A Model of the Evolution of Human Stature*

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Abstract

We still do not have a model of adult heights, but we do have a fairly good model of children's height – in which the evolution of height is linked to changes in the quality of life during childhood. By assuming that adult height is the result of the combined effect of nature and nurture, however, we can derive a model of adult height. The objective of this paper is to introduce such a model; to show that it explains well the evolution of adult heights observed during the last 200 years in England; and that it can be used to forecast the future evolution of heights as well. Economic and biological factors are assumed to jointly determine adult height in this model. Nature affects adult height because there is a potential maximum adult height determined by human genetic evolution, while nurture affects it because a proportion of adult height is achieved during childhood and depends on the quality of life of children. Both factors are jointly important because although there is a catch-up process during the first years of adulthood by which the human body makes up for the height not achieved during childhood, this catch-up process is far from perfect. I mentioned that two important objectives of the paper are to show that the model explains the past evolution of height and to forecast its future evolution. In order to achieve the second objective, we need to introduce some modifications to the model of children's height; the modifications chosen are by no means the only ones possible but they rely on those features of the current model that help most to successfully explain the historical evolution of adults' and children's height.

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1. Introduction

There is considerable medical and epidemiological evidence showing that height achieved during childhood is closely related to the quality of life: on average the better children fare the taller they are at a given age. This evidence has been the one guiding researchers in their search for an economic model of height. In particular, researchers have sought to relate average height with an aggregate indicator of well-being such as income per capita.

Although the scientific evidence on the link between well-being and height is strongest for children's height, long enough time series are only available for the case of adults' height. So the task of relating mean adult's height to income per capita has been carried out without the aid of a formal model. Researchers implicitly assumed that if there was an effect of income per capita on mean children's height this effect could still be found in adults' height, for which enough data were available.

Thus Van Meerten (1990) proposed a distributed lag model in which the mean height of adults of age q in year t was a function of the income per capita levels for the years going from t-q to t. Weir (1993) and Schneider (1996) realized that in order to capture the effect of well-being during childhood on height, the relation between adults' height and income per capita should be controlled for those variables that economics found important for children's well-being, namely infant mortality and fertility. This was an improvement but the authors did not take into account that modern economic growth theory and evidence show that fertility and mortality also depend on income per capita.

The task of taking into account the endogenous nature of fertility and infant mortality was undertaken in Delajara (2001). In this paper the relation between children's height and income per capita is theoretically derived and empirically estimated. The main finding was that children's height and income per capita were related in a nonlinear function; in particular, children's height was found to be a convex function of income per capita: children's height seem to fall with income per capita in the initial stages of economic development, but once a threshold level of income is reached, children's height become positively associated with income per capita. This finding helped to explain the decline in children's height observed in England during the second part of the eighteenth century [Komlos (1993)], as well as similar episodes in Sweden [Sandberg and Steckel (1988)] and the US [Komlos and Coclanis(1997)].

Therefore, Delajara (2001) seems to provide a good model of children's height. The objective of this paper is to use that model as the basic building block in the construction of a model of adult's height. The construction of such a model will require: i) showing that the basic children' smodel explains well the evolution of children's height in England from 1750 to the year 2000; ii) assuming that a particular relation, in which nature also plays an important role, holds between children's and adults' height; and iii) calibrating the resulting model to yield a series of adults’ height that closely matches the evolution of adult height in England from 1820 to the present days.

The main task then is to study the link between children’s height and final adult height; the following considerations will prove to be useful.

The starting point is to realize that final adult height is not (yet) achieved by the end of childhood, say at age 13. Particularly in the past, human growth continued for many years after childhood had ended. The age by which final adult height is achieved has been decreasing continuously during the last 200 years. Today final adult height is achieved by the age of 18 in most developed nations, and there is no reason why it could not be achieved at even younger ages.

The mechanism behind the human growth achieved in the years following childhood has to do with the genetic potential for growth. Growth not achieved by the end of childhood was to be done so at a slower pace during the following several years. The process can be seen as a “catch–up” process. People who suffered malnutrition during childhood could catch-up in terms of stature upon entering the labor market and getting a wage that would allow them to feed themselves better. This is possible because, in order to survive, the human organism adapts to malnutrition by slowing down the pace of body growth [Dasgupta (1993)]. The improvements in nutrition and quality of life of children of the last century have indeed brought an increase in the speed of human growth during childhood with the result that children’s height has grown considerably while adults’ height has grown comparatively much less.

The catch-up process is a biological feature of human growth. There is a genetic tendency for the human body to grow in order to reach the genetically-determined potential height. If, because of malnutrition, the process of growth is hampered or impaired during childhood, then when better conditions of living are achieved, the process of growth is let free to continue. However, if the bad living conditions during childhood remain the same or do not improve much during the early adulthood the "catch-up" process can not be expected to be strong. This was certainly the case when the now developed nations were much poorer; the catch-up process was not enough to bridge the whole gap between the height achieved by the end of childhood and the potential adult height. This shows that adult height must have been affected by living conditions as well. The catch-up process must have been important nonetheless, since adult heights have remained clearly differentiated from children' s height until now.

The net effect is a weakening of the catch-up process. For example, adults’ mean height has grown about 13-14 cm in England in the last two centuries, while children' s height (at age 13) has grown 23 cm in the same period.

All these considerations help us to intuitively grasp the form that a model of adult height should have. The model should assume that adult height is determined by factors related to both nature and nurture. The nurture component will be associated with the quality of life during childhood, while the nature component will be associated with what we shall call the "potential adult height", determined by human evolution. Thus, our conceptual model is very simple: Adult height ≡ nurture-determined component + nature-determined component. We introduce the corresponding formal model in the next section.

2. The Model

In this section we introduce a model to study the evolution of mean adult height. In what follows, whenever we mention the word height we will be referring to mean or average height.

Based on the discussion of the previous section, we assume here that adult height has the following functional form:

(1) $$H^{a} = \left(H^{p}\right)^{\lambda}\left(H^{c}\right)^{1-\lambda}$$

Adult height, H^{a}, is a geometric index of height achieved during childhood[1], H^{c}, and the genetically-determined potential adult height, H^{p}; where the coefficient λ is a constant with $0 < \lambda < 1$. This functional form is known as the Cobb-Douglas production function in Economics.

Let h be the logarithm of H, then the formula for adult height can be written as

(2) $$h^{a} = \lambda h^{p} + (1-\lambda)h^{c}.$$

That is, the log of the final adult height achieved is a weighed average of the log of height achieved during childhood and the log of the potential adult height, where the weights depend on the production function coefficient λ.

We can yet re-write this functional form in order to recover our original intuition regarding the role of nurture and nature in the determination of adult height. Notice that (2) can be written as

(3) $$h^{a} = h^{c} + \lambda\left(h^{p} - h^{c}\right),$$

That is, in logs terms, final adult height achieved is height achieved during childhood plus a proportion λ of the difference between the potential adult height and height achieved during childhood.

We further assume that the quality of life during childhood determines children’s height. The quality of life of children in a given economy is determined mainly by two variables: income per capita and the level of education of the population. Let y be the log of income per capita and E be the schooling level of the adults in the economy, then I postulate the following functional form for the log of children' s height

(4) $$h^{c} = f(y, E).$$

Following Delajara(2001), I assume that the log of children's height, h^c, is quadratic in the log of income per capita[2] and linear in schooling, so that

(5) $$f(y) = f_0 + f_1 y + f_2 y^2 + f_3 E$$

where $f_3 > 0$, $f_0 > 0$, $f_1 < 0$ and $f_2 > 0$, so that children's height is a convex function of GDP per capita.

This U-shaped relation between children's height and income per capita means that children's height decrease with income per capita in the initial stages of economic development, when income per capita is small, and that it increases with economic growth for large enough income per capita levels. The threshold level at which the decline in height is softened and height eventually starts to increase depends on the parameters of $f(y)$. Delajara (2001) studies the relation between children's height and income per capita in a cross-section of contemporary countries and finds that this threshold level is situated at about 1000 dollars (in international 1985 prices).

3. Explaining the Recent History of Stature

In this section I use the model of the previous section to explain the evolution of children's and adult's stature observed in England since 1820.

The first task is to assign values to the parameters of the model. The main parameters of the model are the coefficients of $f(y,E)$; the coefficient of the production function of adult height λ; and the English rate of growth of income per capita during the last two centuries.

The values of the parameters of $f(y,E)$ are taken from Delajara(2001). Then, $f_1 = -0.18$ and $f_2 = 0.013$; this two parameters are enough to determine the income elasticity of children's height. For E, a variable which is proxied by the percentage of population with primary education, Delajara (2001) finds that $f_3 = 0.00063$.

In order to match the level of heights at different period of times, however, we will need to the calibrate parameter f_0 and the value of E; It is clear that the extent of primary school enrollment has changed over time; it is less clear why f_0 changes over time: this parameter is the constant in a regression function that was estimated in a cross-section of contemporary countries; therefore, its estimated value is related to the distribution of height across countries today. To the extent that the world average of children's height might change for reasons

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[1] The period of life defined as childhood will be more clearly defined below, but in general I mean the period of nourishment under parental care.

[2] As mentioned in the Introduction, Delajara (2001) shows that a quadratic function of income per capita explains very well the difference observed across countries in children's height, and that this particular shape emerges as a result of the interaction between income per capita, fertility, and children's height.

different than changes in income per capita and schooling, parameter f_0 might change over time.

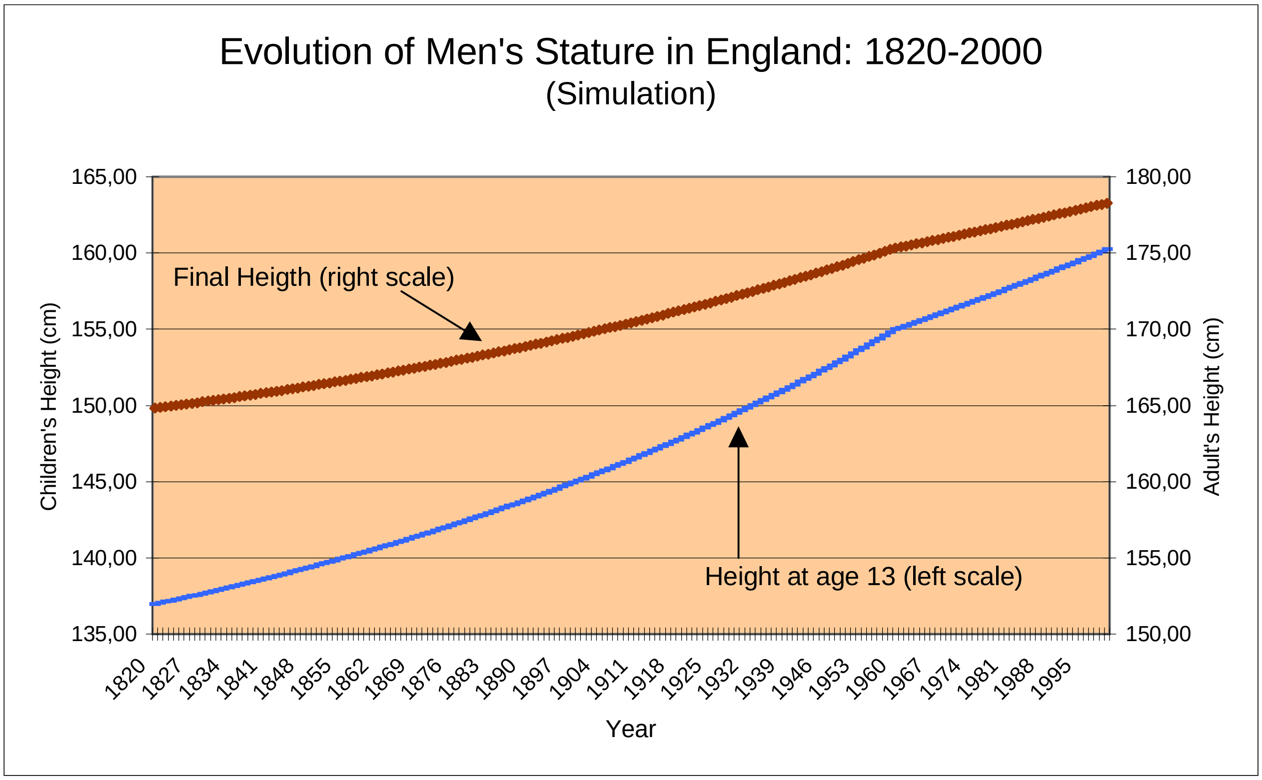
For the calibration of f_0 and E I proceed in the following way:

1. I pick two years of England's recent history that are sufficiently separated in time and for which we have reliable and comparable data on income per capita and the height of 13-year-old boys: This two years turn out to be 1820 and 1952. Maddison (1995) reports that income per capita was 6987 (1990 Geary-Khamis) dollars in England in 1952, and 1756 (1990 Geary-Khamis) dollars in 1820. According to Tanner, Whitehouse and Takaishi (1966) the mean height of 13-year-old English boys born in 1952 was 153,4 cm, while it was 137,3 cm for those born in 1820 [Floud, Wachter and Gregory (1990)] or even lower, 129,43 cm [Komlos (1993)].
2. Then I assume that the value of f_0 in 1952 is the one reported in Delajara(2001), 5.55, and that the value of E is such that formula (4) gives exactly the height of boys at age 13 in 1952. By this process I establish that primary school enrollment in England must have been about 92% in that year.
3. I proceed in the same way for the case of year 1820; for that year what we know is E and it is f_0 that must be calibrated. From data reported by Crafts (1997) I estimate that primary school enrollment prevailing in England in 1820 must have been about 30%. Then to match the height of children in 1820 reported by Floud et al. (1990) f_0 must be equal to 5.52.
4. The values of E and f_0 corresponding to the years 1821-1951 are found by interpolation, assuming that E and f_0 change smoothly over time.
5. To predict the evolution of the height of children for the period 1821-1951 we compute the average rate of growth of income per capita for that period from our knowledge of income per capita in 1820 and in 1952 reported above. The resulting growth rate of income per capita is 1,05 % per year.
6. For the period 1952-2000, I let primary school enrollment to increase up to 98,5% and stay at that level thereafter; I keep f_0 growing at the same rate it does in the period 1820-1952; and I also keep income per capita growing at the same rate of 1.05% per year.

Now we can simulate the evolution of children's heights for these mix of estimated and calibrated parameters.

In order to simulate the evolution of adults' height, however, we need to give a value to λ, the parameter related to the catch-up process of height between age 13 and adulthood. We assume (and this will prove a good guess) that $\lambda = 0{,}5$. That is, final adult height is the height achieved at age 13 plus half of the difference between the genetically-determined potential adult height and height achieved during childhood. Finally the potential average adult height is set at 198.3 cm.

Graph 1: Evolution of stature predicted by the model.



Note: The year reported refers to the year of birth

Graph 1, shows the result of our simulation. The model has been calibrated to match children's height at age 13 for those born in 1820 and for those born in 1952. Let's see what the model predicts based on this calibration.

The first prediction is that children's height increase smoothly from 137 cm in 1820 to 153,4 cm in 1953; the second prediction is that 13 -year-old boys born in the year 2000 are going to achieve a stature of about 160 cm: that is an increase 23 cm in 180 years, with an average of 1.23 cm per decade.

More importantly, the model predicts that adults born in 1820 achieved a mean adult height of 164.8 cm; those born in 1952 reached 174.4 cm; while those born in the year 2000 are to reach on average an adult height of 178.3 cm. That is, the model predicts an increase of about 13.5 cm in 180 years, or 0.75 cm per decade. In terms of growth rates, the model predicts an annual rate of 0.04% for adult height, and 0.09% for children's.

This simulation exercise, based on a model of children's height and on the stylized facts of this evolution, replicates very well the observed evolution of adult height. Both the evolution in levels and in growth rates match the evidence we have regarding the evolution of adult height in England.

Summarizing, the model of children's height supplemented with the assumption that adults' height is produced by the geometric combination (with coefficient 0,5) of the genetically-determined potential height (of 198.3 cm) and the height achieved at age 13, explains well the evolution of adults height in England. Moreover, the next section shows that the model also accounts for the fall in children's and adult's height during the initial stages of the industrial revolution, as documented by Komlos (1993).

4. Explaining the Episodes of Height Decline of the Late Eighteenth Century

To trace the evolution of children's and adult's height backwards from 1820 to 1750 we assume that the growth rate of income per capita between 1750 to 1820 was a bit larger than the one prevailing during the period 1820-2000: 2% per year. I assume this in order for GDP per capita to fall well under 1000 dollars as we go back in time; it is for income values smaller than 1000 dollars that our model of children's height replicates the phenomenon described in Komlos (1993) -that heights had declined during the second part of the eighteenth century in England.

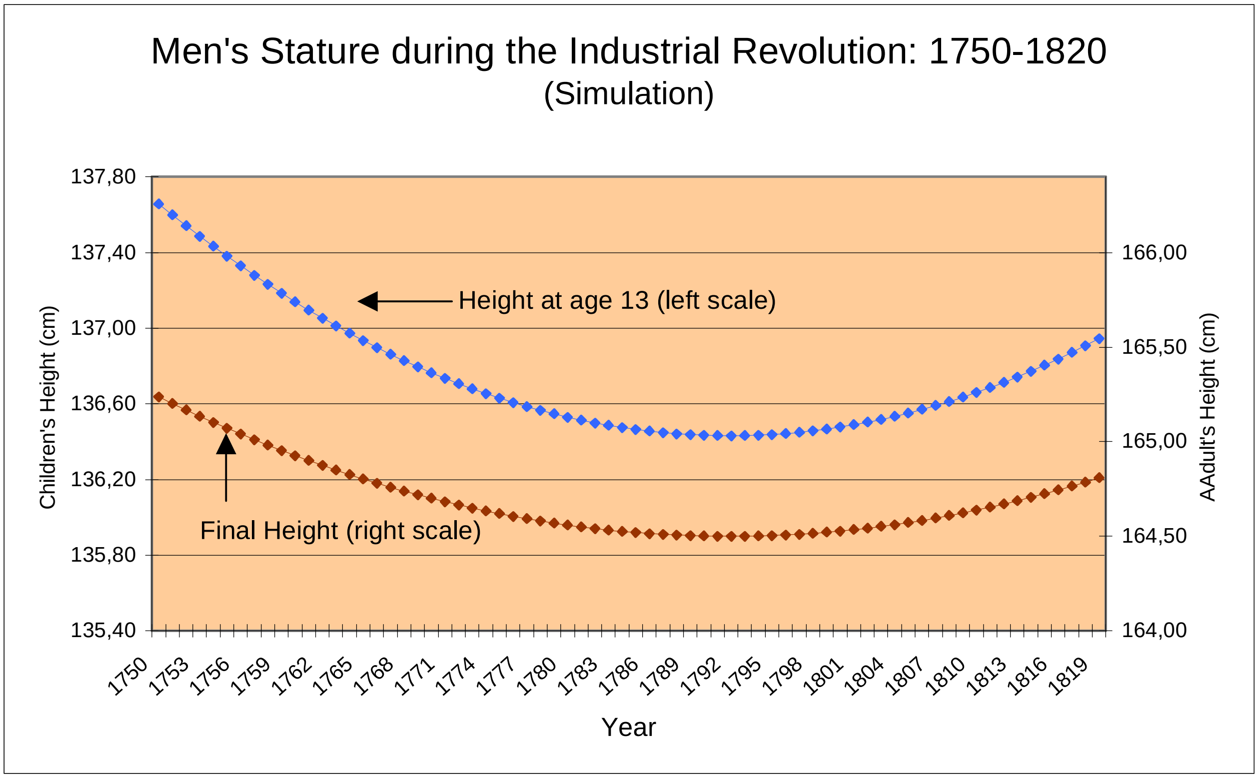
For simplicity I keep the values of $f_0 = 5.52$ and $E = 30$ that holds for 1820, for the period 1750-1820; the cost of doing this is that the resulting height levels might not be the right ones - yet, what is important for us now is to replicate the dynamics of height, not its level. The rest of the parameters remain the same as well.

Graph 2 shows the result of this exercise. According to our simulation children's height would have decrease 1,23 cm in the period 1750 - 1795. For adults' height the model predicts a smaller decline: 0,75 cm, in the same period. Notice that the fall in adult's height is smaller than the corresponding one for children, because children's height are more sensitive to income per capita changes.

The size of the decline in height, and more relevant, the size of the decline in adults' height relative to the size of the decline in children's height is very similar to the one reported in Komlos (1993). Komlos (1993) reports a decline of 0,69 cm for children's height and 0.33 cm for adults' height in the period going from 1750-9 to 1790-9. Notice that both our model's and Komlos' estimates coincide in the fact that adults' height fell by roughly half of the size of the corresponding decline in children's height.

I conclude then that our model also explains well the evolution of men's average height during the initial stages of the industrial revolution, in which the combination of fast growth and increases in fertility caused the height of children, and therefore of adults, to fall.

Graph 2: Accounting for the episode of height decline during the early industrial revolution



Note: The year reported refers to the year of birth

5. The Future of Stature

This model, which explains so well the recent historical evolution of adults' and children's stature, has the inconvenient feature -derived from the quadratic form of $f(y,\cdot)$- that the income elasticity of children's height increases with the income per capita; which means that children's stature could grow without limit if income per capita were to keep growing for several centuries in the future.

The quadratic function $f(y)$ explains well the evolution of children heights during the first 200 years of industrialization, when the range of income per capita levels is not that big. But if we want to forecast what will happen to adult height in the next 500 years or so, the model has to be amended. Fortunately, it can be amended to explain the future of stature and still remain useful to explain the transition from low to high stature discussed in the previous sections.

The idea is to have a new model of children's height which behaves pretty much the same as the one discussed in the previous sections for a range of income levels similar to the ones observed in the last 200 years, but that behaves in a way such that children's height converges to an upper bound for a range of larger -and even increasing- income per capita levels.

To amend the model I will assume that children's height does not only depend on $f(y)$ but that the growth of children's height is also guided by human evolution: children's height will keep growing with income per capita but, guided by nature, it will converge to a genetically-determined potential children's height. I will also assume that potential children's height coincides with the potential adult height. In other words, I now assume that in the future final adult height will be achieved at age 13, and that this height will be the genetically-determined potential adult height of 198,3 cm of the previous simulations.

Formally, I keep the specification $H^a = (H^p)^\lambda (H^c)^{1-\lambda}$, but instead of (4) we now have

$$H^c = (H^p)^\theta (F(y,E))^{1-\theta}, \tag{6}$$

so that in logs we have,

$$h^c = \theta h^p + (1-\theta) f(y,E), \tag{7}$$

which states that (in logs) children's height is the weighted average of the nutrition function $f(y,E)$ and the potential adult height h^p, with weights $0 < \theta < 1$.

As mentioned above we want h^c to behave similar to $f(y,E)$ for low values of y, but to behave like h^p for large values of y. That is, we would like children's heights to be driven by nurture in initial stages of economic growth and then be made to converge to the potential adult height in the long-run. In order to achieve this we shall assume that θ is endogenous, i.e. it depends on the level of development of the country.

In particular we assume that $\theta = \exp(-\delta Y)$; where $0 < \delta < 1$, and Y is income per capita level. Under this specification $\theta \to 0$ when income per capita tends to zero as well, and $\theta \to 1$ as income per capita tends to infinity.

For the parameters of the model used in the previous section, and for a value of $\delta = 0{,}00003$, children's height converges smoothly to the genetically-determined potential height as income per capita grows. What happens to adults' height?

To answer this question, we can re-write the production function of adult height as

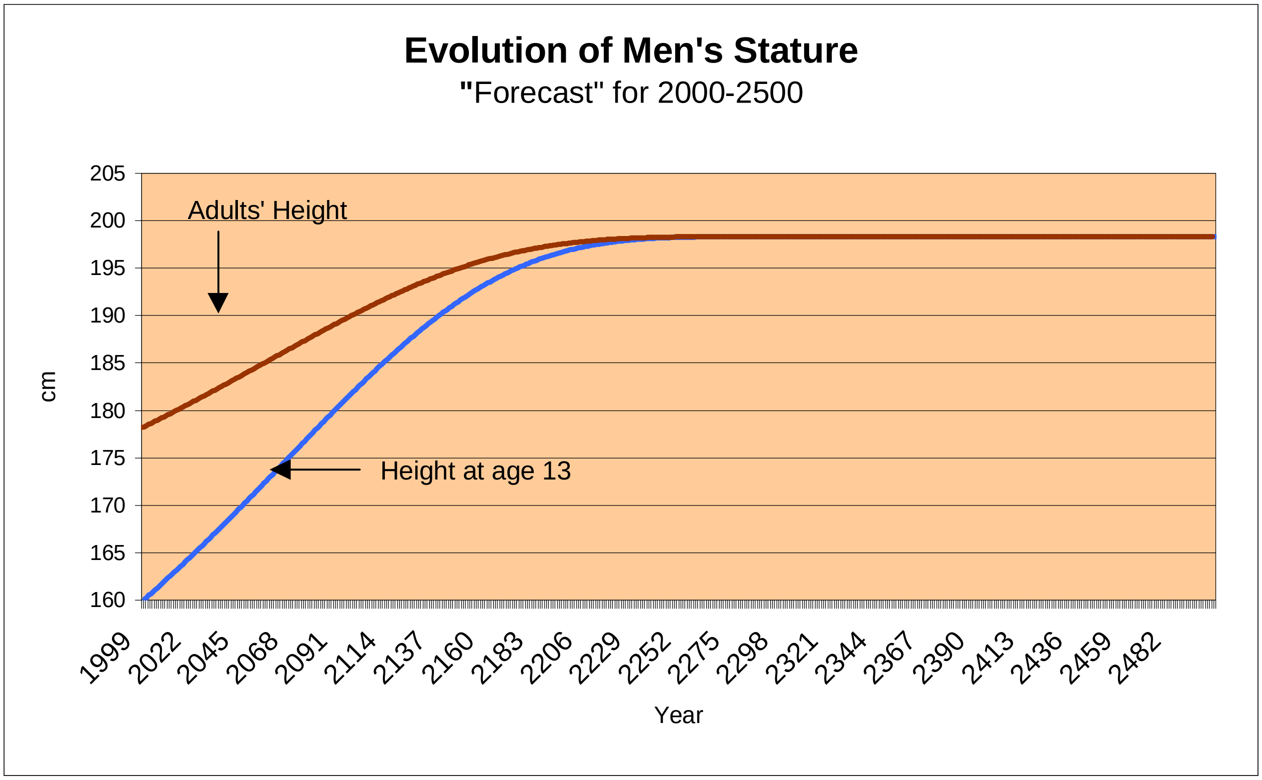
$$H^a = (H^p)^\alpha (F(y,E))^{1-\alpha}, \tag{8}$$

where $\alpha = \lambda + (1-\lambda)(1-\theta)$ and $1-\alpha = \theta(1-\lambda)$. This is essentially the same production function we had before, but with α in the place of λ.

Notice that as $\theta \to 0$ and children's height converges to the genetically-determined potential height, $\alpha \to 1$ and adult height converges to its potential value as well. That is, in the long-run, adult height equals the genetically-determined height and this is achieved at age 13.

Graph 3 shows the simulation of the model. Children's height at age 13 keeps growing with income per capita and converges with adult height when adult height reaches its genetic potential.

Graph 3: The future of men's stature



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Under the parameters chosen -which are the ones that successfully explain the evolution of heights observed in the last two centuries- the model predicts that an increasing proportion of adult height will be achieved during childhood (at age 13, in our simulations) as income per capita grows. The model predicts that by the year 2300 final adult height will be achieved by age 13, and that this height will be the maximum height genetically attainable, 198,34 in our model.

There are alternative ways to amend the model. The one chosen here is one of many the that could deliver similar results, but it has the compelling feature that we extend the model to forecast the future of heights without changing the features that help explained the evolution of heights of the last two centuries.

6. Conclusion

I show that a model of children's height supplemented with the assumption that nature and nurture jointly determine final adult height can be use to derive a model that successfully explains the recent historical evolution of men's stature in England. I also show a way to use the model to forecast the future evolution of heights.

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