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RESEARCH PAPER

Measuring catch-up growth in malnourished populations

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Abstract

Background and aim: Numerous recent studies measure catch-up growth by regressing adult or pre-adolescent height on early childhood height. Using simple statistical theory and data from a healthy and well-nourished population, this paper shows that these tests are uninformative about the extent of catch-up growth. The study also provides new empirical evidence on pubertal catch-up growth using longitudinal data for rural Tanzania.
Subjects and methods: The 1970 British Cohort Study is used to demonstrate the flaws in the recent literature using regression techniques to study catch-up growth. The data for the empirical analysis come from the Kagera Health and Development survey—a longitudinal study spanning two decades. The final sample includes 540 children whose heights are measured in early childhood and in adulthood. Catch-up growth is measured as the change in height-for-age *z*-score over time.
Results: The mean HAZ-score in the cohort improves from −1.86 in early childhood to −1.20 in adulthood. Without catch-up growth, children would have been 4.5–5 centimetres shorter adults. Graphical analysis shows that most of this catch-up growth takes place in puberty.
Conclusion: Catch-up growth after early childhood is possible. Puberty seems to offer an opportunity window for recovery.

Keywords

African height puzzle, compensatory growth, children, height, under-nutrition

History

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Introduction

Growth faltering in developing countries typically begins in the first 3 months of life and persists until the age of 2–3 years (Eveleth & Tanner, 1976; Shrimpton et al., 2001; Victora et al., 2010). This is usually caused by insufficient or poor nutrition or by infectious diseases (Golden, 1994). Since children are growing rapidly during these years, even a short retarded growth spell in this period quickly leads children to fall behind from their fast growing peers (Shrimpton et al., 2001; Victora et al., 2010). To bounce back to their original growth curves, short and stunted children need to experience higher growth rates than their healthy and well-nourished peers.

In the clinical and epidemiological literature, such catch-up growth is defined as height velocity that is above the expected for the child's age and occurs after a period of growth retardation (Ashworth & Millward, 1986; Boersma & Wit, 1997; Tanner, 1981; Williams, 1981). A complete catch-up takes place if the original, pre-retardation, growth curve is attained (Ashworth & Millward, 1986; Williams, 1981). Height-for-age *z*-score (HAZ) measures the distance in height to the median child of a healthy and well-nourished population providing the exact empirical counterpart for this definition. An increase in HAZ means that height velocity is above what is expected for the child's age and gender.

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Recent literature has studied the existence of catch-up growth by regressing adult or pre-adolescent height on early childhood height (e.g. Alderman et al., 2006; Fedorov & Sahn, 2005; Hoddinott & Kinsey, 2001; Martorell et al., 1992; Mani, 2012; Outes & Porter, 2013; Victora et al., 2008). This paper demonstrates that these tests misinterpret catch-up growth with within-population convergence. Such convergence occurs if short and stunted children experience faster growth than others or taller children grow at a slower pace than others—or because of some combination of both. By regressing current height on early childhood height researchers cannot tell whether children are catching-up or faltering. Moreover, by focusing on the movement *within* the population these regressions fail to capture catch-up growth at the population level. The interpretation of these regression coefficients is further hampered by regression-to-the-mean (Friedman, 1992; Quah, 1993).

The evidence on catch-up growth is further limited due to the scarcity of longitudinal data sets that follow children over their entire childhood (Eckhardt et al., 2005a). The empirical part of this paper provides new evidence for Sub-Saharan Africa. Using a 19-year longitudinal data set for the Kagera region in Tanzania, I find considerable catch-up growth. The mean HAZ-score in the cohort improves from −1.86 in early childhood to −1.20 in adulthood. Without catch-up growth, the average girl in the sample would have been a nearly 5 centimetres shorter adult. For boys, the difference between the predicted adult height in early childhood and the actual adult height is ~4.5 centimetres. Graphical analysis shows that this catch-up growth takes place in puberty. Recently, Coly et al. (2006) and Prentice et al. (2013) documented similar extensive pubertal catch-up growth among Senegalese and Gambian children.

The findings from these three African cohorts challenge the conventional view in the literature where catch-up growth after early childhood is difficult and seldom observed (e.g. Grantham-McGregor et al., 2007; Martorell et al., 1990; Schroeder, 2008). The results in this paper add to the emerging evidence that puberty offers an opportunity window for catch-up growth (Haas & Campirano, 2006; Moradi, 2010; Prentice et al., 2013) and call for re-thinking the policy recommendation where nutritional interventions are *only* targeted to young children (for a similar point, see Prentice et al., 2013). Furthermore, a number of studies use adult height as a proxy for health and wealth in early childhood (Almond & Currie, 2011). The findings in this paper imply that height in adulthood may not be such a good indicator of childhood conditions.

Finally, the pubertal catch-up growth may provide a missing piece to the *African height puzzle*. In a seminal paper, Deaton (2007) shows that, contrary to most other countries in the world, disease environment and national income are not good predictors of female adult height in African countries. African women are taller than their economic and disease environment suggests. Deaton (2007), Bozzoli et al. (2009) and Gørgens et al. (2012) explain this puzzle with a selection effect: childhood mortality is concentrated on the genetically short children, thus shifting the mean adult height right. Moradi (2010, 2012) proposes an alternative explanation that African children experience a considerable catch-up growth in puberty. The results presented here provide support to this hypothesis.

The structure of this paper can now be outlined. The next section demonstrates the methodological flaws in the recent empirical literature. This is followed by a brief survey of studies employing longitudinal surveys and defining catch-up growth as the change in height-for-age *z*-score. The two subsequent sections present the data used in the empirical analysis and the results. The penultimate section analyses the timing of the catch-up growth in the Kagera cohort. The final section provides a concluding discussion.

How not to measure catch-up growth

Recent empirical literature (Alderman et al., 2006; Fedorov & Sahn, 2005; Hoddinott & Kinsey, 2001; Martorell et al., 1992; Mani, 2012; Outes & Porter, 2013; Victora et al., 2008) subscribes to the definition of catch-up growth used in the medical literature, but employs regression analysis, usually using the following type of specification:

$$h_{it} = \alpha + \beta h_{i,t-1} + e_{it}, \tag{1}$$

where α is the intercept and e_{it} the error term. The term h_{it} is height (or height-for-age *z*-score) of individual i in period t and $h_{i,t-1}$ height (or height-for-age *z*-score) in a previous period. In studies that have an access to a sufficiently long data set, t usually refers to height measured in adulthood and $t-1$ to height measured in early childhood. The β coefficient is then interpreted as the measure of catch-up growth. A zero β coefficient on the lagged height is taken as a complete catch-up: initial height does not predict adult height. A coefficient equal to one is interpreted as evidence that no catch-up growth takes place: short or stunted children remain locked into their lower growth trajectory. Finally, few studies (e.g. Hoddinott & Kinsey, 2001) use change in height as the dependent variable. This growth specification changes the interpretation of β but leads to qualitatively identical conclusions about the extent of catch-up growth (see Fedorov & Sahn, 2005).

There are a number of problems with the regression approach. Most importantly, these tests confuse catch-up growth with within-population convergence. To illustrate this, we can express the β coefficient as the ratio of covariance between the adult height and initial height, $cov(y, x)$, and the variance of the initial height, $var(x)$, where y refers to h_{it} and x to $h_{i,t-1}$:

$$\beta = \frac{cov(y, x)}{var(x)} \tag{2}$$

Abstracting from the case when the variance of childhood height approaches infinity, β approaches zero if the covariance between adult height and childhood height approaches zero. In other words, β approaches zero when childhood height is not a good predictor of adult height. Such an outcome is possible if short and stunted children catch-up others—or if the growth of the taller children in the sample stagnates. As such, β is only picking up movements within the HAZ distribution over time, but researchers cannot tell whether this is due to improvements in HAZ or not.

Second, as the β coefficient focuses on the changes *within* the distribution it fails to capture a widespread catch-up growth in the population. Such uniform movement of the distribution (as for example in Figure 3 presented later) only affects the estimated constant (α), not the β coefficient. This is a particular concern if the population under scrutiny is largely malnourished.

Another important caveat is introduced by regression-to-the-mean (even in the absence of measurement error). Finding that $\beta < 1$ may imply convergence (reduction in the dispersion of the height distribution over time) or simply natural variation in growth rates (height distribution remains intact). Quah (1993) demonstrates this algebraically using the Cauchy-Schwarz inequality:

$$cov(y, x) \leq \sqrt{var(x)}\sqrt{var(y)}. \tag{3}$$

Now, if there is no convergence or dispersion it follows that:

$$var(y) = var(x). \tag{4}$$

Using this and the Cauchy-Schwarz inequality in Equation (2) gives:

$$\beta \leq \frac{\sqrt{var(x)}\sqrt{var(x)}}{var(x)} = 1. \tag{5}$$

As such, even when imposing constant variance over time, β is smaller than one (the equality in the Cauchy-Schwarz holds only in the degenerate case when x and y are linearly dependent). This is why $\beta < 1$ does not necessarily imply convergence—let alone catch-up growth. It is of no surprise then that most of these studies document partial convergence (i.e. $0<\beta<1$). The β estimates vary between 0.2 (Fedorov & Sahn, 2005) to 0.7 (Martorell et al., 1992).

I further demonstrate these concerns using the 1970 British Cohort Study (Elliott & Shepherd, 2006). The cohort represents a healthy and well-nourished population. By default, it does not contain malnourished children and, therefore, I should not find any catch-up growth. Table A1 of Appendix A contains the summary statistics for the final sample of 9635 individuals. Figure 1 provides the distribution of the children's HAZ scores in early childhood (solid line) and adulthood (dashed line). As expected, the means lie close to zero in both periods and the distributions are virtually on top of each other.

I then estimate Equation (1) using height-for-age z-scores (see Appendix B on why using raw measures of height is not appropriate here). Table 1 presents the regression results. The β coefficient is estimated as 0.601. The 99% confidence interval for this point estimate is [0.578; 0.623]. This finding seriously questions the validity and the interpretation of findings in the previous literature using a regression approach to study catch-up growth. First, it is inconceivable to find catch-up growth in a healthy and well-nourished population. The descriptive and graphical analyses also show that there is negligible movement in the distribution over time. Yet, the current literature would interpret this regression result as partial catch-up growth. Second, a more sensible interpretation of the result is convergence in the height distribution (i.e. the dispersion diminished over time). Neither this is supported by the graphical analysis.

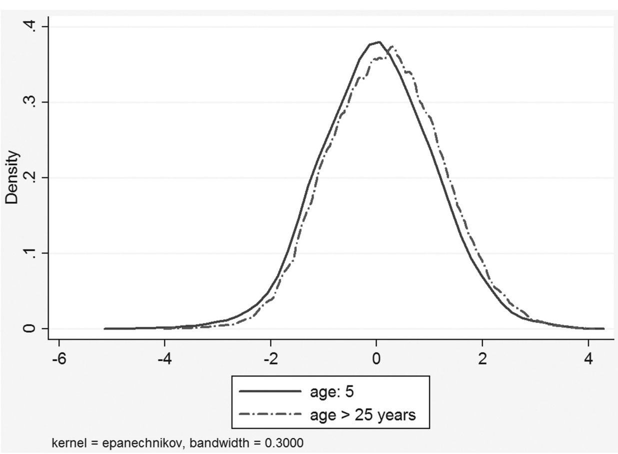

Figure 1. The evolution of the height-for-age z-scores (HAZ) distribution over time in British cohort study (BCS70). Kernel density estimates.

Table 1. Estimating convergence in the British cohort (BCS70) (dependent variable: HAZ in adulthood).

	BCS70
HAZ in early childhood	0.601*** (0.009)
Intercept	0.164*** (0.008)
Number of observations	9635
R^2	0.383

***$p<0.01$.
White (1980) adjusted standard errors are in parentheses.

Could this be explained by measurement error? It is true that measurement error in initial height ($h_{i,t-1}$) causes a downward bias, potentially leading to a false inference on convergence. Measurement error in h_{it} is less harmful as it only leads to inflated standard errors. These statements hold if we make the plausible assumption that measurement error is random (i.e. not correlated with children's characteristics) with zero mean. In Appendix C, I show that the magnitude of the potential measurement error is too small to drive the results in Table 1.

To further analyse what is going on, in Figure 2 I plot HAZ in adulthood on HAZ in early childhood. If the nutritional status in early childhood perfectly predicted adult outcomes (i.e. children remain locked into their growth trajectories), the regression line (dashed line in the figure) would lie on the 45-degree line (solid line). Instead, the regression line is flatter. From the figure it becomes clear that this is an outcome of regression-to-the-mean: those initially unusually short (the dots lying on the middle-left in the figure) and tall (the dots lying on the middle-right) reverted towards the mean by adulthood.

The economics literature appends Equation (1) with control variables, such as child, household and community characteristics. This shifts the focus from *unconditional* to *conditional* convergence but does not address any of the criticisms raised in this paper. Furthermore, the same literature is concerned with establishing the causal effect of initial height on adult height. In the presence of time-invariant unobserved characteristics, such as child's innate healthiness or parents' preferences, the lagged height variable ($h_{i,t-1}$) is, by construction, correlated with the error term (e_{it}). As a result, β captures both the relationship of adult height and early childhood height (i.e. convergence) as well as the relationship between adult height and the omitted or unobserved variables. The usual strategy is to use instrumental variable (IV) techniques to eliminate the role of unobserved omitted characteristics (Alderman et al., 2006; Fedorov & Sahn, 2005; Hoddinott & Kinsey, 2001; Mani, 2012; Outes & Porter, 2013). The approach starts with a quest for variables that are correlated with the initial height but not with adult height (other than through initial height). In the first stage, these *instrumental* variables are used to predict the initial

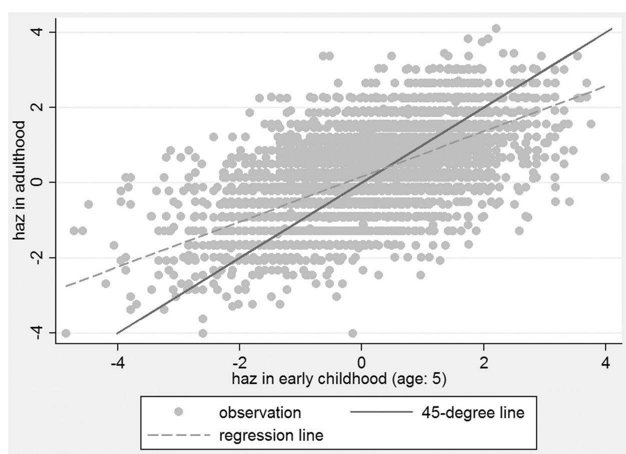

Figure 2. HAZ in adulthood on HAZ in early childhood, the British cohort (BCS70).

height. In the second stage, the predictions are plugged into the original equation in order to remove the correlation with the error term and the initial height. The IV-approach is not, however, a panacea. These IV-estimates continue to measure within-sample convergence. Moreover, the approach does not solve the issue with the regression-to-the-mean (see Quah, 1993). Finally, researchers often remove the time-invariant unobserved variables from Equation (1) by taking first differences and then use an instrument to purge the remaining correlation with the lagged height variable and the error term (e.g. Fedorov & Sahn, 2005; Mani, 2012). This is unfortunate as it is precisely the impact of these variables, rather than the β coefficient, that would provide useful information to the health practitioners and policy-makers (see Durlauf & Quah, 1998, for a similar point in the context of economic growth analysis).

Review of studies measuring catch-up growth as the change in HAZ

In an influential study, Adair (1999) defines catch-up growth as a recovery from stunting. Using the Cebu Longitudinal Health and Nutrition Survey from the Philippines, she finds that the proportion of the stunted children (HAZ < -2) fell from 63% at the age of 2 years to 50% by the age of 12. Using the NCHS/WHO 1977 growth reference to convert heights into HAZ scores, she finds that the mean HAZ scores improved from -2.41 at the age of 2 to -1.94 by the age of 12. As she does not observe the adult heights, these catch-up growth estimates provide only tentative evidence of the final catch-up growth in the cohort. Later analyses by Eckhardt et al. (2005a, b) show that growth faltering took place during puberty, especially among females.

A few studies group children according to their degree of stunting in early childhood and compare the height increments from early childhood to adulthood between groups and to an external healthy and well-nourished reference population. Martorell et al. (1990) use data from Guatemala where more than half of the children in the sample were stunted at the age of 5 years. These children did not experience larger height gains than their American peers; if anything, the opposite is true. In addition, the authors did not find any marked differences in height increments between initially shorter and taller Guatemalan children. Satyanarayana et al. (1980, 1981) study growth increments using Indian cohorts of boys and girls, respectively. They group children according to their severity of stunting at the age of 5 and compare the height increments until early adulthood between the groups and to a longitudinal study from Boston. These Indian boys were not found to experience any catch-up growth and also the height gains between the groups were similar (Satyanarayana et al., 1980). The initially most nutritionally deprived girls (HAZ < -4) were found growing considerably faster than the Boston girls and other Indian girls in the same sample (Satyanarayana et al., 1981). This result may, however, be an outcome of measurement error in initial height leading to incorrect grouping of the children.

Among the very few longitudinal studies from sub-Saharan Africa, Coly et al. (2006) follow more than 2800 Senegalese children for nearly two decades and compare their growth rates to the NCHS/WHO 1977 reference. The mean HAZ in early childhood among girls was -1.3 and among boys was -1.4. By adulthood these means reduced to -0.41 for girls and -0.58 for boys, implying nearly complete catch-up. This widely neglected study also makes a clear distinction between catch-up growth relative to a healthy reference population (global catch-up growth) and relative to other children in the population (local catch-up growth). More recently, Prentice et al. (2013) provided similar evidence from Gambia. Exploiting longitudinal data of 160 children whose heights were measured multiple times between the ages of 8–24 and measuring heights against the UK-1990 reference population, they also document nearly complete catch-up growth. The mean HAZ among boys improved from -1.25 to -0.5 and from -1.1 to -0.2 among girls.

Data

The data for the empirical part of the paper originate from the Kagera Health and Development Survey (KHDS) from Tanzania. The survey design follows the World Bank's Living Standard Measurement Survey (LSMS) framework with a special emphasis on health. At 19-years, KHDS is one of the longest running LSMS-type of longitudinal surveys from sub-Saharan Africa.

Kagera is a region in the north-western part of Tanzania. According to the latest National census in 2002, the region has a population of $\sim$2 million people. The first interviews were held in 1991–1994, with follow-up surveys in 2004 and 2010. At the baseline in 1991–1994, more than 800 households were interviewed up to 4-times. The interval between the interviews was 6–7 months. These survey waves were designed and implemented by the World Bank and the Muhimbili University College of Health Sciences. The sample was drawn from a random sample stratified by adult mortality rates in the communities and the agro-climatic zones in the region. Statistical tests (not reported but available from the author) did not reveal statistical differences in HAZ scores between children residing in high or low adult mortality communities. The World Bank (2004) provides a comprehensive description of the baseline survey. The 2004 and 2010 follow-up surveys aimed to re-interview all individuals that were ever interviewed in the baseline survey. Beegle et al. (2006) and De Weerdt et al. (2012) provide a description of these survey rounds.

Anthropometric measurements were taken from all respondents who were present at the time of the household interview. In 1991–1994, trained anthropometrists were responsible for measuring all household members. In 2004 and 2010, enumerators, carefully trained by a qualified nurse, took the measurements usually after the household questionnaire was administered in the household. In all survey rounds, heights of children less than 3 years old were measured using a length board with a sliding foot piece. The heights of adults and children older than 3 years were measured using a height board with a sliding head piece. All heights were recorded to the nearest millimetre.

Height-for-age Z-scores were calculated using the *zanthro* command in Stata 11.2 (see Vidmar et al., 2004). I use the US 2000 NCHS/CDC as the reference population (see Kuczmarski et al., 2002). The 2006 WHO Child Growth Standards (see WHO, 2006) in conjunction with the WHO Reference 2007 for 5–19 years (see de Onis et al., 2007b) resulted in more catch-up growth than NCHS/CDC. This is driven by the differences between the two references. In early childhood (ages 0–5), the median child in the WHO Child Growth Standards is taller than in the NCHS/CDC reference population (de Onis et al., 2007a). In adulthood (at the age of 19), however, the height difference is negligible when comparing the WHO Reference 2007 for 5–19 years and NCHS/CDC. This highlights the difficulty in comparing studies that employ different growth standards or reference populations. I prefer the NCHS/CDC growth reference as it allows the calculation of HAZ scores from birth to 20 years of age, and is constructed using the same reference throughout the entire growth period.

The sample for this study is constructed from children who were between 12–59 months old at the time of the four waves of the baseline survey in 1991–1994 and who are at least 18 years old in 2010. This cohort of 884 children is followed from the 1991–1994 rounds through the 2010 round. In 2010, 559 of these children were interviewed and measured, 69 had died and 256 were not found or their heights were not measured. I drop all children whose height was not measured in 2010 or whose date of birth is not known. After dropping the few children with implausible height measurements ($HAZ < -5$ or $\Delta HAZ > \pm 4$) the final sample contains 540 children (269 girls and 271 boys) from 365 households. If the child was measured more than once when she was 12–59 months old during the four interview rounds at the baseline, I took the last measurement. An alternative strategy would have been to take the mean over these observations to address the potential measurement error in these data. This yields a nearly identical mean HAZ score, suggesting that the potential measurement error is either random or absent in these data. Finally, I use the difference between the date of the interview and the child's date-of-birth to calculate the ages.

The sample attrition poses a concern to the analysis. Attrition due to death is less of a problem, as catch-up growth analysis is focused on the height developments of the surviving. Attrition due to other causes is more problematic. If such attrition is positively correlated with health, then studies are likely to under-report catch-up growth in the sample. To address this, in Table 2, I compare children's height-for-age scores by the attrition status. Children who did not form the final sample have slightly higher HAZ scores than those who did. A two-tailed *t*-test shows, however, that this difference is not statistically significant. Further examination, presented in Table D1 in Appendix D, reveals that children who deceased after the first round had lower HAZ-scores than those who survived and form the final sample. Children who were not traced or present at the time of the measurement have slightly better HAZ scores than children who form the final sample. However, according to a two-tailed *t*-test, neither of these observed differences is statistically significant. Sample attrition does not seem to be, therefore, associated with higher or lower HAZ scores.

Table 2. Attrition in the Kagera (KHDS) survey: Initial HAZ-scores by sample category.

	KHDS	
Final sample	No	Yes
Observations	344	540
HAZ:		
Mean	−1.804	−1.864
SD	1.262	1.155
Difference	0.06	
t-Test	0.71	

t-Test based on Welch *t*-test on the difference in means between the two groups.

Finally, Table D2 of Appendix D provides an overview of the HAZ-scores in KHDS by migration status for each child in the sample. By 2010, I find that half of the sample had migrated. Had we not tracked individuals, I would have lost half of the sample. Surprisingly, however, migration does not seem to be correlated with nutrition status. According to a two-tailed *t*-test, the difference in the adult HAZ-scores between children who remained in the baseline village and those who migrated by 2010 is not statistically different from zero.

Catch-up growth in the Kagera cohort

Next, I analyse the extent of catch-up growth in the Kagera cohort. Table 3 shows the summary statistics for the cohort. The mean HAZ scores in 1991–1994, when the children are less than 5 years old, is 1.86 standard deviations below the median of the US-reference group. Approximately 44% of the children are stunted ($HAZ < -2$) and 16% are severely stunted ($HAZ < -3$). These percentages agree with the statistics reported in the 1991/92 Tanzanian Demographic and Health Survey for the same region: 44% of the children under 5 years old in Kagera were found stunted and 19.5% severely stunted (Ngallaba et al., 1993).

Interestingly, in 2010, the cohort has been able to catch-up with the reference group: the mean height-for-age *z*-score in the sample is now −1.20. In 2010, 20% were stunted and only 3% severely stunted. There is also a clear gender difference. The mean HAZ-score in the female sample increases from −1.71 to −0.98, whereas for males the catch-up growth is somewhat more modest: mean HAZ increases from −2.01 to −1.42. These statistics show that the Kagera children are able

Table 3. Evolution of HAZ scores in the Kagera (KHDS) cohorts.

	KHDS	
	Mean	SD
Age in months ($t=0$)	41.08	14.686
Age in years ($t=1$)	20.25	1.591
Height ($t=0$)	89.64	10.269
Height ($t=1$)	161.7	8.267
HAZ ($t=0$)	−1.86	1.155
HAZ ($t=1$)	−1.20	1.002
Difference in HAZ	0.66	1.07
t-Test: $HAZ_{t=0} = HAZ_{t=1}$	10.01	
Percentage: $HAZ_{t=0} < -2$	44%	
Percentage: $HAZ_{t=1} < -2$	20%	
Percentage: $HAZ_{t=0} < -3$	16%	
Percentage: $HAZ_{t=1} < -3$	3%	
Observations	540	

$t=0$ refers to early childhood, $t=1$ to adulthood. HAZ scores calculated using the US 2000 NCHS/CDC as the reference population.

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to catch-up the growth losses incurred in early childhood. Figure 3 shows the full distributions of the HAZ scores in both periods. The figure reinforces the summary statistics: there is considerable catch-up growth in the sample. This can be seen as the adult height distribution shifting right relative to the early childhood distribution.

Figure 4 offers another cut of the data. Here I plot the change in HAZ on HAZ in early childhood. The horizontal line goes through zero. The dots above this line are children whose HAZ score improved between the two periods. The dots below this line belong to children whose HAZ score worsened. The figure also contains a vertical line that goes through zero. The dots on the left of this line belong to children who had a negative HAZ score in early childhood. The top left corner (marked with A) contains the children who experienced catch-up growth: after initial growth retardation ($HAZ_{t-1} < 0$), they experienced growth that was above what was expected for their age ($\Delta HAZ > 0$). This corner corresponds directly to the definition of catch-up growth used in the clinical and epidemiological literature.

Figure 4 shows that 95% of Kagera children had negative HAZ scores when they were first measured. More than 74% of the sample experienced catch-up growth. The mean improvement in HAZ scores among these children is 1.1 units of standard deviation (median = 0.97). Nearly 21% of the children had negative HAZ-scores in early childhood and fell further behind later in life. Only 5% of the children had initially positive HAZ-scores. Most of these children experienced slower growth than was expected.

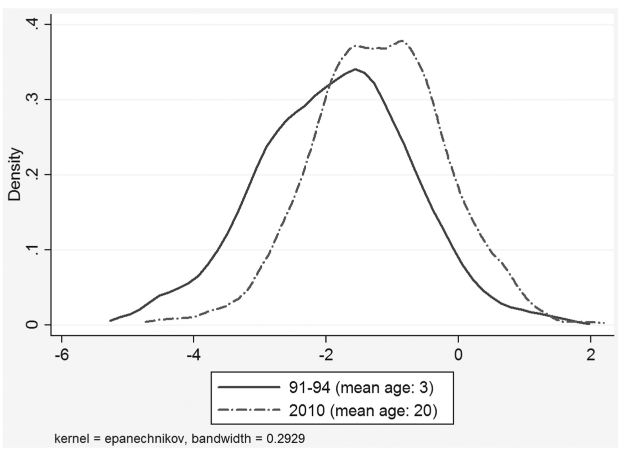

Figure 3. The evolution of the HAZ distribution over time in Kagera cohort (KHDS). Kernel density estimates.

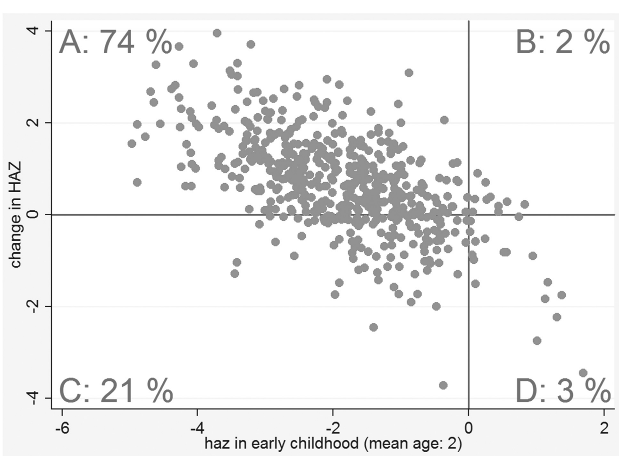

Figure 4. Change in HAZ between early childhood and adulthood on HAZ in early childhood the Kagera cohort (KHDS). (A) Undernourished and growing; (B) well-nourished and growing; (C) undernourished and faltering; (D) well-nourished and faltering.

Timing of the catch-up growth in the Kagera cohort

The analysis in the previous section finds considerable catch-up growth in the KHDS cohort. Coly et al. (2006) find that the near complete catch-up growth documented in the Senegalese cohort takes place in puberty. In a recent paper combining longitudinal and cross-sectional data from rural Gambia, Prentice et al. (2013) show how children experience substantial catch-up growth during puberty.

To analyse the timing of the catch-up growth in the Kagera cohort, I would need to compare growth rates at different points in childhood. Unfortunately, assessing children's annual growth patterns is not feasible using the longitudinal data as I only have two or three data points for each child. Fortunately, I can use the cross-sectional data to mimic children's growth patterns (see Moradi, 2010, for a similar exercise using data for Cote d'Ivoire and Ghana). Using the baseline data in 1991–1994, I constructed mean HAZ-scores at each age until the age of 23. To account for concerns that the observed catch-up growth in these cross-sectional data is an artefact of selective mortality (see Bozzoli et al., 2009; Rouanet, 2011), I drop all children who did not survive their 18th birthday. This mortality information originates from the 2010 survey when the panel respondents are adults. Figure 5 shows the growth patterns for both gender groups (solid lines). Similar to the evidence presented in Shrimpton et al. (2001), growth retardation begins immediately after birth and continues until 2–3 years of life. After 4 years of age, the HAZ-scores remain relatively stable until the age of 10–11 years. At this age, the median child in the US reference group enters the adolescent growth spurt. The HAZ-scores fall rapidly at this point, suggesting that puberty is delayed for the Kagera children. For boys, the HAZ-scores continue to fall until the age of 15 at which point the HAZ-curve shoots up. The growth ceases at the age of 19 for girls and at the age of 22 for boys. By now boys have caught-up the height losses

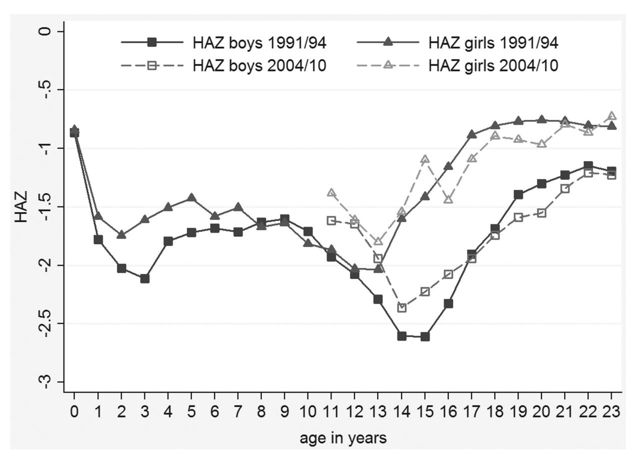

Figure 5. HAZ scores by age (cross-sectional data) in Kagera (KHDS). The dashed curves are less smooth because of fewer observations.

incurred during puberty but HAZ-scores have also improved further to nearly restore their early childhood levels. Girls begin their adolescent growth spurt earlier and are able to completely restore their initial growth curves.

The shortcoming of using cross-sectional data to construct growth curves is that I cannot be sure whether the observed growth patterns are driven by age or by birth cohort effects. That is, whether the observed differences between the age cohorts are arising because they are observed at different ages (age effect) or because they were born into different environmental conditions (birth cohort effect). To circumvent this, I exploit the longitudinal feature of the data and plot the growth curves for the same children whose pre-adult HAZ-scores I have in the later rounds of the survey (i.e. 2004 and 2010 rounds). These are the two dashed lines in Figure 5 starting at the age of 11. These curves lie very close to the original growth curves lending support to the age effects story. The three longitudinal data observations further confirm these patterns. At the average age of 3 years, the mean HAZ score for girls is -1.71 and for boys is -2.02. In puberty (average age of 14), girls' mean HAZ score has improved to -1.25 and boys' to -1.89. In adulthood, the girls' mean HAZ score stands at -0.98 and boys' at -1.42.

This evidence shows that puberty is an important opportunity window for the Kagera children to catch-up their healthy and well-nourished peers. Moreover, this growth pattern does not seem to be cohort-specific.

The finding is in tune with the recently emerged evidence from studies employing cross-sectional data sets suggesting that puberty is a sensitive period for children's growth. Interestingly, most of this evidence is from studies analysing populations originating from Sub-Saharan Africa. Moradi (2010), using multivariate regression analysis and a sample of more than 200 000 women from Sub-Saharan Africa, finds that economic growth has a positive effect on adult height during early childhood but also during puberty. Akresh et al. (2012) provide indirect evidence on this by comparing female adult heights between cohorts exposed to the Nigerian civil war in 1967–1970. Strikingly, they find that the most negatively affected children were the ones aged 13–16 during the war. Economic historians have documented intense pubertal catch-up growth among 19th century African Americans. In a famous study, Steckel (1987) documents a remarkable catch-up growth of African American slaves during puberty. Using manifests of 50 000 slaves transported in 1820–1860, he shows that children remain highly malnourished until puberty, during which the height deficit to an external reference population halved. This catch-up is credited to improved diets when the slaves entered the labour force between 8–12 years (Steckel, 1987, 2000). Komlos (1992) documents similar catch-up growth among free African Americans in Antebellum, Maryland.

Among studies based on non-African populations, Stein (1975) shows that children exposed to the Dutch Winter Famine in 1944–1945 were able to completely catch-up other, non-exposed, cohorts. Finally, Haas and Campirano (2006), using cross-country data, plot the pubertal growth rate on height just before the onset of puberty. They find that children from populations that have lower pre-pubertal heights seem to experience greatest growth during puberty.

Concluding discussion

The empirical analysis of catch-up growth requires longitudinal data or cohort studies that span the entire growth period. Catch-up growth is defined as growth in height that is above the expected for the child's age and occurs after a period of growth retardation. Height-for-age z-score measures the height distance in standard deviations to a healthy and well-nourished reference population. The evolution of HAZ scores over time therefore provides the exact counterpart of the definition used in the clinical and epidemiological literature.

Part of the existing evidence is plagued by studies that confuse catch-up growth with convergence. By regressing HAZ in adulthood on childhood HAZ researchers cannot tell whether children are catching-up or faltering. In addition, these tests focus on movement *within* the cohort and are therefore not able to detect widespread catch-up growth in populations. The interpretations of these regression estimates are further hampered by regression-to-the-mean.

Aside from the methodological contribution, I also provide new evidence for sub-Saharan Africa. Using longitudinal data for the Kagera region in Tanzania, I document considerable catch-up growth. Nearly 75% of the children experienced catch-up growth: after a period of growth retardation ($HAZ < 0$) in early childhood they experienced growth that was above the expected ($\Delta HAZ > 0$). The mean HAZ-score in the cohort improves from -1.86 in early childhood to -1.20 by adulthood. The difference between the predicted adult height in early childhood and the actual adult height is $\sim$4.5 centimetres for boys and 5 centimetres for girls. The graphical analysis shows that most of this observed catch-up growth takes place in puberty.

The existing literature emphasizes the importance of early childhood conditions on adult outcomes. This paper shows that not everything is set in stone after early-life: short and stunted children do not necessarily end up short and stunted adults. The observed pubertal catch-up growth may also have implications to economic outcomes in adulthood. Several studies have documented strong correlation between adult height and earnings in both developed and developing countries (for recent reviews, see Currie & Vogl, 2013; Steckel, 2009). Studies from developing countries find that taller people are more productive, and therefore earn more, in tasks that require physical strength (Dinda et al., 2006; Haddad & Bouis, 1991; Thomas & Strauss, 1997; Schultz, 2002). In rich developed countries, the existence of the height premium is more puzzling as occupations increasingly require more brain than brawn. Studies using data for the US and the UK have attributed the height premium to the correlation between adult height and non-cognitive skills (Persico et al., 2004) or cognitive development in early childhood (Case & Paxson, 2008) or both (Schick & Steckel, 2010). Recently, Lundborg et al. (2013), employing rich data on Swedish conscripts, found that taller individuals earn more because adult height is positively correlated with having a better family background and better cognitive and non-cognitive skills. Somewhat surprisingly, also physical capacity, measured as muscular strength, plays a role in explaining the height premium in Sweden. Due to data limitations, these types of studies are rare in developing country contexts.

Therefore, whether the origins of the height premium in poor countries lie in the early-life conditions (through early childhood nutrition affecting cognitive development) or in adult outcomes (e.g. physical strength) remains an unresolved question (Currie & Vogl, 2013; Vogl, 2012).

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Declaration of interest

The author reports no conflicts of interest. The author alone is responsible for the content and writing of the paper.

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Supplementary material available online

Appendix A, B, C and D

Appendix A: Descriptive statistics for the British Cohort Study

Table A1. Evolution of HAZ scores in the British cohort (BCS70).

	BCS70	
	Mean	SD
Age in months ($t = 0$)	60.84	1.307
Height ($t = 0$)	108.8	5.035
Height ($t = 1$)	171.0	9.881
HAZ_1 ($t = 0$)	0.01	1.056
HAZ_2 ($t = 1$)	0.17	1.026
Difference in HAZ	0.16	0.91
t-test: $HAZ_{t=0} = HAZ_{t=1}$	10.56	
Percentage: $HAZ_{t=0} < -2$	3%	
Percentage: $HAZ_{t=1} < -2$	1%	
Percentage: $HAZ_{t=0} < -3$	1%	
Percentage: $HAZ_{t=1} < -3$	0%	
Sample size	9635	

$t = 0$ refers to early childhood, $t = 1$ to adulthood.
HAZ scores calculated using the US 2000 NCHS/CDC as the reference population.
Adult heights are based on self-reports. Sensitivity tests (available from the author) were conducted to see if the main findings are affected by this. They were not.

Appendix B: Why estimating equation (1) using raw measures of height is not appropriate?

Estimating Equation (1) using raw measures of height artificially inflates the β coefficient. This can be demonstrated if we transform Equation (2) to $= r_{y,x}\frac{\theta_y}{\theta_x}$, where $r_{y,x}$ is the correlation coefficient and $\frac{\theta_y}{\theta_x}$ is the ratio of standard deviations of the two variables. The dispersion in the height distribution varies with age and increases as children grow older. This inflates the ratio of standard deviations and leads to a larger β coefficient (other things being equal). The use of height-for-age z-scores circumvents this problem as they measure the distance to the normal growth curve at each age, making the standard deviations less dependent of the age when the child was measured. Cameron et al. (2005) make a similar point discussing the relationship between catch-up growth and regression-to-the-mean

Appendix C: The impact of measurement error on β

In a simple linear bivariate regression such as Equation (1), the magnitude of the downward bias can be calculated using the following formula (see, for example, Deaton, 1997):

$$\beta\frac{\theta_x^2}{\theta_e^2 + \theta_x^2} = \beta\lambda, \tag{7}$$

where θ_x is the true standard deviation of the correctly measured height (unobserved), and θ_e is the standard deviation of the measurement error. The measurement error inflates the denominator causing a downward bias in the convergence estimate. The term λ is then the reliability ratio measuring the magnitude of the downward bias.

Table C1. The impact of measurement error (ME) on β.

SD of ME	Reliability ratio
0.01	0.999 996
0.1	0.999 606
0.25	0.997 541
0.5	0.990 235
0.75	0.978 293
1	0.962 051
1.25	0.941 944
1.5	0.918 482

Standard deviation of height used in this example is 5.034, based on my own calculations from the BCS70 data.

The standard deviation in the early childhood height observed in the British cohort is 5.034. To get a sense of the potential bias, I calculate the impact of various level of zero-mean measurement error on β. As can be seen in Table C1, a small level of measurement error leads to a negligible downward bias in the β coefficient. Even measurement error that has a standard deviation of 1 cm (i.e. 32% of the height measurements contain more than 1 centimetre of measurement error), biases the estimate downward only by four percentage points and cannot explain the convergence finding in Table I. It is difficult to imagine measurement error of this magnitude in any carefully constructed survey. In this light, adjustments, such as instrumental variables techniques, to address measurement error seem unnecessary.

Appendix D. Additional attrition tests for the Kagera Health and Development Survey

Table D1. KHDS attrition tests: Initial HAZ scores by sample category.

	n	Mean	SD	t-stat*
In the final sample	540	−1.86	1.155	n/a
Deceased after 1991–1994	69	−2.10	1.396	1.37
Not measured in 2010	257	−1.74	1.220	−1.32
Missing date of birth	18	−1.51	1.198	−1.22

*Welch t-test testing the difference in means against the first category (in the final sample).

Table D2. KHDS adult HAZ scores by migration status in 2010.

	2010			
	n	Mean	SD	t-stat*
Non-migrant	258	−1.21	1.012	n/a
Migrant	282	−1.20	0.995	−0.0299

*Welch t-test testing the difference in means against the first category (non-migrant).