing of puberty over time could relate to the increased PHV over time, as it implies that the duration of the growth spurt may have shortened. However, this idea is not supported by the present data, as we found no evidence of the latest birth year cohort having a lower SD for age at PHV compared to the earliest cohort.

There are other examples in the literature that describe a change in the association between two biologically related variables over time. One of these is infant weight gain and subsequent BMI, two variables which commonly show a strong positive association. Surprisingly, infant weight gain did not increase much across the second half of the 20th century despite the increasingly obesogenic environment, and there is some evidence that it decreased in some populations (Johnson et al. 2012). This does not, however, mean that infant weight gain played no part in the secular increase in adolescent and adulthood BMI. In two separate papers, using data from two different countries, Johnson et al. documented how the association between infant weight gain and subsequent BMI strengthened significantly over time, and thus potentially contributed to the obesity epidemic (Johnson et al. 2013; Johnson et al. 2018). In Great Britain, this phenomenon was estimated to account for 23% of the difference (secular increase) in BMI at age 11 years between 1957 and 2012, while a small secular increase in infant weight gain only accounted for 9% of the difference (Johnson et al. 2018). Even if average infant weight gain had decreased over time, the strengthening association could implicate this variable in the development of the obesity epidemic.

Comparable approaches have also been applied to address questions about secular changes in associations between biological variables and non-biological variables, for example, to document the changing contribution of childhood social characteristics on mortality (Martikainen et al. 2020), or the effectiveness of a growth assessment program in the prevention of stillbirths (Iliodromiti et al. 2020). Taken together, the findings from these studies clearly demonstrate the need to explicitly model time trends in both variables, and their possibly changing association, when investigating why there has been an increase or a decrease in the prevalence of any health outcome.

There were some limitations to the present analyses. Owing to a small sample size, some of our estimates were imprecise with 95% CI crossing zero. However, both the relationship of age at PHV with birth year and age at menarche with birth year were in the hypothesized direction and the magnitude of the effects fits in with previous literature (Malina 2004; Aksglaede et al. 2008). That some estimates did not reach the traditional definition of being “statistically significant” ($p < 0.05$) does not diminish the relevance of what we are showing and discussing in this report. Finally, we also assumed linear secular trends and associations in the present study, but future work with larger samples may investigate this topic further.

Conclusions

Two variables can have opposing secular trends yet be positively related in individuals or have the same secular trends but be negatively related. Both situations imply a changing association over time between the two variables. To understand different secular trends in related variables, each trend needs to be modelled over time, together with the changing association between the two variables.

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Competing interest's statement

The authors declare that they have no conflict of interest.

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Author contributions

LM and WJ conceptualized the study, carried out the analyses, and drafted the initial manuscript. Both authors made substantial contributions to the interpretation of the data, revised the manuscript critically for important intellectual content, gave final approval of the version to be published, and agree to be accountable for all aspects of the work.

References

- Aksglaede L, Olsen LW, Sørensen TIA, Juul A. 2008. Forty years trends in timing of pubertal growth spurt in 157,000 Danish school children. *PLoS One*. 3:1–8.
- Bogin B, Keep R. 1999. Eight thousand years of economic and political history in Latin America revealed by anthropometry. *Ann Hum Biol*. 26:333–351.

- Bonilla C, Lewis SJ, Martin RM, Donovan JL, Hamdy FC, Neal DE, Eeles R, Easton D, Kote-Jarai Z, Al Olama AA, et al. 2016. Pubertal development and prostate cancer risk: Mendelian randomization study in a population-based cohort. *BMC Med.* 14:1–11.
- Bots SH, Peters SAE, Woodward M. 2017. Sex differences in coronary heart disease and stroke mortality: A global assessment of the effect of ageing between 1980 and 2010. *BMJ Glob Heal.* 2:1–8.
- Cole TJ. 2000. Secular trends in growth. *Proc Nutr Soc.* 59:317–324.
- Cole TJ. 2003. The secular trend in human physical growth: a biological view. *Econ Hum Biol.* 1:161–8.
- Cole TJ, Donaldson MDC, Ben-shlomo Y. 2010. SITAR-a useful instrument for growth curve analysis. *Int J Epidemiol.* 39:1558–1566.
- Demerath EW, Towne B, Chumlea WC, Sun SS, Czerwinski SA, Remsberg KE, Siervogel RM. 2004. Recent decline in age at menarche: The Fels longitudinal study. *Am J Hum Biol.* 16:453–457.
- Eckert-Lind C, Busch AS, Petersen JH, Biro FM, Butler G, Bräuner E V., Juul A. 2020. Worldwide Secular Trends in Age at Pubertal Onset Assessed by Breast Development among Girls: A Systematic Review and Meta-analysis. *JAMA Pediatr.*:1–11.
- Garenne M. 2020. Trends in age at menarche and adult height in selected African countries (1950–1980). *Ann Hum Biol.* 47:25–31.
- Hägg U, Taranger J. 1991. Height and height velocity in early, average and late maturers followed to the age of 25: A prospective longitudinal study of Swedish urban children from birth to adulthood. *Ann Hum Biol.* 18:47–56.
- Hauspie R, Vercauteren M, Susanne C. 1997. Secular changes in growth and maturation: an update. *Acta Paediatr Suppl.* 423:20–27.
- Herrington W, Lacey B, Sherliker P, Armitage J, Lewington S. 2016. Epidemiology of Atherosclerosis and the Potential to Reduce the Global Burden of Atherothrombotic Disease. *Circ Res.* 118:535–546. doi:10.1161/CIRCRESAHA.115.307611.
- Iliodromiti S, Smith GCS, Lawlor DA, Pell JP, Nelson SM. 2020. UK stillbirth trends in over 11 million births provide no evidence to support effectiveness of Growth Assessment Protocol program. *Ultrasounds Obs Gynecol.*
- Johnson W, Bann D, Hardy R. 2018. Infant weight gain and adolescent body mass index: Comparison across two British cohorts born in 1946 and 2001. *Arch Dis Child.* 103:974–980.

- Johnson W, Choh A, Soloway L, Czerwinski S, Towne B, Demerath E. 2012. Eighty years of trends in infant weight and length growth: the Fels Longitudinal Study. *J Pediatr*. 160:762–768.
- Johnson W, Choh AC, Lee M, Towne B, Czerwinski SA, Demerath EW. 2013. Characterization of the infant BMI peak: Sex differences, birth year cohort effects, association with concurrent adiposity, and heritability. *Am J Hum Biol*. 25:378–388.
- Krzyżanowska M, Mascie-Taylor CGN, Thalabard JC. 2016. Biosocial correlates of age at menarche in a British cohort. *Ann Hum Biol*. 43:235–240.
- Limony Y, Koziel S, Friger M. 2015. Age of onset of a normally timed pubertal growth spurt affects the final height of children. *Pediatr Res*. 78:351–355.
- Lohman T, Roche A, Martorell R. 1998. Anthropometric standardization reference manual. Champaign, IL.
- Magnus MC, Guyatt AL, Lawn RB, Wyss AB, Trajanoska K, Küpers LK, Rivadeneira F, Tobin MD, London SJ, Lawlor DA, et al. 2020. Identifying potential causal effects of age at menarche: a Mendelian randomization phenome-wide association study. *BMC Med*. 18:1–17.
- Malina RM. 2004. Secular trends in growth, maturation and physical performance: A review. *Przegląd Antropol – Anthropol Rev*. 67:3–31.
- Martikainen P, Elo I, Tarkiainen L, Mikkonen J, Myrskylä M, Moustgaard H. 2020. The changing contribution of childhood social characteristics to mortality: a comparison of Finnish cohorts born in 1936–50 and 1961–75. *Int J Epidemiol*.:1–12.
- NCD-RisC. 2016. A century of trends in adult human height. *Elife*. 5:1–29.
- NCD-RisC. 2017. Worldwide trends in body-mass index, underweight, overweight, and obesity from 1975 to 2016: a pooled analysis of 2416 population-based measurement studies in 128·9 million children, adolescents, and adults. *Lancet*. 390:2627–2642.
- Roche A. 1992. Growth, maturation and body composition: the Fels Longitudinal Study 1929-1991. Cambridge: Cambridge University Press.
- Rodgers A, Woodward A, Swinburn B, Dietz WH. 2018. Prevalence trends tell us what did not precipitate the US obesity epidemic. *Lancet Public Heal*. 3:e162–e163.
- Sievert C. 2020. Interactive Web-Based Data Visualization with R, plotly, and shiny. <https://plotly-r.com>.
- Simpkin AJ, Sayers A, Gilthorpe MS, Heron J, Tilling K. 2017. Modelling height in adolescence: a comparison of methods for estimating the age at peak height velocity. *Ann Hum Biol*. 44:715–722.

Tanner JM. 1981. Growth and maturation during adolescence. *Nutr Rev.* 39:43–55.

Tanner JM. 1986. Growth as a mirror for the conditions of society: secular trends and class distinctions. In: Demirjian A, editor. *Human Growth: A Multidisciplinary Review*. London: Taylor and Francis. p. 3–34.

Figure captions

Figure 1. Hypothesised associations between adult height and birth year cohort (1), age at peak height velocity (PHV) and birth year cohort (2), and between adult height and age at PHV, by birth year cohort (3).

Figure 2. Secular trends in adult height, age at peak height velocity (PHV) and age at menarche

Figure 3. The association of age at peak height velocity (PHV) with adult height, by birth year cohort

Supplementary Figure 1. The interaction effect of age at PHV and birth year on adult height.

Estimates are unadjusted for family-level.