BMJ Global Health

A novel development indicator based on population-average height trajectories of children aged 0–5 years modelled using 145 surveys in 64 countries, 2000–2018

Eric O Ohuma [ID],[1,2] Diego G Bassani,[1,3,4] Huma Qamar,[1] Seungmi Yang,[5] Daniel E Roth[1,3,4,6]

ABSTRACT

Introduction Children's growth status is an important measure commonly used as a proxy indicator of advancements in a country's health, human capital and economic development. We aimed to assess the feasibility of using Super-Imposition by Translation And Rotation (SITAR) models for summarising population-based cross-sectional height-by-age data of children under 5 years across 64 countries.

Methods Using 145 publicly available Demographic and Health Surveys of children under 5 years across 64 low-income and middle-income countries from 2000 to 2018, we created a multicountry pseudo-longitudinal dataset of children's heights.

Results SITAR models including two parameters (size and intensity) explained 81% of the between-survey variation in mean boys' height and 80% in mean girls' height. Size parameters for boys and girls (relative to the WHO child growth standards) were distributed non-normally around a mean of −5.2 cm for boys (range: −7.9 cm to −1.6 cm) and −4.9 cm for girls (range: −7.7 cm to −1.2 cm). Boys exhibited 10% slower linear growth compared with the WHO (range: 19.7% slower to 1.6% faster) and girls 11% slower linear growth compared with the WHO (range: 21.4% slower to 1.0% faster). Variation in the SITAR size parameter was ≥90% explained by the combination of average length within the first 60 days of birth (as a proxy for fetal growth) and intensity, regardless of sex, with much greater contribution by postnatal intensity (r≥0.89 between size and intensity).

Conclusions SITAR models with two random effects can be used to model child linear growth using multicountry pseudo-longitudinal data, and thereby provide a feasible alternative approach to summarising early childhood height trajectories based on survey data. The SITAR intensity parameter may be a novel indicator for specifically tracking progress in the determinants of postnatal growth in low-income and middle-income countries.

Key questions

What is already known?
► Child height is widely used as an indicator of health, human capital and economic development.
► Country progress towards achieving the Sustainable Development Goals and WHO global targets is conventionally demonstrated by analysing secular trends in stunting and/or, less frequently, using mean height/length-for-age z-scores (HAZ/LAZ) over time.

What are the new findings?
► Super-Imposition by Translation And Rotation (SITAR) can be applied to modelling child linear growth using cross-sectional data from multicountry Demographic and Health Surveys, providing a feasible alternative approach to summarising linear growth trajectories using cross-sectional data.
► SITAR parameters are strongly correlated with stunting and mean height-for-age.
► Postnatal size is explained by the combination of average starting length within the first 60 days of birth (proxy for fetal growth) and postnatal growth intensity.

What do the new findings imply?
► The SITAR intensity parameter may be a novel and informative indicator for specifically tracking progress in the determinants of postnatal growth in low-income and middle-income countries.
► Further research should be conducted on the usefulness of the SITAR intensity for describing variations in postnatal growth between countries as well as within countries over time.

INTRODUCTION

The remarkable increases in average height of adults across all countries in the last century[1][2] have been mainly attributed to improvements in nutrition, health and living conditions.[2] These increases have been also notable in fundamental secular changes in the pattern of child and adolescent growth.[3–5] Children are growing taller than previous cohorts, experiencing earlier pubertal growth spurt (and earlier general maturation) as well as faster rates of growth, especially in

high-income countries.[6] Understanding how and why child growth patterns have changed is necessary for characterising global health inequalities as well as predicting future secular changes in population height.[7]

Child height is widely used as an indicator of health, human capital and economic development.[1–3] The most commonly used population indicator based on child height is the under-5 stunting prevalence (stunting), defined as the proportion of all children between the ages of 0 and 5 years whose height-for-age is more than 2 SD below the median of the WHO child growth standards for age and sex.[8] Reducing the prevalence of child stunting is a global public health priority that is embedded within the Sustainable Development Goals (SDGs)[9] and the WHO global targets for 2025, which include a 40% reduction in the number of stunted children under 5 years.[10]

Country progress towards achieving SDGs and WHO global targets is conventionally demonstrated by analysing secular trends in stunting and/or, less frequently, using mean length/height-for-age z-scores (LAZ/HAZ) over time.[1 6 11 12] Most low/middle-income countries (LMICs) have high stunting prevalences as well as low mean LAZ/HAZ,[11 13 14] indicating nearly all children in these populations are, on average, attaining a suboptimal size for age and sex relative to healthy children growing in optimal conditions.[13] Using 179 Demographic and Health Survey (DHS) datasets from 64 LMICs (1993–2015), we previously showed that linear growth faltering is a whole-population phenomenon characterised by downward shifts in the entire population HAZ distribution rather than deviations limited to a small, high-risk subgroup, as may be implied by the binary stunting indicator.[13] Stunting is a population-level statistical indicator of children's social and economic deprivation and does not equate to malnutrition as commonly used in nutritional and epidemiological studies of child health and public health programmes.[15–18] In addition, binary indicators, such as stunting, are more likely to be affected by the quality of anthropometric measurements which can vary within and between surveys.[19 20]

We hypothesise that Super-Imposition by Translation And Rotation (SITAR) random parameters convey between-country variations in linear growth in more detail than what is captured by conventional cross-sectional indicators such as under-5 stunting prevalence. Height-derived indicators that capture the whole population distribution have potential advantages over indicators that identify a subgroup of affected or at-risk children, by characterising more nuanced variations in age-related linear growth trajectories.

Our goal was to apply the SITAR models to summarise and compare population-level child height data across a sample of LMICs. The SITAR modelling approach for growth data has been demonstrated to efficiently summarise growth trajectories relative to an underlying population-average height-by-age growth curve and three child-specific random effects that reflect between-child

variations in absolute size (average vertical displacement of a child's growth curve relative to the population mean), intensity (a scaling factor applied to the age scale, that reflects relative expansion or contraction of the time period of growth), and timing of growth (average lateral shift in the child's growth curve on the age axis).[21] An advantage of SITAR growth curve analysis is that these estimated random parameters are easily interpretable, in the original units of the modelled parameter (eg, size parameter is expressed in centimetres), and estimates are specific values along a continuous scale that can be used in further analyses of child linear growth such as exploring their associations with exposures or outcomes.[22–24] Furthermore, the intensity parameter reflects a uniquely postnatal pattern, in contrast to the majority of child growth indicators that are expressions of attained size, which reflect both fetal and postnatal growth. SITAR models have been recently used to describe population-average trajectories using country cross-sectional data in Japan and South Korea,[7 25] but the model has not been applied to multicountry survey data such as the DHS from LMICs.

The goal of this study was to demonstrate the application of SITAR to derive alternative metrics for summarising population-level child height data across a sample of cross-sectional surveys from LMICs.

METHODS

Data source

We used publicly available DHS anthropometric data (length/height, age and sex) for children under 5 years across 145 surveys from 64 countries conducted between 2000 and 2018.[26] All available DHS surveys for the study period were accessed through the DHS programme online repository.[26] As described in detail elsewhere,[27 28] children under 2 years were measured in supine position (recumbent length), whereas children between 2 and 5 years were measured standing up (height). We used DHS surveys conducted since 2000 because that is when the DHS programme employed a standardised questionnaire and a unified anthropometry data collection process across all surveys and all children in the sampled households were surveyed. The DHS data are the largest nationally representative data available for many LMICs as they cover all administrative divisions and districts within countries. The DHS are usually conducted every 3–5 years per country, with the exception of a few countries that implement continuous DHS, with annual data collection. The DHS surveys are cross-sectional studies that follow a two-stage stratified random sampling of enumeration areas (first stage) and households (second stage). All DHS samples are representative at least at national and regional levels in all included countries.

Statistical methodology

Many child growth models assume parametric non-linear functions (usually exponential) which often fit data

poorly, especially during the first year of life.[29–31] In 2007, Beath[32] introduced a considerable simplification to the analysis of growth curves by applying previously proposed shape invariant models (SIMs)[33] to describe infant weight trajectories from birth to 2 years of age. SIMs fit a single function to a trajectory, and transform it, by shifting and scaling, to improve its fit to each subject. This results in a single growth curve which can be applied to all subjects using three subject-specific translation and rotation paramaters of the population-average curve to fit individual growth curves. This model was later named by Cole *et al*[21] as the SITAR model.

A key assumption of SITAR is that height trajectories assume a common shape when developmental age is used as the time scale. In contrast to chronological age (time since birth), developmental age is based on markers of a child's growth and development to convey the extent of biological maturation from conception to their current status. A single population mean curve is fitted as a cubic spline function with all individuals assumed to have the same underlying shape of the growth curve subject to three simple transformations estimated as subject-specific random effects that represent deviations from the population mean curve.[21] In the present study, we considered the primary unit of analysis to be the survey, for which data (mean height) were available at multiple age intervals between ages 0 and 5 years, and we compared curves derived from individual surveys to the WHO child growth standards. Applying SITAR, an individual survey-specific growth curve has a relationship with the global mean curve that is estimated by its deviation up or down from the mean curve (differences in mean size represented by the random intercept on the height scale) and left or right (differences in growth timing represented by the random intercept on the chronological age scale), and by shrinking or stretching the curve on the age scale to indicate how fast average growth is in the survey setting (differences in growth rate represented by the random slope of growth rate using the chronological age scale). Size is expressed in units of the measurement (cm), timing in units of age (months) and intensity as a fraction or percentage of the mean growth rate. The SITAR growth model is defined by the following equation:

$$Length/height_{it} = \alpha_i + h[\exp(\gamma_i) \times (t - \beta_i)] + \epsilon_{it} \quad \text{Equation 1}$$

where *length/height_{it}* is the measurement for subject *i* at age *t*; *h(.)* is a natural cubic B-spline function in transformed age defining the mean spline curve chosen to minimise the Bayesian Information Criterion (BIC); α_i, β_i and γ_i are survey-specific random effects for size, timing and intensity, respectively; and the ϵ_{it} are normally distributed residuals. Fixed effects for α_i, β_i and γ_i are also included to ensure the mean random effects are set to zero. Note that γ is exponentiated to provide a multiplier centred on one. For all surveys, trajectories are estimated separately for each sex and for countries with multiple surveys, trajectories were modelled by year as well. The SITAR model fit is based on a non-linear mixed-effect (NLME) model and estimation is by maximum

likelihood.[34] A best linear unbiased prediction of each of the random effects for each survey (equivalent to subjects in the conventional application of SITAR) was used to obtain survey-specific predicted curves.[35]

Data analysis

The dataset includes 1 351 926 individual children across the surveys. Of the total number of eligible children 0–59 months of age, 37 671 (2.8%) were excluded as they were not *de facto* members of the household (ie, had not slept in the household the previous night).[36] Age was considered missing if month and/or year of birth was missing. If month and year of birth was only available, the day of birth was imputed as 15. Exclusions due to missing age, sex or height data totalled 77 131 (5.7%) children (figure 1). We then applied the 2006 WHO standard[37] macro to the raw DHS height data to derive estimates for HAZ and prevalence of stunting among children 0–59 months of age. Data were excluded if a child's HAZ was below −6 SD or above +6 SD (most likely a result of errors in measurement or data entry), as recommended by the WHO,[38] for a total of 28 641 (2.1%) excluded children, resulting in a sample size of 1 208 483 (89%) children (figure 1). All estimates of mean HAZ and prevalence of stunting were calculated accounting for DHS sample survey weights to make sample data representative of the entire population.

A pseudo-longitudinal dataset was created from cross-sectional data by summarising all observations of children's heights within each survey into a single trajectory from birth to 5 years of age for each sex (and survey year in the case of countries with multiple surveys). To account for sampling variations by age and across surveys and also ensure height measurements increased monotonically with age, individual child-level height data in each DHS were binned in 2-month child age intervals and a mean height was obtained for each interval. Each country, survey year and sex was thus represented by 30 interval-specific mean heights. For 41 countries, more than one survey was available. For example, we included six surveys from Peru (in survey years 2005, 2007, 2008, 2009, 2010 and 2012), thereby generating six growth trajectories (ie, curves) for boys and six trajectories for girls.

To enable expression of survey-specific parameters relative to the WHO child growth standards rather than the empirical sample mean (of all 145 surveys), we included the mean height for boys and girls according to the WHO child growth standards for ages 0–5 years[8] as one of the surveys (total n=146 surveys). The mean heights of WHO child growth standards included were estimated for the same 30 intervals used for the DHS. The SITAR growth models were then applied to the dataset comprised of 4380 height data points for boys and 4380 for girls (ie, 30 data points across 146 'surveys' for each sex) to estimate the SITAR parameters for the WHO reference data along with those from 145 DHS data. Separate models were fit for boys and girls.[39] We re-parameterised the SITAR random effects in relation to the WHO reference
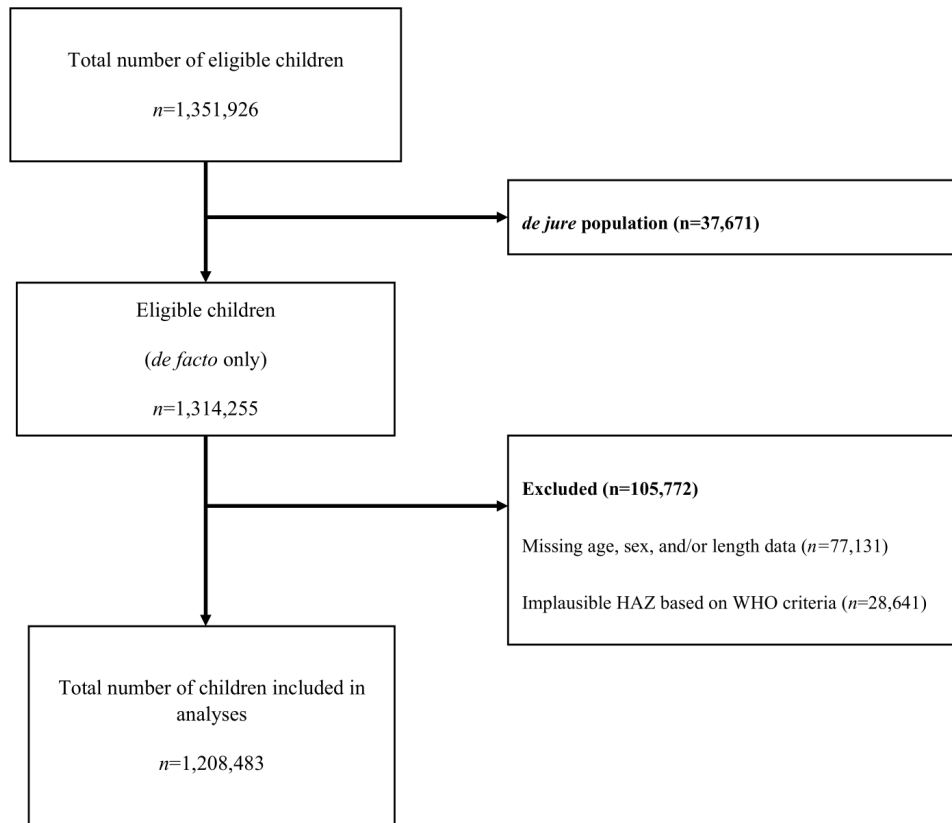
Figure 1 Flow chart for 145 Demographic and Health surveys from 64 countries between 2000 and 2018. de facto children refer to members of the household 0 to 59 months of age who slept in the household the previous night whereas de jure refer to members of the household 0 to 59 months of age who did not sleep in the household the previous night. HAZ, height-for-age z-scores.

by subtracting the WHO SITAR random effects from the random effects of each of the 145 DHS (online supplemental file 1).

We experienced convergence issues for some models and in such instances we applied commonly recommended transformation approaches such as log transformation of either height, age or both, and also explored dropping one of the random effects.[25 40] In addition, the SITAR models were optimised by choosing the df for the cubic B-spline curve to minimise the BIC.[41] SITAR model convergence was not achieved for the full model with three random effects. The timing parameter was dropped because it showed the least variability across the surveys leading to a simplified SITAR model given by:

$$\text{Length/height}_{it} = \alpha_i + h[\exp(\gamma_i) \times t] + \epsilon_{it.} \quad \text{Equation 2}$$

where $length/height_{it}$ is the measurement for subject i at age t; $h(.)$ is a natural cubic B-spline function in transformed age defining the mean spline curve; and α_i and γ_i are survey-specific random effects for size and intensity, respectively, and the ϵ_{it} are normally distributed residuals. The difference between equation 2 of SITAR and the more conventional mixed-effects model, the random-intercept-random-slope (RIRS) model, is that SITAR applies the scale factor to the age axis whereas RIRS scales the height axis.

Models were evaluated by comparing the BIC of different models. We quantified the percentage variance in height that was explained by each SITAR model using:

$$\% \text{ variance in height explained} = 100 \times (1 - (\sigma_2/\sigma_1)^2)$$

where σ_1 is the fixed-effects residual SD (RSD) and σ_2 the SITAR random-effects RSD, that is, the SD of the spread of the data points around the fitted curve.[42]

The BIC penalises the deviance by $\log_e(n)$ units for each additional df where n is the sample size. Better models have a lower BIC value. Height was modelled in the original scale (centimetres) whereas age in months was log transformed for all models. We used the *dfset* command available in the *sitar* package in R[43] to determine the appropriate number of df (knots) for a natural spline curve that minimised the BIC for our fitted models. All models were fit with 4 df.

Having obtained the SITAR-fitted random effects for each survey-year and sex, we correlated the two SITAR parameters with each other, and also with stunting prevalence and mean HAZ. As age was aggregated in 2-month child age intervals, the earliest aggregated mean length was within the first 60 days of birth and therefore used as a proxy for 'starting size' (reflecting fetal growth). To partition postnatal size into its components of 'starting size' (reflecting fetal growth) and postnatal velocity, we performed correlation analyses of the SITAR size and

intensity parameters with mean length within the first 60 days of birth. We then estimated a multiple linear regression model with SITAR size parameter as the outcome and both intensity and average length within the first 60 days of birth as covariates.

Since 41 countries contribute more than one trajectory, we performed sensitivity analyses by repeating the analysis using only the most recent survey from each country. Additional subgroup analyses were performed by fitting SITAR models to DHS data classified according to World Bank regions.[44]

The models were fit in statistical software R using the *nlme* package,[34] Tim Cole's *sitar* package[43] (https://rdrr.io/cran/sitar/) and STATA V.15 (College Station, Texas, USA). The R-code used to perform all the analyses is provided in online supplemental file 2.

Patient and public involvement

Our study does not involve the participation of patients or any members of the public. All data used in this study are aggregated and publicly available DHS anthropometric data and can be accessed through the DHS programme online repository.[26]

RESULTS

The weighted median sample size, median age in months and percentage of boys for each of the six world regions are summarised in table 1. Most surveys were from the sub-Saharan Africa region followed by Latin America and the Carribean, Europe and Central Asia, South Asia, North Africa and the Middle East (table 1). The median number of children per survey was 5473 (~90 children in each month); 82% included between 1000 and 10 000 children, and the median age was 29.6 months (IQR: 14.6–44.4 months) (online supplemental file 3).

Of the models that achieved convergence, those containing two random effects (size and intensity) fit best based on the BIC (table 2). The final selected models (table 3) explained 81% and 80% of the between-survey variation in mean height for boys and girls, respectively (table 2; Figures 2 and 3). Two example surveys and the WHO child height standards were used to illustrate that the modelled trajectories closely fit the observed data (online supplemental file 4). As expected, there were negligible differences in size (maximum difference was <0.05 cm for girls and boys) and intensity (maximum difference was <0.2% for boys and girls) between the random effects generated with and without inclusion of the WHO data in the multicountry dataset (online supplemental files 5 and 6).

Fitted growth trajectories for boys and girls were below the WHO child growth standards for all surveys (figure 4). Sex-specific height-by-age and velocity-by-age curves were similarly shaped although boys were, as expected, taller at every age (figure 4). Size

Table 1 Summary of Demographic and Health Surveys disaggregated by world region (n=145 overall)

	East Asia and Pacific (n=7)	Europe and Central Asia (n=10)	Latin America and the Caribbean (n=21)	Middle East and North Africa (n=11)	South Asia (n=13)	Sub-Saharan Africa (n=83)
	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)	Median (IQR)
Date of birth complete (%)	100 (99–100)	100 (99–100)	99 (98–99)	100 (100–100)	99 (97–100)	99 (97–99)
Anthropometry measurement complete (%)	97 (92–98)	95 (93–97)	95 (93–98)	96 (92–99)	95 (90–98)	96 (94–98)
Total sample	4648 (3853–6661)	1821 (1473–4618)	9193 (6436–10275)	6412 (4990–12907)	5473 (3316–7235)	5329 (3810–7938)
Median age (months)	30 (16–45)	29 (15–44)	30 (15–45)	29 (14–44)	30 (15–45)	29 (14–44)
Boys (%)	51 (50–52)	51 (51–53)	51 (50–51)	51 (50–52)	51 (51–52)	50 (50–51)

Table 2 Comparison of SITAR models applied to Demographic and Health Survey data from 145 surveys (64 countries) from 2000 to 2018

Model specification	Fixed effects	Random effects	Bayesian Information Criteria	Percentage of variance explained
Boys' height				
M1	Absolute size	Absolute size	14 298	68.5
M2*	Absolute size+intensity	Absolute size+intensity	12 471	80.6
M3	Absolute size+timing+intensity	Absolute size+timing+intensity	No convergence	N/A
Girls' height				
F1	Absolute size	Absolute size	14 253	67.7
F2*	Absolute size+intensity	Absolute size +Intensity	12 421	80.2
F3	Absolute size+timing+intensity	Absolute size+timing+intensity	No convergence	N/A

Age in months was log transformed for all models; all models were fit using 4 df.
*Final model selected.
N/A, not applicable; SITAR, Super-Imposition by Translation And Rotation.

parameters for boys (relative to the WHO growth reference) were distributed non-normally with a mean of −5.2 cm (shorter) compared with the reference (figure 5), and ranging from −7.9 cm (Niger 2006) to −1.6 cm (Armenia 2016). Girls were, on average, −4.9 cm below the WHO reference median (figure 5), ranging from −7.7 cm (Nepal 2001) to −1.2 cm (Armenia 2016). Across all surveys, boys' intensity parameter was 10% below the WHO intensity reference, ranging from 19.7% below (Niger 2006) to 1.6% above the reference (Armenia 2016). Similarly, girls exhibited 11% lower intensity, on average, compared with the WHO reference (figure 5), with cross-survey values ranging from 21.4% below (Ethiopia 2000) to 1.0% above the reference (Armenia 2016).

Table 3 Best-fitting SITAR models for boys and girls applied to Demographic and Health Survey mean height data from 145 surveys (64 countries) from 2000 to 2018

	Mean height (cm) Estimate±SE	
Fixed coefficients	Boys	Girls
Size (cm)	58.97±1.14	53.47±1.71
Intensity (fractional)	0.30±0.06	0.08±0.08
Random coefficients		
Standard deviations (SD)		
Size	1.46	1.42
Intensity	0.05	0.05
Residual SD	0.90	0.89
Degrees of freedom	4	4

All models were adjusted for age in months (log transformed).
.SE, Standard error; SITAR, Super-Imposition by Translation And Rotation.

Size and intensity parameters were highly correlated (r=0.91 for boys; r=0.89 for girls) (online supplemental file 7), such that intensity explained ~80% of the variability in size for boys and girls. The mean HAZ was perfectly correlated with the SITAR size parameter (r=1) for boys and girls. Prevalence of stunting was highly correlated with the SITAR size parameter (r=−0.96 for boys and r=−0.97 for girls). The correlation of stunting with SITAR intensity parameter was also strong (r=−0.91 for boys; r=−0.90 for girls) and the mean HAZ was highly correlated with the SITAR intensity (r=0.89 for girls and r=0.91 for boys) (online supplemental files 8 and 9).

Results of the sensitivity analyses to evaluate the impact of varying number of surveys between countries (145 surveys compared with 64 latest surveys) were remarkably similar to the main findings despite the more than 50% reduction in the number of surveys (online supplemental file 10). The subgroup analyses of fitted SITAR models to DHS data according to World Bank regions showed the percentage variability in mean height ranged between 70%–84% in boys and 69%–82% in girls. Model convergence was not achieved for two regions (East Asia and Pacific and Europe and Central Asia) which had the least number of countries, that is, ≤10 countries (online supplemental file 11).

The correlation of the size parameter with average length within the first 60 days of birth was moderate (r=0.41 for boys and r=0.43 for girls), but the correlation of intensity with average length within the first 60 days of birth was low (r=0.14 for boys and r=0.16 for girls). The combination of average starting length within the first 60 days of birth and postnatal intensity in both models for boys and girls explained more than 90% of the variability in postnatal size (online supplemental file 12).
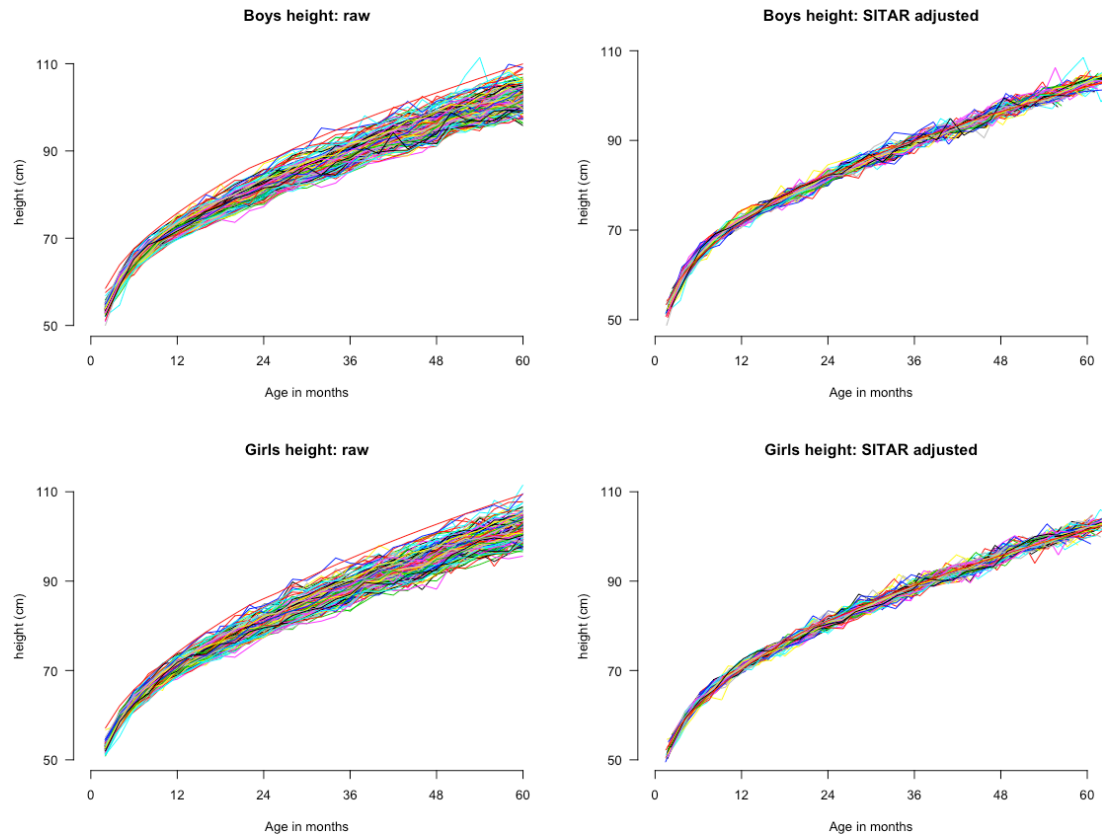
Figure 2 Mean height trajectories for boys (top panels) and girls (bottom panels) before (left panels) and after (right panels) adjustment using SITAR size and intensity parameters, for 145 Demographic and Health Surveys from 64 countries. SITAR, Super-Imposition by Translation And Rotation.

DISCUSSION

We have demonstrated that a commonly used statistical method for modelling adolescent growth at individual level (SITAR) can be feasibly applied to describe population-average patterns of early child linear growth across a set of anthropometric survey datasets. The SITAR random effects efficiently summarise country-specific height trajectories for children 0–5 years of age using cross-sectional survey data. The final model, including two random effects (size and intensity) explained over 80% of the between-survey variability in mean height for boys and girls, highlighting a between-country consistency of the shape of the mean postnatal linear growth trajectory despite the surveys being conducted in diverse geographical contexts and over a span of 18 years.[13 45] Sensitivity analyses performed using only the most recent survey for each country with much improved data quality revealed minimal differences between the fitted population mean curves, providing confidence in the robustness of our final selected SITAR models.

A subgroup analyses performed separately on each of the six defined World Bank regions showed substantial differences in the amount of variability in mean height (in both boys and girls) that was explained by the fitted SITAR models that converged. The percentage variance in mean height (in both boys and girls) that was explained was lowest in sub-Saharan Africa and South

Asia. We do not know the reason for the lowerpercentage variability explained in these two regions but note that (1) sub-Saharan Africa and South Asia have the highest prevalence of stunting and shorter height on average compared with the other regions; and (2) each country dataset includes cohorts of children across 5 different years, such that any acute health shock (eg, humanitarian disaster) affecting one cohort more than others would affect the age-related trajectories and could therefore affect how much variability is explained by the SITAR models; such health shocks are likely more common in sub-Saharan Africa and South Asia than other world regions.

SITAR was originally developed to model individual child or adolescent trajectories using longitudinal data. However, Cole and Mori[25] and Schneider and Ogasawara[7] have recently demonstrated the application of SITAR to cross-sectional height and weight data by sex between the ages of 1 and 20 years (Cole and Mori), and also for cross-sectional height data among children aged 6–18 years (Schneider and Ogasawara). In both examples, the data have been grouped in 1-year bins for modelling. Here, we extend this application of the SITAR model to population-based cross-sectional surveys of children under-5 years from 64 LMICs with high prevalence of linear growth deficits.[11 13 46] Characterisation of the population-average child growth trajectories using the SITAR parameters in our study confirmed that in resource-limited settings,
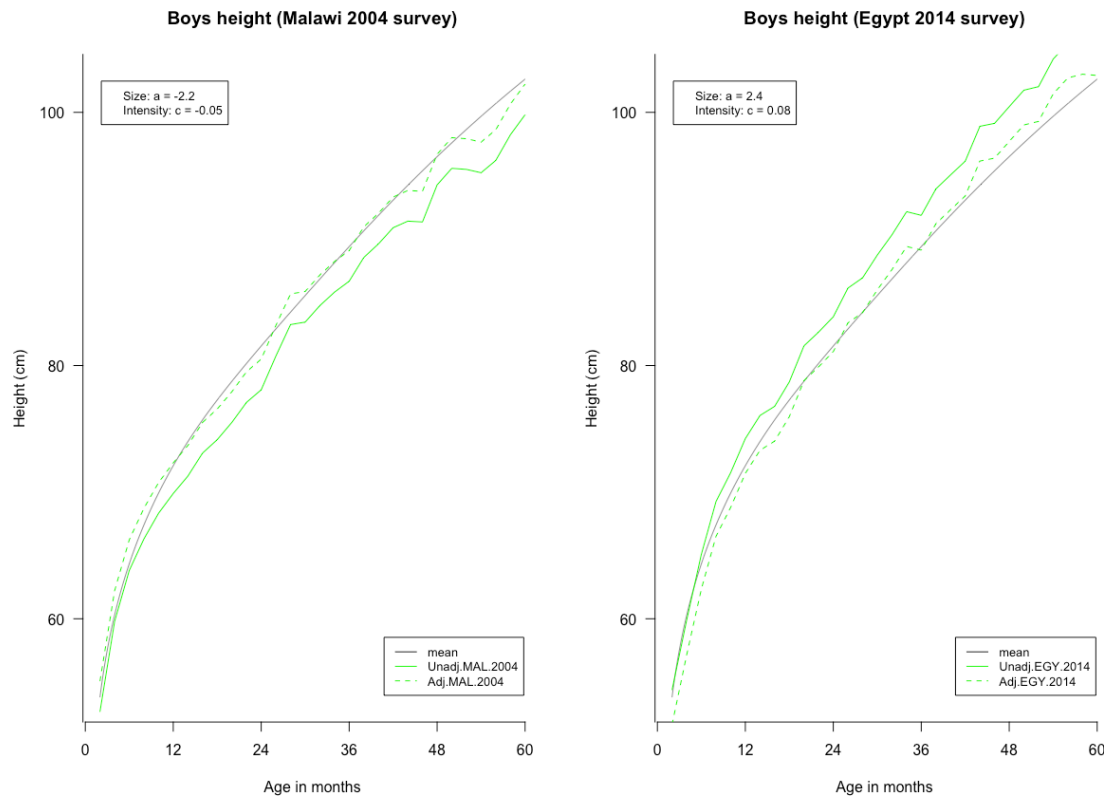
Figure 3 An illustration of the SITAR transformation of a crude height trajectory for a given survey to the population-level average modelled trajectory shown using height trajectory for boys in Malawi in the 2004 survey before SITAR adjustment (solid green line, left panel) and after SITAR adjustment (dotted green line, left panel); Egypt 2014 survey for boys, before SITAR adjustment (solid green line, right panel) and after SITAR adjustment (dotted green line, right panel). The fitted SITAR population-mean curve is shown by solid black line in both plots. SITAR, Super-Imposition by Translation And Rotation.

mean population heights and mean growth intensity are below those expected using the WHO child growth reference, and the deficits worsen with age.[13 46] Our estimates based on raw length/height-for-age data reveal that the size and growth intensity deficits continue to accrue through to age 5 years, corroborating inferences from studies using height-for-age difference that suggest that linear growth faltering continues past the point at which HAZ trajectories appear to plateau.[47] The intensity parameter is a proxy for speed of maturation and consequently, low intensity reflects linear growth faltering.

The main motivation for using SITAR in this context was to identify alternative or complementary metrics for summarising child linear growth and tracking country progress. In contrast to conventional cross-sectional indicators such as under-5 stunting prevalence and mean HAZ, the SITAR parameters are derived by explicitly assuming that there is a linear relationship between chronological age and developmental age and subsequently modelling each component on the proper scale (size on the height scale, and intensity and timing on the age scale), thereby estimating biologically relevant non-linear trajectories for each component. We had hypothesised that these parameters would convey between-country variations in linear growth in more detail than what is captured by traditional cross-sectional aggregated measures, such as under-5 stunting prevalence. However, empirically we found very high correlations between the prevalence of

stunting (and mean HAZ) and the size and intensity parameters; in fact, the correlations were nearly perfect for the size parameter. The near perfect correlation between the size parameter and the prevalence of stunting (and mean HAZ) suggests that inequities in size between countries estimated using SITAR are identical to those observed when comparing mean HAZ or stunting prevalences. Since the SITAR size parameter is nearly exchangeable with those indicators, there may be no advantage to estimating SITAR solely to derive the size parameter, particularly given the relative complexity of SITAR modelling. In contrast, the intensity parameter had a somewhat weaker correlation with mean HAZ and stunting prevalence and therefore may provide complementary information. We found that in both boys and girls, more than 90% of the variability in postnatal size represented by the SITAR size parameter was explained by the combination of average length within the first 60 days of birth and postnatal intensity. Most of the variation was attributable to postnatal intensity, which was nearly independent of very early postnatal size (a proxy for fetal growth). Thus, unlike conventional height-derived indicators that are based on attained size alone, SITAR partitions size into two components—fetal growth (captured by size at or near birth) and postnatal growth (represented by the intensity parameter). We have demonstrated that the intensity parameter on its own may serve as a specific measure of the postnatal experience to a much greater extent independent of the prenatal
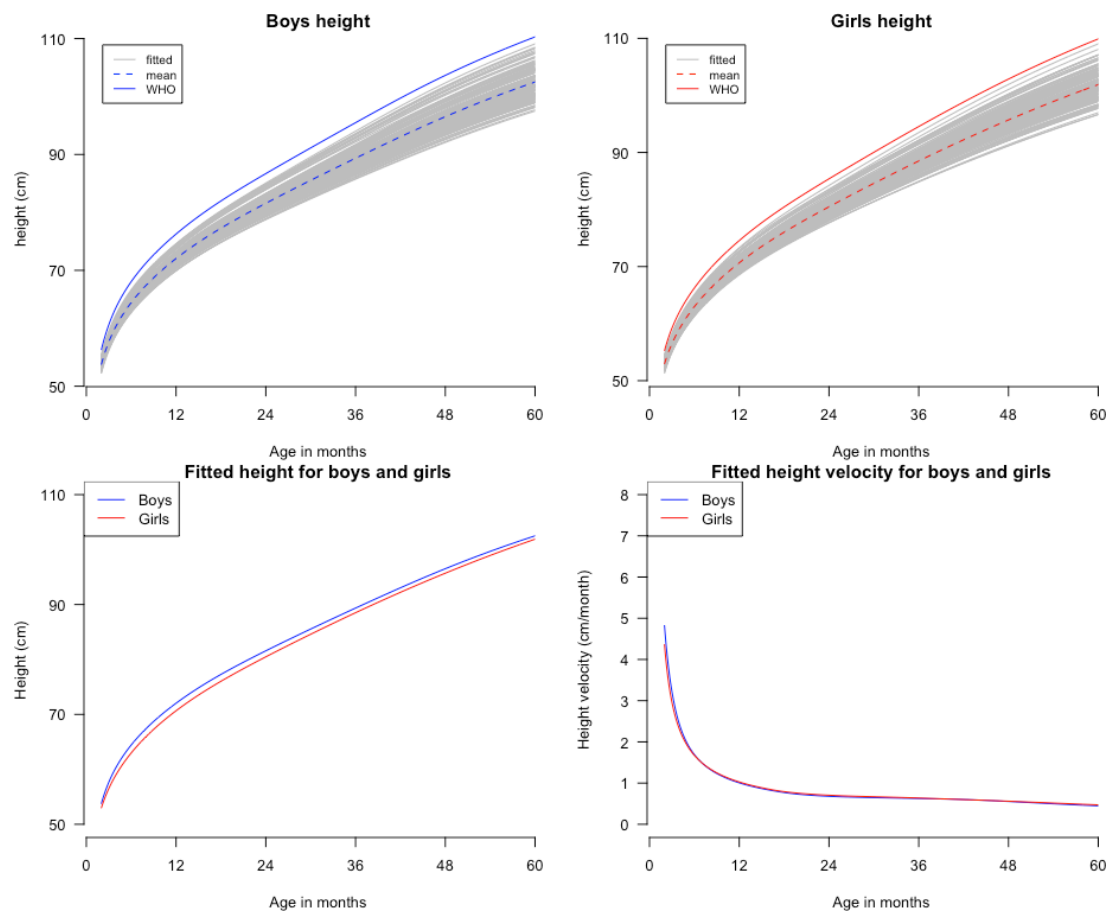
Figure 4 Smoothed-fitted height curves for each survey for boys (grey, top-left panel) and the median WHO boys height trajectory (solid blue line, top-left panel); girls (grey, top-right panel) and the median WHO girls height trajectory (solid red line, top-right panel). The bottom-left panel shows a comparison of the fitted mean population height-by-age curve for boys (blue) and girls (red), and the bottom-right panel shows the corresponding height velocity-by-age curve for boys (blue) and girls (red).

period compared with the size parameter; the size parameter (similar to stunting prevalence and mean HAZ) is a composite of both the prenatal (fetal growth) and postnatal period (infant/child growth) periods.

In the assessment of our primary objective which was to assess the feasibility of using SITAR models for summarising multicountry comparisons of population-based cross-sectional data from 0 to 5 years, we experienced some challenges with SITAR regarding convergence issues for some of the models. The random effect that represents timing did not vary across surveys and convergence was only achieved after excluding this random effect from the model. Notably, this parameter has no clear meaning for the linear growth of children below 5 years of age where peak velocity is not present as a prominent feature within the observation period in contrast with growth during adolescence, where SITAR is more commonly applied. SITAR is a complex non-linear model that may require a combination of variable transformations and model fit optimisation in order to achieve convergence. Convergence was not achieved in all world regions, and the lower variability explained in sub-Saharan Africa and South Asia suggests that perhaps additional parameters are required (eg, a timing parameter). SITAR assumes no measurement error when in fact there is probably differential

measurement error across surveys due to differences in data quality across surveys (both across years and across countries), whether children were measured lying down or standing up, difficulty to obtain accurate measurements of length/height of children in the field especially for younger children, and the impact of associated measurement errors in age and height.[19 20] Our analyses combined children born at different years to form a cohort and this approach could potentially introduce bias especially if selected cohorts were exposed to health shocks to a greater extent than other children included in the same survey. Furthermore, the current formulation of SITAR does not account for survey design or clustering of observations as the number of surveys differed by country.

In conclusion, we applied SITAR for modelling child height-for-age based on cross-sectional data from multicountry surveys, and demonstrated that SITAR models with two random effects provide a feasible alternative approach to summarising child length/height trajectories for populations based on survey data. Although the estimated SITAR parameters (size and intensity) were strongly correlated with more conventional indicators such as prevalence of stunting and mean HAZ, the SITAR intensity parameter may be a novel indicator for specifically tracking progress
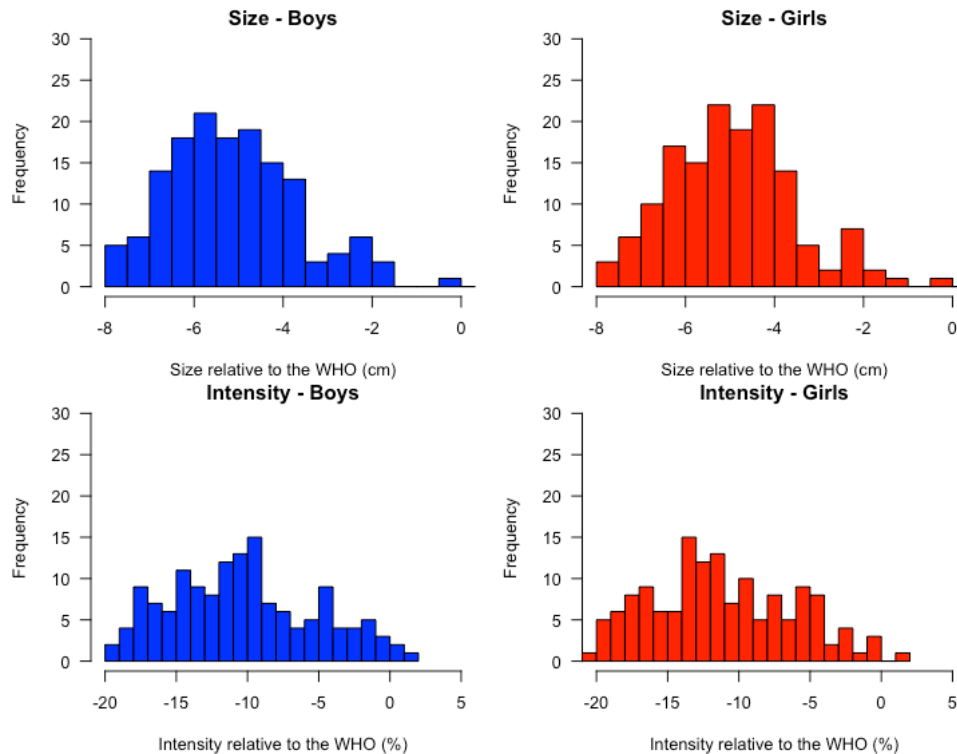
Figure 5 Distribution of SITAR size (top panel) and intensity (bottom panel) parameters for boys (blue) and girls (red) in 145 Demographic and Health Surveys from 64 countries. SITAR, Super-Imposition by Translation And Rotation.

in the determinants of postnatal growth in LMICs. Further research will therefore focus on whether the intensity parameter is practically useful for describing variations in postnatal growth between countries as well as within countries over time, that are not fully captured by traditional indicators such as stunting prevalence and mean HAZ.

Author affiliations
[1]Centre for Global Child Health & Child Health Evaluative Sciences, Hospital for Sick Children, Toronto, Ontario, Canada
[2]Centre for Tropical Medicine and Global Health, Nuffield Department of Medicine, University of Oxford, Oxford, UK, Oxford, UK
[3]Dalla Lana School of Public Health, University of Toronto, Toronto, Ontario, Canada
[4]Department of Pediatrics, Hospital for Sick Children & University of Toronto, Toronto, Ontario, Canada
[5]Department of Epidemiology, Biostatistics, and Occupational Health, McGill University, Montreal, Canada, Montreal, Quebec, Canada
[6]Department of Nutritional Sciences, University of Toronto, Toronto, Ontario, Canada

Twitter Eric O Ohuma @ohumaeric

Map disclaimer The depiction of boundaries on this map does not imply the expression of any opinion whatsoever on the part of BMJ (or any member of its group) concerning the legal status of any country, territory, jurisdiction or area or of its authorities. This map is provided without any warranty of any kind, either express or implied.

Competing interests None declared.

Patient consent for publication Not required.

Ethics approval This work is a secondary analysis of publicly available de-identified data which are exempt from ethical review at the Hospital for Sick Children Ethics Review Board.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement Data are available in a public, open access repository. The data used are DHS and are publicly available at https://dhsprogram.com/data/available-datasets.cfm.

ORCID iD
Eric O Ohuma http://orcid.org/0000-0002-3116-2593

REFERENCES
1 NCD Risk Factor Collaboration (NCD-RisC). A century of trends in adult human height. *Elife* 2016;5:e13410.

2 Baten J, Blum M. Growing tall but unequal: new findings and new background evidence on anthropometric welfare in 156 countries, 1810–1989. *Economic History of Developing Regions* 2012;27:S66–85.

3 Cole TJ. The secular trend in human physical growth: a biological view. *Econ Hum Biol* 2003;1:161–8.

4 Steckel RH. Growth depression and recovery: the remarkable case of American slaves. *Ann Hum Biol* 1987;14:111–32.

5 Cameron N. The growth of London schoolchildren 1904-1966: an analysis of secular trend and intra-county variation. *Ann Hum Biol* 1979;6:505–25.

6 Cole TJ. Secular trends in growth. *Proceedings of the Nutrition Society* 2000;59:317–24.

7 Schneider EB, Ogasawara K. Disease and child growth in industrialising Japan: critical windows and the growth pattern, 1917–39. *Explor Econ Hist* 2018;69:64–80.

8 World Health Organization. Who multicentre growth reference study. who child growth standards based on length/height, weight and age. *Acta Pædiatrica* 2006:76–85.

9 Harnden D, Kumar R, Holick MF, *et al*. Side chain metabolism of 25-hydroxy-[26,27-14C] vitamin D3 and 1,25-dihydroxy-[26,27-14C] vitamin D3 in vivo. *Science* 1976;193:493–4.

10 Holick MF, de Blanco MC, Clark MB, *et al*. The metabolism of [6-3H]1alpha, hydroxycholecalciferol to [6-3H]1alpha,25-dihydroxycholecalciferol in a patient with renal insufficiency. *J Clin Endocrinol Metab* 1977;44:595–8.

11 de Onis M, Branca F. Childhood stunting: a global perspective. *Matern Child Nutr* 2016;12:12–26.

12 Stevens GA, Finucane MM, Paciorek CJ, *et al*. Trends in mild, moderate, and severe stunting and underweight, and progress towards mdg 1 in 141 developing countries: a systematic analysis of population representative data. *Lancet* 2012;380:824–34.

13 Roth DE, Krishna A, Leung M, *et al*. Early childhood linear growth faltering in low-income and middle-income countries as a whole-population condition: analysis of 179 demographic and health surveys from 64 countries (1993-2015). *Lancet Glob Health* 2017;5:e1249–57.

14 United Nations Children's Fund (UNICEF), World Health Organization, International Bank for Reconstruction and Development/The World Bank. *Levels and trends in child malnutrition: key findings of the 2019 edition of the joint child malnutrition estimates*. Geneva: World Health Organization, 2019Licence: CC BY-NC-SA 3.0 IGO.

15 Finaret AB, Masters WA. Can shorter mothers have taller children? nutritional mobility, health equity and the intergenerational transmission of relative height. *Econ Hum Biol* 2020;39:100928.

16 Leroy JL, Frongillo EA. Perspective: what does stunting really mean? A critical review of the evidence. *Adv Nutr* 2019;10:196–204.

17 Perumal N, Bassani DG, Roth DE. Use and misuse of stunting as a measure of child health. *J Nutr* 2018;148:311–5.

18 Scheffler C, Hermanussen M, Bogin B, *et al*. Stunting is not a synonym of malnutrition. *Eur J Clin Nutr* 2020;74:377–86.

19 Assaf S, Kothari MT, Pullum T. *An assessment of the quality of DHS anthropometric data, 2005-2014. DHS methodological reports No. 16*. Rockville, Maryland, USA: ICF International, 2015.

20 Corsi DJ, Perkins JM, Subramanian SV. Child anthropometry data quality from demographic and health surveys, multiple indicator cluster surveys. *and National Nutrition Surveys in the West Central Africa region: are we comparing apples and oranges? Global health action* 2017;10:1328185.

21 Cole TJ, Donaldson MDC, Ben-Shlomo Y. SITAR—a useful instrument for growth curve analysis. *Int J Epidemiol* 2010;39:1558–66.

22 Cole TJ, Kuh D, Johnson W, *et al*. Using Super-Imposition by translation and rotation (SITAR) to relate pubertal growth to bone health in later life: the medical Research Council (MRC) national survey of health and development. *Int J Epidemiol* 2016;45:dyw134–34.

23 Ong KK, Ahmed ML, Emmett PM, *et al*. Association between postnatal catch-up growth and obesity in childhood: prospective cohort study. *BMJ* 2000;320:967–71.

24 Mansukoski L, Johnson W, Brooke-Wavell K, *et al*. Life course associations of height, weight, fatness, grip strength, and all-cause mortality for high socioeconomic status Guatemalans. *Am J Hum Biol* 2019;31:e23253.

25 Cole TJ, Mori H. Fifty years of child height and weight in Japan and South Korea: contrasting secular trend patterns analyzed by SITAR. *Am J Hum Biol* 2018;30:e23054.

26 ICF. Available Datasets. The DHS program website. funded by USAID. Available: https://dhsprogram.com/data/available-datasets.cfm [Accessed June, 18th, 2020].

27 Corsi DJ, Neuman M, Finlay JE, *et al*. Demographic and health surveys: a profile. *Int J Epidemiol* 2012;41:1602–13.

28 MEASURE DHS. Survey indicators, 201920 Augustdate last accessed. Available: http://www.measuredhs.com/data/Survey-Indicators.cfm

29 Karlberg J. On the modelling of human growth. *Stat Med* 1987;6:185–92.

30 Jenss RM. A mathematical model for studying the growth of a child. *Human Biology* 1937;9:556–63.

31 Berkey CS. Comparison of two longitudinal growth models for preschool children. *Biometrics* 1982;38:221–34.

32 Beath KJ. Infant growth modelling using a shape invariant model with random effects. *Stat Med* 2007;26:2547–64.

33 Lindstrom MJ. Self-modelling with random shift and scale parameters and a free-knot spline shape function. *Stat Med* 1995;14:2009–21.

34 Pinheiro JBD, DebRoy S, Sarkar D, R Core Team. nlme: linear and nonlinear mixed effects models. R package version 3.1-140, 2019. Available: https://CRAN.R-project.org/package=nlme

35 Robinson GK. That BLUP is a good thing: the estimation of random effects. *Statistical Science* 1991;6:15–32.

36 Croft TMA, Allen CK, *et al*. *Guide to DHS statistics*. Rockville, Maryland, 2018.

37 World Health Organization. Child growth standards software. who Anthro (version 3.2.2, January 2011) and macros. Internet. Available: http://www.who.int/childgrowth/software/en/

38 World Health Organization. *WHO child growth standards: length/height-for-age, weight-for-age, weight-for-length, weight -for-height and body mass index-for-age : methods and development*. World Health Organization, 2006.

39 Tanner JM. The assessment of growth and development in children. *Arch Dis Child* 1952;27:10–33.

40 Cole TJ, Donaldson MDC, Ben-Shlomo Y. SITAR--a useful instrument for growth curve analysis. *Int J Epidemiol* 2010;39:1558–66.

41 Schwarz G. Estimating the dimension of a model. *Ann. Statist.* 1978;6:461–4.

42 Hauspie R, Molinari L. Parametric models for postnatal growth. In: Hauspie R, Cameron N, Molinari L, eds. *Methods in human growth research*. Cambridge: Cambridge University Press, 2004: 205–33.

43 Levine MM, Black RE, Clements ML, *et al*. Texas Star-SR: attenuated "Vibrio cholerae" oral vaccine candidate. *Dev Biol Stand* 1983;53:59–65.

44 The World Bank Group. World bank country and lending groups. Available: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups [Accessed June 15, 2020].

45 de Onis M, Branca F. Childhood stunting: a global perspective. *Matern Child Nutr* 2016;12 Suppl 1:12–26.

46 Victora CG, de Onis M, Hallal PC, *et al*. Worldwide timing of growth faltering: revisiting implications for interventions. *Pediatrics* 2010;125:e473–80.

47 Leroy JL, Ruel M, Habicht J-P, *et al*. Using height-for-age differences (had) instead of height-for-age z-scores (HAZ) for the meaningful measurement of population-level catch-up in linear growth in children less than 5 years of age. *BMC Pediatr* 2015;15:145.

Supplementary File 1

October 24, 2019

1 Reparameterization of SITAR's random effect

The SITAR growth curve is a shape-invariant growth that assumes all individuals to have the same underlying shape of the growth curve [1, 2]. The SITAR formula is expressed as:

$$y_{it} = \alpha_i + h\left\{\frac{t - \beta_i}{e^{-\gamma_i}}\right\} + \epsilon_{it}, \tag{1}$$

where y_{it} is the measurement for subject i at age t; α_i, β_i, and γ_i are, respectively, size, tempo, and intensity random effects; $h(\cdot)$ is a cubic regression spline curve; and ϵ_{it} are independent normally distributed errors.

To reparameterize the intensity random parameter γ_i;

Let γ_w be the new intensity parameter. If we multiply both sides of equation 1 by $\frac{e^{\gamma_w}}{e^{\gamma_w}}$, equation 1 becomes:

$$y_{it} = \alpha_i + h'\left\{\frac{t - \beta_i}{e^{-\gamma_i + \gamma_w}}\right\} + \epsilon_{it}, \tag{2}$$

where $h' = \left\{\frac{h}{e^{\gamma_w}}\right\}$.

Equation 2 can thus be generalized to:

$$y_{it} = \alpha_i + h'\left\{\frac{t - \beta_i}{e^{-(\gamma_i - \gamma_w)}}\right\} + \epsilon_{it}, \tag{3}$$

A general form of the new reparametrized intensity parameter based on γ_w for each individual can thus be obtained as $\gamma_i - \gamma_w$

1

Supplemental material

BMJ Publishing Group Limited (BMJ) disclaims all liability and responsibility arising from any reliance placed on this supplemental material which has been supplied by the author(s)

BMJ Global Health

References

[1] Tim J Cole, Malcolm D C Donaldson, and Yoav Ben-Shlomo. SITAR - a useful instrument for growth curve analysis. International Journal of Epidemiology, 39(6):1558–1566, 2010.

[2] TJ Cole, D Kuh, W Johnson, KA Ward, LD Howe, JE Adams, R Hardy, and KK Ong. Using Super-Imposition by Translation And Rotation (SITAR) to relate pubertal growth to bone health in later life: the Medical Research Council (MRC) National Survey of Health and Development. International Journal of Epidemiology, 45(4):1125–1134, 2016.

Supplemental material

BMJ Publishing Group Limited (BMJ) disclaims all liability and responsibility arising from any reliance placed on this supplemental material which has been supplied by the author(s)

BMJ Global Health

Table of Contents

Supplementary File 2: R code used for the SITAR analysis

```
rm(list=ls(all=TRUE))

require(gamlss, haven, foreign, sitar, fdapace, hbgd, dplyr, ggplot2, ggpubr, growthstandards,
PerformanceAnalytics)

# install.packages("remotes") # if "remotes" is not already installed

# remotes::install_github("ki-tools/growthstandards")


#### DHS HEIGHT DATA ####

dhs <- read.dta("DHS_ALL_DATA_WHO.dta") # Read DHS data

# Males

dhs_b <- subset(dhs, sex=="male") # selects male height

dhs_b$year <- as.factor(dhs_b$year) #sets year as a factor variable

dhs_b$country <- as.factor(dhs_b$country) #sets country as a factor variable

# Determining the appropriate number of degrees of freedom (knots)

dfset(ageint_mths, height, dhs_b, FUN=BIC, plot=TRUE) # untransformed age: df = 11

dfset(log(ageint_mths), height, dhs_b, FUN=BIC, plot=TRUE) # log-transformed age: df = 4


# fit sitar model of height vs log-transformed age

# checking the influence of each SITAR parameter

m1 <- sitar(x=log(ageint_mths), y=height, id=id, df=4, data=dhs_b, random='a')

# fits sitar using 'a' as fixed and random effect


m2 <- sitar(x=log(ageint_mths), y=height, id=id, df=4, data=dhs_b, fixed='a+c', random='a+c')

# fits sitar using 'a+c' as fixed and random effects
```

Supplemental material

BMJ Publishing Group Limited (BMJ) disclaims all liability and responsibility arising from any reliance placed on this supplemental material which has been supplied by the author(s)

BMJ Global Health

```
m3 <- sitar(x=log(ageint_mths), y=height, id=id, df=4, data=dhs_b, random='a+c')
```

fits sitar using 'a+c' as fixed and random effects


```
# male <- sitar(x=log(ageint_mths), y=height, id=id, df=4, data=dhs_b,random='a+b+c')
```

fits sitar using 'a+b+c' as fixed and random effects # Did not converge


```
summary(m3)
```

```
intervals(m3) # generates the 95% CI for the SD of random effects
```


```
# Females
```

```
dhs_g <- subset(dhs, sex=="female") # selects female height
```

```
dhs_g$year <- as.factor(dhs_g$year)
```

```
dhs_g$country <- as.factor(dhs_g$country)
```


```
# Determining the appropriate number of degrees of freedom (knots)
```

```
dfset(ageint_mths, height, dhs_g, FUN=BIC, plot=TRUE) # untransformed age: df = 11
```

```
dfset(log(ageint_mths), height, dhs_g, FUN=BIC, plot=TRUE) # log-transformed age: df = 4
```

fit sitar model of height vs log-transformed age

checking the influence of each SITAR parameter

```
m4 <- sitar(x=log(ageint_mths), y=height, id=id, df=4, data=dhs_g, random='a')
```

fits sitar using 'a' as fixed and random effect

```
m5 <- sitar(x=log(ageint_mths), y=height, id=id, df=4, data=dhs_g, fixed='a+c', random='a+c')
```

fits sitar using 'a+c' as fixed and random effects

3

Supplemental material

BMJ Publishing Group Limited (BMJ) disclaims all liability and responsibility arising from any reliance placed on this supplemental material which has been supplied by the author(s)

BMJ Global Health

```
m6 <- sitar(x=log(ageint_mths), y=height, id=id, df=4, data=dhs_g, random='a+c')

# fits sitar using 'a+c' as fixed and random effects

# female <- sitar(x=log(ageint_mths), y=height, id=id, df=4, data=dhs_g,random='a+b+c')

# fits sitar using 'a+b+c' as fixed and random effects

summary(m6)

intervals(m6) # generates the 95% CI for the SD of random effects

varexp(pattern='m') # variance explained by each model

BICadj(pattern='m') # BIC for each model

AICadj(pattern='m') # AIC for each model

# Models m3 for boys and m6 for girls selected as final models


## Figure 2

par(mfrow=c(2,2))

mplot(x = ageint_mths, y = height, id = id, vlim=c(50, 120), xlim=c(0,60),data = dhs_b, col = id,
las = 1, axes=FALSE,

    ylab="Height (cm)", xlab="Age in months",main="Boys height: raw")

axis(side=1, at=seq(0, 60, by=12))

axis(side=2, at=seq(50, 120, by=20),las=1)


plot(m3, opt = 'a', col = id, vlim=c(50, 120), xlim=c(0,60),las = 1, axes=FALSE,

    ylab="Height (cm)", xlab="Age in months",

    main="Boys height: SITAR adjusted")

axis(side=1, at=seq(0, 60, by=12))

axis(side=2, at=seq(50, 120, by=20),las=1)
```

Supplemental material

BMJ Publishing Group Limited (BMJ) disclaims all liability and responsibility arising from any reliance placed on this supplemental material which has been supplied by the author(s)

BMJ Global Health

```
mplot(x = ageint_mths, y = height, id = id, ylim=c(50, 110), xlim=c(0,60),data = dhs_g, col = id,
las = 1, axes=FALSE,

    ylab="Height (cm)", xlab="Age in months",main="Girls height: raw")

axis(side=1, at=seq(0, 60, by=12))

axis(side=2, at=seq(50, 110, by=20),las=1)


plot(m6, opt = 'a', col = id, las = 1, ylim=c(50, 110), xlim=c(0,60),axes=FALSE,

    ylab="Height (cm)", xlab="Age in months",

    main="Girls height: SITAR adjusted")

axis(side=1, at=seq(0, 60, by=12))

axis(side=2, at=seq(50, 110, by=20),las=1)


## Figure 3

par(mfrow=c(1,2))

Malawi_ht_boys <- plot(m1, opt = 'd', lty = 1, col="black", axes=FALSE,lwd=0.5,

            ylab="Height (cm)", xlab="Age in months",

            main="Boys height (Malawi 2004 survey)")

axis(side=1, at=seq(0, 60, by=12))

axis(side=2, at=seq(40, 120, by=20),las=1)

lines(m1, opt = 'u', subset = id == 27, col="green", lty=1)

lines(m1, opt = 'a', subset = id == 27, col="green", lty=2)

legend('bottomright', c('mean', 'Unadj.MAL.2004', 'Adj.MAL.2004'),

    lty = c(1, 1, 2), col = c("black", "green", "green"), cex = 0.8, inset=0.04)

legend('topleft', c('Size: a = -2.2', 'Intensity: c = -0.05'), cex = 0.8, inset=0.04)
```

5

```
Egypt_ht_boys <- plot(m1, opt = 'd', lty = 1, col="black", axes=FALSE,lwd=0.5,

          ylab="Height (cm)", xlab="Age in months",

          main="Boys height (Egypt 2014 survey)")

axis(side=1, at=seq(0, 60, by=12))

axis(side=2, at=seq(40, 120, by=20),las=1)

lines(m1, opt = 'u', subset = id == 117, col="green", lty=1)

lines(m1, opt = 'a', subset = id == 117, col="green", lty=2)

legend('bottomright', c('mean', 'Unadj.EGY.2014', 'Adj.EGY.2014'),

    lty = c(1, 1, 2), col = c("black", "green", "green"), cex = 0.8, inset=0.04)

legend('topleft', c('Size: a = 2.4', 'Intensity: c = 0.08'), cex = 0.8,
inset=0.04)

## Supplementary Figure 4

par(mfrow=c(2,2))

par(mar = c(4,4,2,2) + 0.1, cex = 0.8)

plot(height ~ ageint_mths, data = dhs_b, ylim=c(50, 110),las=1,subset = id == 118, main="Boys:
Egypt 2014",

    ylab="Height (cm)", xlab="Age in months")

lines(m3, opt = 'D', subset = id == 118, lty = 1, col="blue")

lines(m3, opt = 'd', lty = 2, col="red")

legend('bottomright', c('Observed', 'Fitted trajectory', 'SITAR average-mean curve'),

    lty = c(NA, 1, 2), pch=c(1,NA,NA), col = c("gray", "blue", "red"), cex = 0.8, inset=0.04)
```

```
plot(height ~ ageint_mths, data = dhs_g, las=1,ylim=c(50, 110), xlim=c(0,60),subset = id == 104, main="Girls: Peru 2012",

    ylab="Height (cm)", xlab="Age in months",pch=1)

lines(m6, opt = 'D', subset = id == 104, lty = 1, col="blue")

lines(m6, opt = 'd', lty = 2, col="red")

legend('bottomright', c('Observed', 'Fitted trajectory', 'SITAR average-mean curve'),

    lty = c(NA, 1, 2), pch=c(1,NA, NA), col = c("gray", "blue", "red"), cex = 0.8, inset=0.04)



plot(height ~ ageint_mths, data = dhs_b, ylim=c(50, 110),las=1,subset = id == 146, main="Boys: WHO height standards",

    ylab="Height (cm)", xlab="Age in months")

lines(m3, opt = 'D', subset = id == 146, lty = 1, col="blue")

lines(m3, opt = 'd', lty = 2, col="red")

legend('bottomright', c('WHO height standards', 'Fitted trajectory', 'SITAR average-mean curve'),

    lty = c(NA, 1, 2), pch=c(1,NA,NA), col = c("gray", "blue", "red"), cex = 0.8, inset=0.04)



plot(height ~ ageint_mths, data = dhs_g, las=1,ylim=c(50, 110), xlim=c(0,60),subset = id == 146, main="Girls: WHO height standards",

    ylab="Height (cm)", xlab="Age in months",pch=1)

lines(m6, opt = 'D', subset = id == 146, lty = 1, col="blue")

lines(m6, opt = 'd', lty = 2, col="red")

legend('bottomright', c('WHO height standards', 'Fitted trajectory', 'SITAR average-mean curve'),
    lty = c(NA, 1, 2), pch=c(1,NA, NA), col = c("gray", "blue", "red"), cex = 0.8, inset=0.04)
```

7

Supplemental material

BMJ Publishing Group Limited (BMJ) disclaims all liability and responsibility arising from any reliance
placed on this supplemental material which has been supplied by the author(s)

BMJ Global Health

```
# WHO CHILD GROWTH STANDARDS DATA

# HEIGHT

#install.packages("remotes") # if "remotes" is not already installed

#remotes::install_github("ki-tools/growthstandards")

who_medht <- data.frame(x = rep(seq(0, 1826.25, length = 61)))


who_medht_boys <- data.frame(who_centile2value(who_medht, p = 50,

                    x_var = "agedays", y_var = "htcm", sex = "Male", data = NULL)) # Boys

who_medht_girls <- data.frame(who_centile2value(who_medht, p = 50,

                    x_var = "agedays", y_var = "htcm", sex = "Female", data = NULL)) #
Girls


who_medht <- cbind(who_medht, who_medht_boys,who_medht_girls)

colnames(who_medht) <- c("ageint_mths","WHO_ht_P50_boys","WHO_ht_P50_girls")

head(who_medht)

who_medht$ageint_mths <- (who_medht$ageint_mths)/30.4375 # convert to months


### Figure 4

who_medht<-subset(who_medht, ageint_mths>1)

par(mfrow=c(2,2))

par(mar = c(4,4,1,1) + 0.1, cex = 0.8)

plot(m3, opt = 'D', col = 8, las = 1, axes=FALSE,subset=id<146,

    ylab="Height (cm)", xlab="Age in months",

    main="Boys height")

axis(side=1, at=seq(0, 60, by=12))
```

8

```
axis(side=2, at=seq(50, 110, by=20),las=1)

lines(m3, opt = 'd', lty = 2, col=4)

lines(m3, opt = 'D', subset=id==146,col="blue",type="l")

#lines(x=who_medht$ageint_mths, y=who_medht$WHO_ht_P50_boys, col='blue', type='l')

legend('topleft', c('fitted', 'mean', 'WHO'),

    lty = c(1, 2, 1), col = c(8, 4, 4), cex = 0.8, inset=0.04)
```

```
plot(m6, opt = 'D', col = 8, las = 1, axes=FALSE,subset=id<146,

    ylab="Height (cm)", xlab="Age in months",

    main="Girls height")

axis(side=1, at=seq(0, 60, by=12))

axis(side=2, at=seq(50, 110, by=20),las=1)

lines(m6, opt = 'd', lty = 2, col=2)

lines(m6, opt = 'D', subset=id==146,col="red",type="l")

#lines(x=who_medht$ageint_mths, y=who_medht$WHO_ht_P50_girls, col='red', type='l')

legend('topleft', c('fitted', 'mean', 'WHO'),

    lty = c(1, 2, 1), col = c(8, 2, 2), cex = 0.8, inset=0.04)


plot(m3, opt = 'd', las = 1, apv = FALSE,col="blue",axes=FALSE,ylim=c(50,110),

    ylab="Height (cm)", xlab="Age in months",

    main="Fitted height for boys and girls")

axis(side=1, at=seq(0, 60, by=12),las=1)

axis(side=2, at=seq(50, 110, by=20),las=1)

lines(m6, opt = 'd', las = 1, apv = FALSE, col="red", lty = 1)

legend("topleft", legend = c("Boys","Girls"), col = c('blue','red'),lwd = c(1, 1))


plot(m3, opt = 'v', las = 1, lty=1, apv = FALSE,col="blue",axes=FALSE,ylim=c(0,8),vlim=c(0,8),

    vlab="Height velocity (cm/month)", xlab="Age in months",

    main="Fitted height velocity for boys and girls")

axis(side=1, at=seq(0, 60, by=12),las=1)

axis(side=2, at=seq(0, 8, by=1),las=1)
```

10

Supplemental material

BMJ Publishing Group Limited (BMJ) disclaims all liability and responsibility arising from any reliance placed on this supplemental material which has been supplied by the author(s)

BMJ Global Health

```
lines(m6, opt = 'v', las = 1, apv = FALSE, col="red", lty = 1)

#points(t(getPeakTrough(dhs_b$ageint_mths, dhs_b$height, peak=FALSE)), pch=25)

legend("topleft", legend = c("Boys","Girls"), col = c('blue','red'),lwd = c(1, 1))



# Random effects for boys

ranef(m3) # SITAR random effects for boys

# Attaching the random effects a and c to the data

random.ht.b<-m3$coefficients$random$id[dhs_b$id,]

colnames(random.ht.b)<-c("a_male_ht", "c_male_ht")

fit_male<-m3$fitted # Renaming the columns in m1$fitted from "fixed" and "id" to "Male fixed
effect" and "Male predicted height"

colnames(fit_male)<-c("Male_Fixed_Effect_HT","Male_Predicted_HT")

dhs_b2<-cbind(random.ht.b,fit_male,dhs_b)

dhs_b2 <- dhs_b2[order(dhs_b2$a_male_ht),]



# Calculating a and c relative to the WHO random effects

a_male_ht = dhs_b2$a_male_ht-5.12974361

c_male_ht = dhs_b2$c_male_ht-0.1030932912

dhs_b2 = cbind(a_male_ht, c_male_ht, dhs_b2$mean_LAZ, dhs_b2$meanStunting_weighted,
dhs_b2$year, dhs_b2$pickcountry, dhs_b2$id)

colnames(dhs_b2)<-c("male_size_ht", "male_velocity_ht", "mean_HAZ", "Stunting",
"year","country","id")

dhs_b2 = as.data.frame(dhs_b2)



# Random effects for girls
```

11

```
ranef(m6) # SITAR random effects for girls

# Attaching the random effects a and c to the data

random.ht.g<-m6$coefficients$random$id[dhs_g$id,]

colnames(random.ht.g)<-c("a_female_ht", "c_female_ht")

fit_female<-m6$fitted # Renaming the columns in m1$fitted from "fixed" and "id" to "Male
fixed effect" and "Male predicted height"

colnames(fit_female)<-c("Female_Fixed_Effect_HT","Female_Predicted_HT")

dhs_g2<-cbind(random.ht.g,fit_female,dhs_g)

dhs_g2 <- dhs_g2[order(dhs_g2$a_female_ht),]


# Calculating a and c relative to the WHO random effects

a_female_ht = dhs_g2$a_female_ht-4.909995490

c_female_ht = dhs_g2$c_female_ht-0.1131823325

dhs_g2 = cbind(a_female_ht, c_female_ht, dhs_g2$mean_LAZ,
dhs_g2$meanStunting_weighted, dhs_g2$year,dhs_g2$pickcountry,dhs_g2$id)

colnames(dhs_g2)<-c("female_size_ht", "female_velocity_ht", "mean_HAZ","Stunting",
"year","country","id")

dhs_g2 = as.data.frame(dhs_g2)


# Figure 5

# Remove duplicate rows of the data frame using cyl and vs variables

boys<-distinct(dhs_b2, male_size_ht, .keep_all= TRUE)

girls<-distinct(dhs_g2, female_size_ht, .keep_all= TRUE)

#

malesize = boys$male_size_ht

femalesize = girls$female_size_ht
```

12

```
maleintensity = boys$male_velocity_ht*100 # expressing intensity as a %

femaleintensity = girls$female_velocity_ht*100 # expressing intensity as a %

par(mfrow=c(2,2))

par(mar = c(4,4,1,1) + 0.1, cex = 0.8)

hist(malesize,main="Size - Boys",xlab="Size relative to the WHO (cm)",

    xlim=c(-8,0), col="blue",las=1,ylim=c(0,30),breaks=25)

hist(femalesize,main="Size - Girls",xlab="Size relative to the WHO (cm)",

    xlim=c(-8,0), col="red",las=1,ylim=c(0,30),breaks=25)

hist(maleintensity,main="Intensity - Boys",xlab="Intensity relative to the WHO (%)",

    xlim=c(-20,5), col="blue",las=1,ylim=c(0,30),breaks=25)

hist(femaleintensity,main="Intensity - Girls",xlab="Intensity relative to the WHO (%)",

    xlim=c(-20,5), col="red",las=1,ylim=c(0,30),breaks=25)


# Stunting for boys

boys = as.data.frame(boys )

Cor_Stunting_b<-cbind(boys$male_size_ht,boys$male_velocity_ht, boys$mean_HAZ,
boys$Stunting)

boys$Stunting = boys$Stunting*100 # converting stunting to a %

Cor_Stunting_b = as.matrix(Cor_Stunting_b )

colnames(Cor_Stunting_b )<-c("Size: Male", "Intensity: Male", "Mean HAZ: Male", "Stunting
(%): Male")


stunting_cor_male = chart.Correlation(Cor_Stunting_b , histogram=FALSE, pch=19)
```

```
# Stunting for girls

girls=as.data.frame(girls)

Cor_Stunting_g<-cbind(girls$female_size_ht,girls$female_velocity_ht,girls$mean_HAZ,
girls$Stunting)

girls$Stunting = girls$Stunting*100 # coverting stunting to a %

Cor_Stunting_g = as.matrix(Cor_Stunting_g)

colnames(Cor_Stunting_g)<-c("Size: Female", "Intensity: Female", "Mean HAZ: Female",
"Stunting (%): Female")


stunting_cor_female = chart.Correlation(Cor_Stunting_g, histogram=FALSE, pch=19)


# Figure 6A - Boys

# Scatter plot with correlation coefficient

# Male size and intensity

p1 = ggscatter(boys, x = "male_velocity_ht", y = "male_size_ht",

        add = "reg.line",  # Add regressin line

        add.params = list(color = "blue", fill = "lightgray"), # Customize reg. line

        conf.int = TRUE, # Add confidence interval

        ylab="Size parameter (cm)", xlab="Intensity parameter (%)",

        main="Boys",

        cor.coef = TRUE, # Add correlation coefficient. see ?stat_cor

        cor.coeff.args = list(method = "pearson", label.x = -0.2, label.sep = "\n"))
```

14

```
# Male size and mean HAZ

p3 = ggscatter(boys, x = "mean_HAZ", y = "male_size_ht",

        add = "reg.line",  # Add regressin line

        add.params = list(color = "blue", fill = "lightgray"), # Customize reg. line

        conf.int = TRUE, # Add confidence interval

        ylab="Size (cm)", xlab="Mean HAZ",

        main="Boys", xlim=c(-3,1), ylim=c(-8,0),

        cor.coef = TRUE, # Add correlation coefficient. see ?stat_cor

        cor.coeff.args = list(method = "pearson", label.x = -3, label.y = -0.5, label.sep = "\n"))


# Male size and % Stunting

p5 = ggscatter(boys, x = "Stunting", y = "male_size_ht",

        add = "reg.line",  # Add regressin line

        add.params = list(color = "blue", fill = "lightgray"), # Customize reg. line

        conf.int = TRUE, # Add confidence interval

        ylab="Size (cm)", xlab="Stunting (%)",

        main="Boys",xlim=c(0,80), ylim=c(-8,0),

        cor.coef = TRUE, # Add correlation coefficient. see ?stat_cor

        cor.coeff.args = list(method = "pearson", label.x = 0, label.y = -0.5, label.sep = "\n"))


# Male intensity and mean HAZ

p7 = ggscatter(boys, x = "mean_HAZ", y = "male_velocity_ht",

        add = "reg.line",  # Add regressin line

        add.params = list(color = "blue", fill = "lightgray"), # Customize reg. line
```

```
        conf.int = TRUE, # Add confidence interval

        ylab="Intensity (%)", xlab="Mean HAZ",

        main="Boys",xlim=c(-3,1), ylim=c(-0.3,0.1),

        cor.coef = TRUE, # Add correlation coefficient. see ?stat_cor

        cor.coeff.args = list(method = "pearson", label.x = -3, label.y = 0.05, label.sep = "\n"))


# Male intensity and mean HAZ

p9 = ggscatter(boys, x = "Stunting", y = "male_velocity_ht",

        add = "reg.line",  # Add regressin line

        add.params = list(color = "blue", fill = "lightgray"), # Customize reg. line

        conf.int = TRUE, # Add confidence interval

        ylab="Intensity (%)", xlab="Stunting (%)",

        main="Boys",xlim=c(0,80), ylim=c(-0.3,0.1),

        cor.coef = TRUE, # Add correlation coefficient. see ?stat_cor

        cor.coeff.args = list(method = "pearson", label.x = 0, label.y = 0.08, label.sep = "\n"))


plot_grid(p3, p5, p7, p9,labels = "AUTO") # combining plots


# Figure 6B - Girls

# Scatter plot with correlation coefficient

# Female size and intensity

p2 = ggscatter(girls, x = "female_velocity_ht", y = "female_size_ht",

        add = "reg.line",  # Add regressin line

        add.params = list(color = "red", fill = "lightgray"), # Customize reg. line
```

16

```
            conf.int = TRUE, # Add confidence interval

            ylab="Size parameter (cm)", xlab="Intensity parameter (%)",

            main="Girls",

            cor.coef = TRUE, # Add correlation coefficient. see ?stat_cor

            cor.coeff.args = list(method = "pearson", label.x = -0.2, label.sep = "\n"))


# Female size and mean HAZ

p4 = ggscatter(girls, x = "mean_HAZ", y = "female_size_ht",

            add = "reg.line",  # Add regressin line

            add.params = list(color = "red", fill = "lightgray"), # Customize reg. line

            conf.int = TRUE, # Add confidence interval

            ylab="Size (cm)", xlab="Mean HAZ",

            main="Girls", xlim=c(-3,1), ylim=c(-8,0),

            cor.coef = TRUE, # Add correlation coefficient. see ?stat_cor

            cor.coeff.args = list(method = "pearson", label.x = -3, label.y = -0.5, label.sep = "\n"))


# Female size and % Stunting

p6 = ggscatter(girls, x = "Stunting", y = "female_size_ht",

            add = "reg.line",  # Add regressin line

            add.params = list(color = "red", fill = "lightgray"), # Customize reg. line

            conf.int = TRUE, # Add confidence interval

            ylab="Size (cm)", xlab="Stunting (%)",

            main="Girls",xlim=c(0,80), ylim=c(-8,0),

            cor.coef = TRUE, # Add correlation coefficient. see ?stat_cor
```

17

```
                cor.coeff.args = list(method = "pearson", label.x = 0, label.y = -0.45, label.sep = "\n"))


  # Female intensity and mean HAZ

  p8 = ggscatter(girls, x = "mean_HAZ", y = "female_velocity_ht",

          add = "reg.line",  # Add regressin line

          add.params = list(color = "red", fill = "lightgray"), # Customize reg. line

          conf.int = TRUE, # Add confidence interval

          ylab="Intensity (%)", xlab="Mean HAZ",

          main="Girls",xlim=c(-3,1), ylim=c(-0.3,0.1),

          cor.coef = TRUE, # Add correlation coefficient. see ?stat_cor

          cor.coeff.args = list(method = "pearson", label.x = -3, label.y = 0.05, label.sep = "\n"))


  # Female intensity and mean HAZ

  p10 = ggscatter(girls, x = "Stunting", y = "female_velocity_ht",

          add = "reg.line",  # Add regressin line

          add.params = list(color = "red", fill = "lightgray"), # Customize reg. line

          conf.int = TRUE, # Add confidence interval

          ylab="Intensity (%)", xlab="Stunting (%)",

          main="Girls",xlim=c(0,80), ylim=c(-0.3,0.1),

          cor.coef = TRUE, # Add correlation coefficient. see ?stat_cor

          cor.coeff.args = list(method = "pearson", label.x = 0, label.y = 0.08, label.sep = "\n"))


  plot_grid(p4, p6, p8, p10,labels = "AUTO") # combining plots
```

18

```
# Male intensity and male size

boys$male_velocity_ht = boys$male_velocity_ht*100

girls$female_velocity_ht = girls$female_velocity_ht*100


p11 = ggscatter(boys, y = "male_size_ht", x = "male_velocity_ht",

        add = "reg.line",  # Add regressin line

        add.params = list(color = "blue", fill = "lightgray"), # Customize reg. line

        conf.int = TRUE, # Add confidence interval

        xlab="Intensity (%)", ylab="Size (cm)",

        main="Boys",xlim=c(-20,5), ylim=c(-8,0),

        cor.coef = TRUE, # Add correlation coefficient. see ?stat_cor

        cor.coeff.args = list(method = "pearson", label.x = 0, label.y = 0.08, label.sep = "\n"))


# Male intensity and male size

p12 = ggscatter(girls, y = "female_size_ht", x = "female_velocity_ht",

        add = "reg.line",  # Add regressin line

        add.params = list(color = "blue", fill = "lightgray"), # Customize reg. line

        conf.int = TRUE, # Add confidence interval

        xlab="Intensity (%)", ylab="Size (cm)",

        main="Girls",xlim=c(-20,5), ylim=c(-8,0),

        cor.coef = TRUE, # Add correlation coefficient. see ?stat_cor

        cor.coeff.args = list(method = "pearson", label.x = 0, label.y = 0.08, label.sep = "\n"))


plot_grid(p11, p12,labels = "AUTO") # Better for combining plots
```

```
## Figure 7A

## add extra space to right margin of plot within frame

boys$year <- boys$year+1999

girls$year <- girls$year+1999


par(mfrow=c(2,2))

par(mar=c(5, 4, 4, 6) + 0.1)

## Plot first set of data and draw its axis

plot(male_size_ht ~year, data=boys, pch=16, axes=FALSE, ylim=c(-8,0),

    xlim=c(2000,2020), xlab="", ylab="", subset = country == 50,

    main="Boys: Peru",col="black")

axis(2, ylim=c(-8,0),col="black",las=1)  ## las=1 makes horizontal labels

axis(1, xlim=c(2000,2020),col="black",las=1)  ## las=1 makes horizontal labels

mtext("Size (cm)",side=2,line=2.5)

box()

## Allow a second plot on the same graph

par(new=TRUE)

## Plot the second plot and put axis scale on right

plot(mean_HAZ ~ year, pch=1, data=boys,  xlab="", ylab="",

    ylim=c(-4,4), xlim=c(2000,2020),

    axes=FALSE, col="black",subset = country == 50)

## a little farther out (line=4) to make room for labels
```

```
mtext("Mean HAZ",side=4,col="black",line=4)

axis(4, ylim=c(-4,4), col="black",col.axis="black",las=1)


## Draw the time axis

mtext("Survey year",side=1,col="black",line=2.5)

box()

## Add Legend

legend("topleft",legend=c("Size parameter","Mean HAZ"),

    text.col=c("black","black"),pch=c(16,1),col=c("black","black"))


par(mar = c(5,4,4,6) + 0.1, cex = 0.8)

## Plot first set of data and draw its axis

plot(male_size_ht ~year, data=boys, pch=16, axes=FALSE, ylim=c(-8,0),

    xlim=c(2000,2020), xlab="", ylab="", subset = country == 53,

    main="Boys: Senegal",col="black")

axis(2, ylim=c(-8,0),col="black",las=1)  ## las=1 makes horizontal labels

axis(1, xlim=c(2000,2020),col="black",las=1)  ## las=1 makes horizontal labels

mtext("Size (cm)",side=2,line=2.5)

box()

## Allow a second plot on the same graph

par(new=TRUE)

## Plot the second plot and put axis scale on right

plot(mean_HAZ ~ year, pch=1, data=boys,  xlab="", ylab="",

    ylim=c(-4,4), xlim=c(2000,2020),
```

21

Supplemental material

BMJ Publishing Group Limited (BMJ) disclaims all liability and responsibility arising from any reliance placed on this supplemental material which has been supplied by the author(s)

BMJ Global Health

```
        axes=FALSE, col="black",subset = country == 53)
```

a little farther out (line=4) to make room for labels

```
mtext("Mean HAZ",side=4,col="black",line=4)

axis(4, ylim=c(-4,4), col="black",col.axis="black",las=1)
```

Draw the time axis

```
mtext("Survey year",side=1,col="black",line=2.5)

#box()
```

Add Legend

```
legend("topleft",legend=c("Size parameter","Mean HAZ"),

    text.col=c("black","black"),pch=c(16,1),col=c("black","black"))


par(mar = c(5,4,4,6) + 0.1, cex = 0.8)
```

Plot first set of data and draw its axis

```
plot(female_size_ht ~year, data=girls, pch=16, axes=FALSE, ylim=c(-8,0),

    xlim=c(2000,2020), xlab="", ylab="", subset = country == 19,

    main="Girls: Egypt",col="black")

axis(2, ylim=c(-8,0),col="black",las=1)  ## las=1 makes horizontal labels

axis(1, xlim=c(2000,2020),col="black",las=1)  ## las=1 makes horizontal labels

mtext("Size (cm)",side=2,line=2.5)

box()
```

Allow a second plot on the same graph

```
par(new=TRUE)
```

Plot the second plot and put axis scale on right

Supplemental material

BMJ Publishing Group Limited (BMJ) disclaims all liability and responsibility arising from any reliance
placed on this supplemental material which has been supplied by the author(s)

BMJ Global Health

```
plot(mean_HAZ ~ year, pch=1, data=girls,  xlab="", ylab="",

    ylim=c(-4,4), xlim=c(2000,2020),

    axes=FALSE, col="black",subset = country == 19)

## a little farther out (line=4) to make room for labels

mtext("Mean HAZ",side=4,col="black",line=4)

axis(4, ylim=c(-4,4), col="black",col.axis="black",las=1)


## Draw the time axis

mtext("Survey year",side=1,col="black",line=2.5)

box()

## Add Legend

legend("topleft",legend=c("Size parameter","Mean HAZ"),

    text.col=c("black","black"),pch=c(16,1),col=c("black","black"))


par(mar=c(5, 4, 4, 6) + 0.1)

## Plot first set of data and draw its axis

plot(female_size_ht ~year, data=girls, pch=16, axes=FALSE, ylim=c(-8,0),

    xlim=c(2000,2020), xlab="", ylab="", subset = country == 45,

    main="Girls: Nepal",col="black")

axis(2, ylim=c(-8,0),col="black",las=1)  ## las=1 makes horizontal labels

axis(1, xlim=c(2000,2020),col="black",las=1)  ## las=1 makes horizontal labels

mtext("Size (cm)",side=2,line=2.5)

box()

## Allow a second plot on the same graph
```

23

```
par(new=TRUE)

## Plot the second plot and put axis scale on right

plot(mean_HAZ ~ year, pch=1, data=girls,  xlab="", ylab="",

    ylim=c(-4,4), xlim=c(2000,2020),

    axes=FALSE, col="black",subset = country == 45)

## a little farther out (line=4) to make room for labels

mtext("Mean HAZ",side=4,col="black",line=4)

axis(4, ylim=c(-4,4), col="black",col.axis="black",las=1)


## Draw the time axis

mtext("Survey year",side=1,col="black",line=2.5)

box()

## Add Legend

legend("topleft",legend=c("Size parameter","Mean HAZ"),

    text.col=c("black","black"),pch=c(16,1),col=c("black","black"))


# Intensity


## Figure 7B


## add extra space to right margin of plot within frame


par(mfrow=c(2,2))

par(mar=c(5, 4, 4, 6) + 0.1)
```

24

```
## Plot first set of data and draw its axis

plot(male_velocity_ht ~year, data=boys, pch=16, axes=FALSE, ylim=c(-10,0),

    xlim=c(2000,2020), xlab="", ylab="", subset = country == 50,

    main="Boys: Peru",col="black")

axis(2, ylim=c(-10,0),col="black",las=1)  ## las=1 makes horizontal labels

axis(1, xlim=c(2000,2020),col="black",las=1)  ## las=1 makes horizontal labels

mtext("Intensity (%)",side=2,line=2.5)

box()

## Allow a second plot on the same graph

par(new=TRUE)

## Plot the second plot and put axis scale on right

plot(mean_HAZ ~ year, pch=1, data=boys,  xlab="", ylab="",

    ylim=c(-4,4), xlim=c(2000,2020),

    axes=FALSE, col="black",subset = country == 50)

## a little farther out (line=4) to make room for labels

mtext("Mean HAZ",side=4,col="black",line=4)

axis(4, ylim=c(-4,4), col="black",col.axis="black",las=1)


## Draw the time axis

mtext("Survey year",side=1,col="black",line=2.5)

box()

## Add Legend

legend("topleft",legend=c("Intensity parameter","Mean HAZ"),

    text.col=c("black","black"),pch=c(16,1),col=c("black","black"))
```

25

```
par(mar = c(5,4,4,6) + 0.1, cex = 0.8)

## Plot first set of data and draw its axis

plot(male_size_ht ~year, data=boys, pch=16, axes=FALSE, ylim=c(-10,0),

    xlim=c(2000,2020), xlab="", ylab="", subset = country == 53,

    main="Boys: Senegal",col="black")

axis(2, ylim=c(-10,0),col="black",las=1)  ## las=1 makes horizontal labels

axis(1, xlim=c(2000,2020),col="black",las=1)  ## las=1 makes horizontal labels

mtext("Intensity (%)",side=2,line=2.5)

box()

## Allow a second plot on the same graph

par(new=TRUE)

## Plot the second plot and put axis scale on right

plot(mean_HAZ ~ year, pch=1, data=boys,  xlab="", ylab="",

    ylim=c(-4,4), xlim=c(2000,2020),

    axes=FALSE, col="black",subset = country == 53)

## a little farther out (line=4) to make room for labels

mtext("Mean HAZ",side=4,col="black",line=4)

axis(4, ylim=c(-4,4), col="black",col.axis="black",las=1)


## Draw the time axis

mtext("Survey year",side=1,col="black",line=2.5)

#box()

## Add Legend
```

```
legend("topleft",legend=c("Intensity parameter","Mean HAZ"),

    text.col=c("black","black"),pch=c(16,1),col=c("black","black"))


par(mar = c(5,4,4,6) + 0.1, cex = 0.8)

## Plot first set of data and draw its axis

plot(female_size_ht ~year, data=girls, pch=16, axes=FALSE, ylim=c(-10,0),

    xlim=c(2000,2020), xlab="", ylab="", subset = country == 19,

    main="Girls: Egypt",col="black")

axis(2, ylim=c(-10,0),col="black",las=1)  ## las=1 makes horizontal labels

axis(1, xlim=c(2000,2020),col="black",las=1)  ## las=1 makes horizontal labels

mtext("Intensity (%)",side=2,line=2.5)

box()

## Allow a second plot on the same graph

par(new=TRUE)

## Plot the second plot and put axis scale on right

plot(mean_HAZ ~ year, pch=1, data=girls,  xlab="", ylab="",

    ylim=c(-4,4), xlim=c(2000,2020),

    axes=FALSE, col="black",subset = country == 19)

## a little farther out (line=4) to make room for labels

mtext("Mean HAZ",side=4,col="black",line=4)

axis(4, ylim=c(-4,4), col="black",col.axis="black",las=1)


## Draw the time axis

mtext("Survey year",side=1,col="black",line=2.5)
```

Supplemental material

BMJ Publishing Group Limited (BMJ) disclaims all liability and responsibility arising from any reliance placed on this supplemental material which has been supplied by the author(s)

BMJ Global Health

```
box()

## Add Legend

legend("topleft",legend=c("Intensity parameter","Mean HAZ"),

    text.col=c("black","black"),pch=c(16,1),col=c("black","black"))


par(mar=c(5, 4, 4, 6) + 0.1)

## Plot first set of data and draw its axis

plot(female_size_ht ~year, data=girls, pch=16, axes=FALSE, ylim=c(-10,0),

    xlim=c(2000,2020), xlab="", ylab="", subset = country == 45,

    main="Girls: Nepal",col="black")

axis(2, ylim=c(-10,0),col="black",las=1)  ## las=1 makes horizontal labels

axis(1, xlim=c(2000,2020),col="black",las=1)  ## las=1 makes horizontal labels

mtext("Intensity (%)",side=2,line=2.5)

box()

## Allow a second plot on the same graph

par(new=TRUE)

## Plot the second plot and put axis scale on right

plot(mean_HAZ ~ year, pch=1, data=girls,  xlab="", ylab="",

    ylim=c(-4,4), xlim=c(2000,2020),

    axes=FALSE, col="black",subset = country == 45)

## a little farther out (line=4) to make room for labels

mtext("Mean HAZ",side=4,col="black",line=4)

axis(4, ylim=c(-4,4), col="black",col.axis="black",las=1)
```

Supplemental material

BMJ Publishing Group Limited (BMJ) disclaims all liability and responsibility arising from any reliance
placed on this supplemental material which has been supplied by the author(s)

BMJ Global Health

```
## Draw the time axis

mtext("Survey year",side=1,col="black",line=2.5)

box()

## Add Legend

legend("topleft",legend=c("Intensity parameter","Mean HAZ"),

    text.col=c("black","black"),pch=c(16,1),col=c("black","black"))




# Effect of size on SITAR parameters

## BOYS

size_birth = subset(dhs_b, ageint_mths==2)

size_birth = merge(size_birth, boys, by="id")

cor(size_birth$height,size_birth$male_size_ht) # 0.41

cor(size_birth$height,size_birth$male_velocity_ht) # 0.14

cor(size_birth$male_size_ht,size_birth$male_velocity_ht) # 0.91

lm1 <- lm(size_birth$male_size_ht ~ size_birth$height, data=size_birth)

print(lm1)

summary(lm1)

AIC(lm1)

confint(lm1)


lm2 <- lm(size_birth$male_velocity_ht ~ size_birth$height, data=size_birth)

print(lm2)
```

29

Supplemental material

BMJ Publishing Group Limited (BMJ) disclaims all liability and responsibility arising from any reliance placed on this supplemental material which has been supplied by the author(s)

BMJ Global Health

```
summary(lm2)

AIC(lm2)

confint(lm2)


lm3 <- lm(size_birth$male_size_ht ~ size_birth$male_velocity_ht, data=size_birth)

print(lm3)

summary(lm3)

AIC(lm3)

confint(lm3)


lm4 <- lm(size_birth$male_size_ht ~ size_birth$height + size_birth$male_velocity_ht,
data=size_birth)

print(lm4)

summary(lm4)

confint(lm4)

BIC(lm1, lm2, lm3, lm4) # BIC for each model


## GIRLS

size_birth = subset(dhs_g, ageint_mths==2)

size_birth = merge(size_birth, girls, by="id")

cor(size_birth$height,size_birth$female_size_ht) # 0.43

cor(size_birth$height,size_birth$female_velocity_ht) # 0.14

cor(size_birth$female_size_ht,size_birth$female_velocity_ht) # 0.89

lf1 <- lm(size_birth$female_size_ht ~ size_birth$height, data=size_birth)

print(lf1)
```

```
summary(lf1)

AIC(lf1)

confint(lf1)


lf2 <- lm(size_birth$female_velocity_ht ~ size_birth$height, data=size_birth)

print(lf2)

summary(lf2)

AIC(lf2)

confint(lf2)


lf3 <- lm(size_birth$female_size_ht ~ size_birth$female_velocity_ht, data=size_birth)

print(lf3)

summary(lf3)

AIC(lf3)

confint(lf3)


lf4 <- lm(size_birth$female_size_ht ~ size_birth$height + size_birth$female_velocity_ht,
data=size_birth)

print(lf4)

summary(lf4)

confint(lf4)

BIC(lf1, lf2, lf3, lf4) # BIC for each model
```

31

Supplemental material

BMJ Publishing Group Limited (BMJ) disclaims all liability and responsibility arising from any reliance
placed on this supplemental material which has been supplied by the author(s)

BMJ Global Health

Supplementary File 3: Summary of 145 Demographic Health Surveys used for analyses

country	year	Total sample	% Boys	Median age in months (IQR)
Albania	2009	1,473	49.8%	33.5 (18.4 - 48.2)
Albania	2017	2,610	51.0%	29.7 (14.7 - 44.9)
Angola	2015	7,513	49.9%	28.9 (13.6 - 43.6)
Armenia	2005	1,290	54.4%	27.4 (13.9 - 42.6)
Armenia	2010	1,390	52.2%	27.7 (14.2 - 43)
Armenia	2016	1,593	52.9%	29 (15.1 - 44.4)
Azerbaijan	2006	2,049	53.4%	27.1 (13.4 - 42.9)
Bangladesh	2004	6,102	50.6%	28.9 (14.4 - 43.9)
Bangladesh	2007	5,473	49.6%	29.3 (15.2 - 44.1)
Bangladesh	2011	7,920	50.6%	31.8 (14.8 - 45.9)
Bangladesh	2014	7,235	52.0%	29.5 (14.3 - 44.7)
Benin	2001	4,098	49.8%	25.8 (11.5 - 40.9)
Benin	2006	13,520	50.0%	27.8 (12.8 - 42.4)
Benin	2012	9,367	50.0%	30.6 (15.6 - 45)
Bolivia	2003	9,823	51.4%	31.3 (15.6 - 46.1)
Bolivia	2008	8,395	50.7%	29.8 (14.9 - 44.9)
Burkina Faso	2003	8,882	51.1%	28.5 (12.7 - 43.2)
Burkina Faso	2010	6,960	51.0%	28.6 (13.9 - 43.7)
Burundi	2010	3,612	51.2%	28.2 (14.5 - 43.4)
Burundi	2016	6,358	50.3%	29.9 (14.6 - 45.5)
Cambodia	2000	3,753	51.4%	31 (14 - 45.5)
Cambodia	2005	3,853	48.4%	29.6 (15 - 44.6)
Cambodia	2010	4,103	51.5%	30.1 (15.1 - 45.2)
Cambodia	2014	4,938	50.9%	29.2 (15.2 - 44.2)
Cameroon	2004	3,756	50.0%	27.5 (13.5 - 44.6)
Cameroon	2011	5,882	48.8%	28.1 (13.5 - 43.4)
Chad	2015	10,760	50.0%	30.6 (13.9 - 45.3)
Colombia	2010	17,749	51.4%	30.6 (15.4 - 45.2)
Comoros	2012	2,883	50.1%	29.3 (14.4 - 43.4)
Congo Brazzaville	2005	4,418	50.8%	27.6 (13.3 - 42.4)
Congo Brazzaville	2011	4,965	49.6%	28.3 (13.3 - 42)
Congo, DRC	2007	3,717	48.8%	29.1 (14.7 - 44.7)
Congo, DRC	2013	9,031	50.2%	29.2 (13.7 - 44.2)
Ivory coast	2012	3,788	49.0%	28.2 (13.3 - 42.6)

32

Dominican Republic	2002	11,017	50.7%	29.9 (15.7 - 44.9)
Dominican Republic	2007	11,084	52.1%	31.5 (16.5 - 45.9)
Dominican Republic	2013	3,678	51.1%	31.1 (15.7 - 45.8)
Egypt	2000	10,692	51.5%	28.5 (13.8 - 43.2)
Egypt	2003	6,213	52.1%	29 (14.7 - 44.3)
Egypt	2005	12,907	50.6%	29.8 (15 - 44.5)
Egypt	2008	10,112	50.5%	27.7 (13.3 - 43.5)
Egypt	2014	14,717	52.2%	28.8 (14.3 - 43.4)
Eritrea	2002	5,627	50.9%	30.6 (13.6 - 46.1)
Ethiopia	2000	9,326	50.2%	29.8 (14.7 - 43.9)
Ethiopia	2005	4,221	50.1%	31.1 (14.7 - 45.4)
Ethiopia	2011	10,400	51.2%	31.5 (14.4 - 45.1)
Ethiopia	2016	9,471	51.1%	29.7 (14 - 45.5)
Gabon	2012	4,155	51.2%	29.5 (13.1 - 43.3)
Gambia	2013	3,598	51.2%	27.5 (12.7 - 42.2)
Ghana	2008	2,714	51.1%	29.9 (15.1 - 45.4)
Ghana	2014	3,049	52.5%	29.3 (14.5 - 43.5)
Guatemala	2015	12,286	51.7%	29.9 (14.8 - 44.6)
Guinea	2012	3,572	51.5%	28.9 (14.1 - 43.4)
Guyana	2009	1,823	49.8%	29.7 (15.9 - 44.9)
Haiti	2000	6,436	49.5%	29.3 (15.5 - 43.8)
Haiti	2006	2,974	48.8%	29.7 (14.7 - 43.7)
Haiti	2012	4,742	51.6%	27.8 (13.5 - 43.5)
Haiti	2017	6,769	49.8%	30.9 (15.4 - 46.1)
Honduras	2006	10,275	51.1%	31.5 (17 - 46)
Honduras	2012	10,943	52.3%	28.6 (14.2 - 44)
India	2006	43,728	52.3%	30.1 (15.3 - 44.8)
India	2015	239,588	52.0%	30.2 (15.3 - 44.6)
Jordan	2002	4,990	50.1%	28.7 (13.8 - 44.3)
Jordan	2007	4,648	50.0%	30.1 (15.4 - 45.3)
Jordan	2009	4,444	51.9%	28 (14.4 - 43)
Jordan	2012	6,412	51.5%	31.3 (16 - 45.2)
Kenya	2003	5,157	50.3%	28.6 (13.2 - 43.7)
Kenya	2009	5,684	51.1%	29.5 (14.9 - 44.5)
Kenya	2014	20,668	50.9%	30 (15 - 44.5)
Kyrgyzstan	2012	4,618	51.7%	27.7 (13.8 - 42.9)
Lesotho	2009	2,235	49.5%	29.5 (14.7 - 45.4)
Lesotho	2014	1,907	48.1%	30.8 (15.4 - 44.7)
Liberia	2007	5,329	51.8%	30.2 (14.8 - 45)

33

Liberia	2013	3,867	53.8%	29.9 (14.2 - 45.1)
Madagascar	2004	5,043	48.9%	28.6 (13.8 - 44.2)
Madagascar	2009	5,841	50.0%	31.2 (15.3 - 45.8)
Malawi	2000	10,226	49.2%	27.5 (12.9 - 42.4)
Malawi	2004	9,098	49.4%	27.9 (13.4 - 43.8)
Malawi	2010	5,007	48.6%	29.3 (15.4 - 44.3)
Malawi	2015	5,686	48.6%	30.8 (15.3 - 45.4)
Maldives	2009	2,636	50.6%	28.7 (13.3 - 44)
Mali	2001	10,427	50.6%	27.5 (12 - 43.3)
Mali	2006	12,062	50.6%	27.2 (13 - 42.5)
Mali	2012	4,951	51.4%	31.6 (16.9 - 45.2)
Moldova	2005	1,506	50.9%	29.6 (15.3 - 43.9)
Morocco	2003	5,694	49.7%	30 (14.9 - 44.9)
Mozambique	2003	9,103	49.3%	28.5 (13.3 - 43.2)
Mozambique	2011	10,411	49.9%	28.3 (13.3 - 43.2)
Myanmar	2016	4,648	51.7%	30 (15 - 45)
Namibia	2000	4,023	49.7%	28.6 (14.2 - 44.2)
Namibia	2007	5,167	49.9%	29 (14 - 43.7)
Namibia	2013	2,617	49.2%	28.7 (14.6 - 44.1)
Nepal	2001	6,389	49.0%	29.6 (14.6 - 44.3)
Nepal	2006	5,450	51.5%	30.8 (15.9 - 45.3)
Nepal	2011	2,441	51.3%	30.3 (15 - 44.1)
Nepal	2016	2,446	52.0%	29.9 (15.7 - 44.9)
Nicaragua	2001	6,650	51.0%	29.8 (15.7 - 44.4)
Niger	2006	4,043	51.5%	27.6 (12.6 - 42.9)
Niger	2012	5,310	50.2%	28.4 (13.1 - 43.5)
Nigeria	2003	4,824	49.9%	26.7 (11.9 - 41.9)
Nigeria	2008	22,394	50.1%	28.6 (13.3 - 43.2)
Nigeria	2013	27,358	50.1%	29 (13.6 - 44.3)
Pakistan	2012	3,316	50.1%	29.5 (14.1 - 44.7)
Pakistan	2018	4,211	51.2%	29 (14.4 - 43.7)
Peru	2005	2,454	51.1%	29.4 (14.3 - 45.1)
Peru	2008	8,554	50.2%	31 (16 - 45.6)
Peru	2009	9,814	51.4%	30.8 (14.6 - 46.1)
Peru	2010	9,249	50.4%	30.2 (15.7 - 45.5)
Peru	2011	9,193	50.8%	30.2 (15.6 - 44.8)
Peru	2012	9,675	50.9%	30.8 (15.5 - 45.1)
Rwanda	2000	6,681	49.6%	28.6 (12 - 44.6)
Rwanda	2005	3,936	49.0%	27.9 (13.4 - 41.8)

Rwanda	2010	4,368	50.2%	31.1 (16.3 - 45.3)
Rwanda	2015	3,810	50.5%	29.3 (14.3 - 43)
Sao Tome and Principe	2008	1,831	49.9%	30 (16.3 - 43.3)
Senegal	2005	3,179	51.1%	27.6 (13.4 - 42.3)
Senegal	2010	4,005	51.5%	27.9 (13.5 - 42.8)
Senegal	2013	6,550	50.0%	28.7 (13.9 - 43.1)
Senegal	2014	6,762	51.1%	29.4 (15.4 - 44.4)
Senegal	2015	6,885	50.2%	29.9 (15.1 - 44.4)
Senegal	2016	6,699	51.3%	30.5 (15.2 - 44.5)
Senegal	2017	11,919	51.3%	30.4 (15.3 - 45.2)
Sierra Leone	2008	2,794	48.8%	28.6 (14.1 - 44.3)
Sierra Leone	2013	5,367	48.6%	30.8 (15.3 - 44.5)
South Africa	2016	1,468	50.8%	31.3 (16 - 46.1)
Swaziland	2006	2,815	49.5%	30.1 (15 - 45.3)
Tajikistan	2012	4,781	50.9%	27.7 (14 - 42.4)
Tajikistan	2017	6,038	50.3%	29.4 (15.3 - 44.6)
Tanzania	2004	7,938	49.9%	28 (13.6 - 43.5)
Tanzania	2010	7,632	49.5%	28.9 (14.2 - 44.3)
Tanzania	2015	10,184	50.5%	29 (14.8 - 44.4)
Timor-Leste	2009	8,452	50.5%	31.2 (16.4 - 44.8)
Timor-Leste	2016	6,661	51.4%	31.2 (16.6 - 45.1)
Togo	2014	3,535	50.4%	29.6 (14.9 - 44.4)
Uganda	2000	5,693	49.8%	27.1 (13.8 - 43)
Uganda	2006	2,661	50.6%	28.6 (13.8 - 43.4)
Uganda	2011	2,360	49.7%	28.6 (14 - 43.6)
Uganda	2016	5,160	50.2%	29.9 (15.6 - 44.9)
Yemen	2013	14,344	50.9%	27.9 (13.6 - 43.5)
Zambia	2002	5,985	49.8%	28 (13.8 - 43.5)
Zambia	2007	5,715	49.4%	28.3 (14.3 - 43.7)
Zambia	2013	12,627	50.3%	30.3 (15.4 - 45.4)
Zimbabwe	2005	5,061	50.0%	31 (15.3 - 45.8)
Zimbabwe	2010	5,359	49.5%	27.5 (12.3 - 42.3)
Zimbabwe	2015	6,084	49.6%	31.8 (16.7 - 46.3)
Total		**1,208,483**	**50.9%**	**29.6 (14.6 - 44.4)**

35

Supplemental material

BMJ Publishing Group Limited (BMJ) disclaims all liability and responsibility arising from any reliance placed on this supplemental material which has been supplied by the author(s)

BMJ Global Health

Supplementary File 4: Goodness of fit plots after SITAR modelling. For illustration, we show crude height data for boy's height in Egypt in 2014 (open circles, top-left panel), girls in Peru in 2012 (open circles, top-right panel), WHO child height standards for boys (open circles, bottom-left panel), and WHO child height standards for girls (open circles, bottom-right panel). The corresponding SITAR fitted growth curves are shown in solid blue line and the fitted SITAR population-mean curves are shown by red dotted line

36

Supplemental material

BMJ Publishing Group Limited (BMJ) disclaims all liability and responsibility arising from any reliance placed on this supplemental material which has been supplied by the author(s)

BMJ Global Health
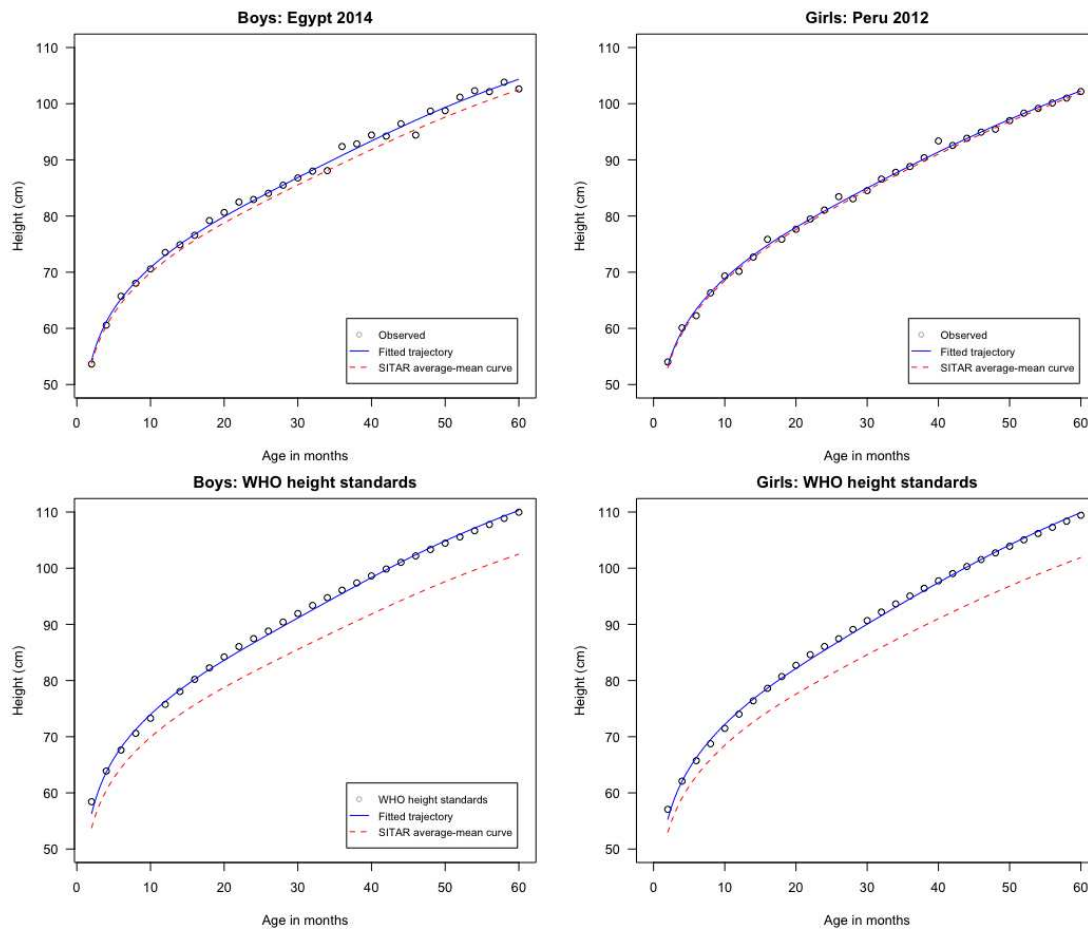
Supplementary File 5: Table of the SITAR random effects for size and intensity parameters with and without inclusion of the mean height of the WHO child growth standards in the multi-country dataset for boys and girls

Country	Survey year	Without WHO data included				With WHO data included			
		Female		Male		Female		Male	
		Size	Intensity	Size	Intensity	Size	Intensity	Size	Intensity
Albania	2009	1.811	0.076	2.216	0.091	1.780	0.075	2.184	0.090
Albania	2017	2.739	0.086	3.355	0.085	2.713	0.085	3.332	0.083
Angola	2015	-0.507	0.020	-0.504	-0.010	-0.545	0.019	-0.543	-0.011
Armenia	2005	2.605	0.125	3.344	0.100	2.575	0.124	3.319	0.099
Armenia	2010	1.687	0.034	1.559	0.057	1.659	0.033	1.526	0.056
Armenia	2016	3.965	0.129	3.753	0.122	3.942	0.128	3.728	0.120
Azerbaijan	2006	0.229	-0.039	0.290	-0.008	0.199	-0.040	0.257	-0.009
Bangladesh	2004	-2.098	-0.050	-1.758	-0.044	-2.139	-0.050	-1.802	-0.044
Bangladesh	2007	-1.420	-0.046	-0.900	-0.034	-1.459	-0.046	-0.939	-0.034
Bangladesh	2011	-1.152	-0.033	-0.766	-0.009	-1.190	-0.034	-0.807	-0.010
Bangladesh	2014	-0.794	-0.033	-0.355	-0.007	-0.830	-0.034	-0.393	-0.008
Benin	2001	-0.417	-0.025	-0.366	-0.038	-0.452	-0.026	-0.400	-0.039
Benin	2006	-1.649	-0.053	-1.904	-0.049	-1.688	-0.053	-1.949	-0.049
Benin	2012	-2.242	-0.083	-2.648	-0.062	-2.282	-0.083	-2.697	-0.062
Bolivia	2003	-0.201	-0.005	0.042	0.008	-0.237	-0.006	0.004	0.007
Bolivia	2008	0.289	0.002	0.588	0.015	0.255	0.002	0.554	0.015
Burkina Faso	2003	-1.123	-0.072	-1.420	-0.074	-1.158	-0.073	-1.457	-0.074
Burkina Faso	2010	-0.281	-0.012	-0.270	-0.006	-0.316	-0.012	-0.308	-0.007
Burundi	2010	-2.378	-0.055	-2.583	-0.071	-2.421	-0.055	-2.630	-0.071
Burundi	2016	-2.309	-0.049	-2.473	-0.061	-2.352	-0.050	-2.520	-0.061
Cambodia	2000	-1.781	-0.070	-1.424	-0.055	-1.820	-0.071	-1.464	-0.055
Cambodia	2005	-1.301	-0.044	-1.182	-0.051	-1.339	-0.045	-1.221	-0.051
Cambodia	2010	-1.052	-0.053	-0.667	-0.054	-1.089	-0.053	-0.702	-0.055
Cambodia	2014	-0.257	-0.025	-0.018	-0.011	-0.292	-0.026	-0.053	-0.012
Cameroon	2004	-0.258	0.004	-0.012	0.012	-0.294	0.003	-0.050	0.011
Cameroon	2011	0.187	-0.018	0.092	-0.013	0.155	-0.019	0.058	-0.014
Chad	2015	-0.551	-0.049	-0.665	-0.066	-0.585	-0.050	-0.697	-0.067
Colombia	2010	1.650	0.076	1.876	0.068	1.618	0.075	1.845	0.067

Country	Survey year	Without WHO data included				With WHO data included			
		Female		Male		Female		Male	
		Size	Intensity	Size	Intensity	Size	Intensity	Size	Intensity
Comoros	2012	0.362	0.007	0.162	0.018	0.329	0.006	0.125	0.018
Congo Brazzaville	2005	0.943	0.000	0.482	0.009	0.914	-0.001	0.448	0.008
Congo Brazzaville	2011	0.808	0.040	1.101	0.041	0.774	0.039	1.068	0.040
Congo, DRC	2007	-1.499	-0.087	-2.667	-0.099	-1.535	-0.088	-2.710	-0.100
Congo, DRC	2013	-0.839	-0.077	-1.042	-0.065	-0.873	-0.078	-1.078	-0.066
Ivory Coast	2012	0.555	-0.007	0.436	-0.006	0.524	-0.008	0.404	-0.008
Dominican Republic	2002	2.800	0.101	2.909	0.101	2.773	0.100	2.880	0.100
Dominican Republic	2007	3.013	0.091	3.134	0.094	2.987	0.089	3.109	0.093
Dominican Republic	2013	3.150	0.124	3.169	0.120	3.122	0.123	3.140	0.118
Egypt	2000	0.828	0.069	0.798	0.061	0.793	0.069	0.759	0.060
Egypt	2003	1.035	0.070	0.778	0.090	1.001	0.069	0.734	0.089
Egypt	2005	1.380	0.067	1.333	0.075	1.348	0.066	1.296	0.074
Egypt	2008	0.918	0.018	0.567	0.017	0.887	0.017	0.533	0.016
Egypt	2014	2.738	0.063	2.828	0.077	2.713	0.062	2.803	0.076
Eritrea	2002	-1.359	-0.049	-1.145	-0.052	-1.397	-0.050	-1.183	-0.052
Ethiopia	2000	-2.820	-0.100	-2.707	-0.083	-2.861	-0.101	-2.753	-0.083
Ethiopia	2005	-2.105	-0.083	-2.157	-0.088	-2.145	-0.083	-2.198	-0.088
Ethiopia	2011	-1.047	-0.060	-1.058	-0.060	-1.083	-0.061	-1.094	-0.061
Ethiopia	2016	-0.329	-0.014	-0.469	-0.038	-0.364	-0.015	-0.504	-0.039
Gabon	2012	1.850	0.072	1.777	0.068	1.820	0.071	1.745	0.067
Gambia	2013	1.257	0.031	1.761	0.053	1.227	0.030	1.731	0.052
Ghana	2008	0.473	-0.011	0.623	-0.006	0.441	-0.012	0.592	-0.008
Ghana	2014	1.218	0.033	1.393	0.033	1.187	0.032	1.362	0.032
Guatemala	2015	-1.621	-0.005	-1.305	0.008	-1.664	-0.005	-1.353	0.008
Guinea	2012	0.695	-0.005	0.830	-0.015	0.665	-0.007	0.802	-0.016
Guyana	2009	0.869	0.101	0.941	0.112	0.832	0.100	0.895	0.112
Haiti	2000	0.818	0.018	0.336	0.012	0.787	0.017	0.300	0.011
Haiti	2006	0.159	0.034	0.029	0.009	0.123	0.034	-0.008	0.008
Haiti	2012	1.073	0.038	1.289	0.029	1.042	0.037	1.258	0.027
Haiti	2017	1.324	0.059	1.190	0.053	1.292	0.058	1.156	0.052

38

Country	Survey year	Without WHO data included				With WHO data included			
		Female		Male		Female		Male	
		Size	Intensity	Size	Intensity	Size	Intensity	Size	Intensity
Honduras	2006	0.347	-0.005	0.589	-0.014	0.315	-0.006	0.559	-0.015
Honduras	2012	0.739	0.021	0.841	0.027	0.707	0.020	0.807	0.026
India	2006	-1.840	-0.044	-1.344	-0.031	-1.880	-0.044	-1.386	-0.031
India	2015	-0.237	-0.025	-0.038	-0.013	-0.271	-0.026	-0.073	-0.014
Jordan	2002	1.923	0.077	2.493	0.077	1.893	0.076	2.465	0.076
Jordan	2007	2.409	0.034	2.382	0.032	2.384	0.033	2.359	0.030
Jordan	2009	2.780	0.068	3.142	0.053	2.755	0.066	3.122	0.051
Jordan	2012	2.920	0.096	3.012	0.085	2.894	0.095	2.987	0.084
Kenya	2003	0.203	0.007	-0.291	0.005	0.169	0.006	-0.331	0.005
Kenya	2009	-0.166	0.010	-0.047	0.005	-0.202	0.009	-0.085	0.004
Kenya	2014	0.964	0.042	0.582	0.025	0.931	0.041	0.546	0.024
Kyrgyzstan	2012	1.735	0.024	1.676	0.034	1.707	0.023	1.647	0.032
Lesotho	2009	0.041	-0.025	-0.408	-0.040	0.008	-0.026	-0.442	-0.041
Lesotho	2014	0.072	0.011	-0.820	0.013	0.037	0.010	-0.865	0.013
Liberia	2007	-0.432	-0.080	-0.935	-0.056	-0.463	-0.081	-0.971	-0.057
Liberia	2013	0.485	-0.029	0.101	-0.038	0.455	-0.031	0.071	-0.039
Madagascar	2004	-1.909	-0.062	-2.214	-0.061	-1.949	-0.062	-2.259	-0.061
Madagascar	2009	-1.375	-0.058	-1.491	-0.066	-1.413	-0.058	-1.530	-0.067
Malawi	2000	-2.511	-0.086	-2.628	-0.084	-2.552	-0.086	-2.673	-0.084
Malawi	2004	-2.068	-0.077	-2.393	-0.063	-2.107	-0.077	-2.440	-0.063
Malawi	2010	-1.068	-0.014	-1.517	-0.025	-1.107	-0.014	-1.562	-0.025
Malawi	2015	-0.310	-0.022	-0.332	-0.024	-0.345	-0.022	-0.368	-0.024
Maldives	2009	1.205	0.069	1.359	0.099	1.172	0.068	1.319	0.099
Mali	2001	-1.199	-0.050	-1.119	-0.061	-1.236	-0.051	-1.155	-0.062
Mali	2006	-0.407	-0.027	-0.342	-0.023	-0.442	-0.028	-0.378	-0.023
Mali	2012	0.200	-0.065	-0.105	-0.048	0.171	-0.066	-0.135	-0.050
Moldova	2005	3.434	0.058	3.703	0.085	3.412	0.057	3.682	0.083
Morocco	2003	1.701	0.049	1.575	0.027	1.672	0.048	1.547	0.026
Mozambique	2003	-1.671	-0.032	-1.851	-0.037	-1.712	-0.032	-1.897	-0.038
Mozambique	2011	-1.042	0.000	-1.211	0.003	-1.081	-0.001	-1.257	0.003
Myanmar	2016	0.000	-0.017	-0.042	-0.004	-0.033	-0.018	-0.078	-0.005
Namibia	2000	0.410	0.030	0.356	0.007	0.375	0.029	0.322	0.006
Namibia	2007	0.368	0.024	0.216	0.011	0.334	0.023	0.179	0.011
Namibia	2013	1.297	0.037	0.927	0.012	1.267	0.036	0.896	0.011

39

Country	Survey year	Without WHO data included				With WHO data included			
		Female		Male		Female		Male	
		Size	Intensity	Size	Intensity	Size	Intensity	Size	Intensity
Nepal	2001	-2.730	-0.079	-2.091	-0.071	-2.772	-0.080	-2.134	-0.071
Nepal	2006	-1.911	-0.063	-1.343	-0.059	-1.951	-0.064	-1.381	-0.060
Nepal	2011	-1.236	-0.065	-0.599	-0.036	-1.272	-0.065	-0.635	-0.037
Nepal	2016	-0.525	-0.027	-0.129	-0.018	-0.560	-0.028	-0.164	-0.019
Nicaragua	2001	0.603	0.006	0.666	0.012	0.571	0.005	0.633	0.011
Niger	2006	-2.899	-0.103	-3.034	-0.098	-2.941	-0.103	-3.080	-0.098
Niger	2012	-1.151	-0.030	-1.234	-0.033	-1.189	-0.031	-1.275	-0.033
Nigeria	2003	-1.069	-0.029	-1.538	-0.052	-1.107	-0.030	-1.579	-0.052
Nigeria	2008	-1.247	-0.026	-1.783	-0.026	-1.286	-0.026	-1.830	-0.026
Nigeria	2013	-0.269	-0.032	-0.449	-0.045	-0.302	-0.033	-0.482	-0.046
Pakistan	2012	-2.422	-0.061	-2.483	-0.049	-2.464	-0.061	-2.532	-0.048
Pakistan	2018	-0.939	-0.028	-0.593	-0.041	-0.976	-0.028	-0.628	-0.041
Peru	2005	0.094	0.008	0.164	0.016	0.059	0.008	0.126	0.016
Peru	2008	0.241	0.036	0.481	0.035	0.205	0.035	0.443	0.035
Peru	2009	0.561	0.043	0.727	0.046	0.526	0.042	0.689	0.045
Peru	2010	0.483	0.051	0.781	0.061	0.447	0.050	0.742	0.060
Peru	2011	0.812	0.062	1.057	0.065	0.778	0.061	1.020	0.064
Peru	2012	0.823	0.066	1.281	0.065	0.788	0.065	1.245	0.064
Rwanda	2000	-1.156	-0.057	-1.328	-0.086	-1.193	-0.058	-1.363	-0.086
Rwanda	2005	-1.993	-0.061	-1.976	-0.062	-2.034	-0.062	-2.019	-0.062
Rwanda	2010	-1.084	-0.039	-1.086	-0.032	-1.121	-0.040	-1.126	-0.032
Rwanda	2015	-0.530	-0.012	-0.873	-0.013	-0.566	-0.013	-0.915	-0.014
Sao Tome	2008	0.371	0.065	0.082	0.067	0.334	0.064	0.036	0.067
Senegal	2005	1.269	0.012	1.545	0.019	1.240	0.011	1.518	0.018
Senegal	2010	0.944	0.020	0.670	0.001	0.913	0.019	0.638	0.000
Senegal	2013	1.483	0.032	1.371	0.040	1.454	0.031	1.339	0.039
Senegal	2014	1.432	0.040	1.466	0.056	1.402	0.039	1.433	0.056
Senegal	2015	0.980	0.048	1.322	0.040	0.947	0.048	1.290	0.039
Senegal	2016	1.482	0.076	1.501	0.071	1.449	0.075	1.466	0.070
Senegal	2017	1.563	0.062	1.737	0.059	1.532	0.061	1.705	0.058
Sierra Leone	2008	0.270	-0.037	-0.276	0.002	0.239	-0.038	-0.315	0.002
Sierra Leone	2013	-0.739	-0.010	-0.465	0.008	-0.776	-0.011	-0.506	0.007
South Africa	2016	0.668	0.065	0.946	0.048	0.632	0.064	0.910	0.047
Swaziland	2006	0.395	0.020	0.120	0.023	0.361	0.019	0.082	0.023

40

Country	Survey year	Without WHO data included				With WHO data included			
		Female		Male		Female		Male	
		Size	Intensity	Size	Intensity	Size	Intensity	Size	Intensity
Tajikistan	2012	0.092	-0.001	0.718	0.007	0.058	-0.002	0.686	0.006
Tajikistan	2017	1.572	0.011	1.805	0.022	1.545	0.010	1.780	0.020
Tanzania	2004	-1.364	-0.035	-1.348	-0.029	-1.403	-0.036	-1.391	-0.029
Tanzania	2010	-0.991	-0.001	-1.193	-0.035	-1.030	-0.002	-1.234	-0.035
Tanzania	2015	-0.279	0.002	-0.256	-0.008	-0.315	0.001	-0.293	-0.008
Timor-Leste	2009	-2.275	-0.084	-2.471	-0.076	-2.315	-0.084	-2.516	-0.076
Timor-Leste	2016	-0.460	-0.026	-0.567	-0.021	-0.495	-0.027	-0.606	-0.022
Togo	2014	0.435	-0.006	0.500	0.006	0.403	-0.007	0.466	0.005
Uganda	2000	-1.315	-0.019	-1.286	-0.038	-1.355	-0.020	-1.327	-0.039
Uganda	2006	-0.199	-0.012	-0.564	-0.024	-0.234	-0.013	-0.601	-0.024
Uganda	2011	0.004	0.023	-0.321	-0.011	-0.032	0.023	-0.359	-0.012
Uganda	2016	0.711	0.040	0.585	0.016	0.678	0.039	0.550	0.015
Yemen	2013	-1.929	-0.070	-1.690	-0.077	-1.969	-0.071	-1.729	-0.078
Zambia	2002	-2.167	-0.062	-2.130	-0.068	-2.208	-0.063	-2.174	-0.069
Zambia	2007	-0.980	-0.022	-1.427	-0.034	-1.018	-0.023	-1.469	-0.035
Zambia	2013	-0.509	0.002	-0.680	0.003	-0.546	0.001	-0.722	0.003
Zimbabwe	2005	-0.317	0.013	-0.766	-0.002	-0.354	0.013	-0.809	-0.003
Zimbabwe	2010	-0.135	0.023	-0.368	0.001	-0.172	0.023	-0.408	0.001
Zimbabwe	2015	0.498	0.053	0.478	0.037	0.462	0.052	0.440	0.037

Supplemental material

BMJ Publishing Group Limited (BMJ) disclaims all liability and responsibility arising from any reliance placed on this supplemental material which has been supplied by the author(s)

BMJ Global Health

Supplementary File 6: Scatter plot of the differences in the SITAR random effects for size and intensity parameters with versus without inclusion of the mean height of the WHO child growth standards in the multi-country dataset for boys and girls
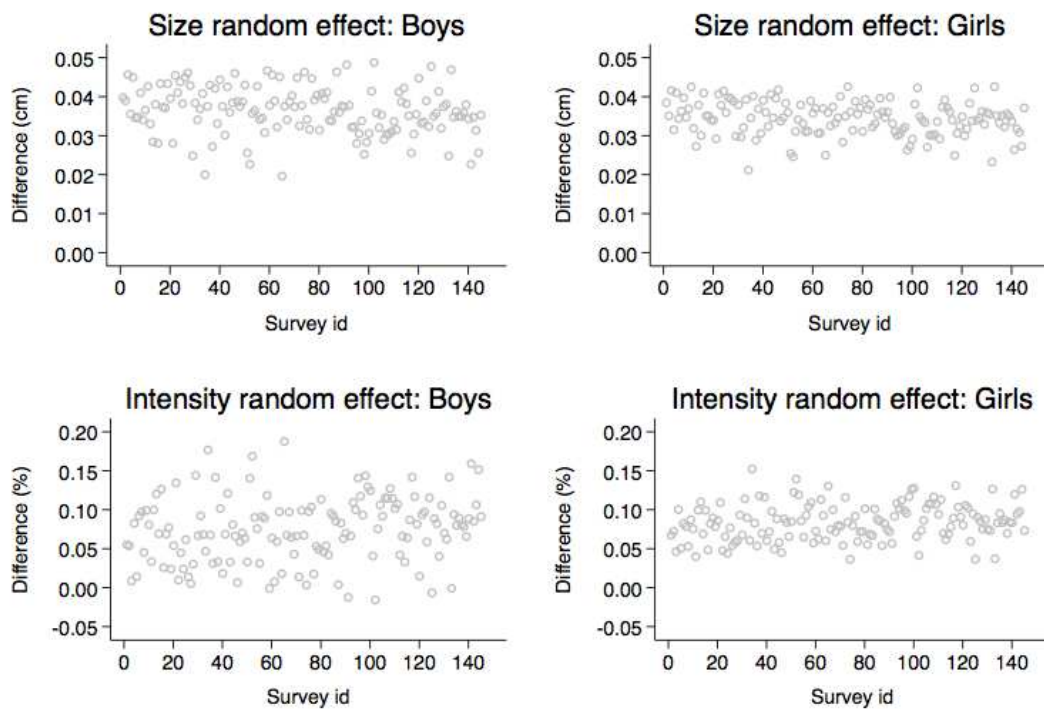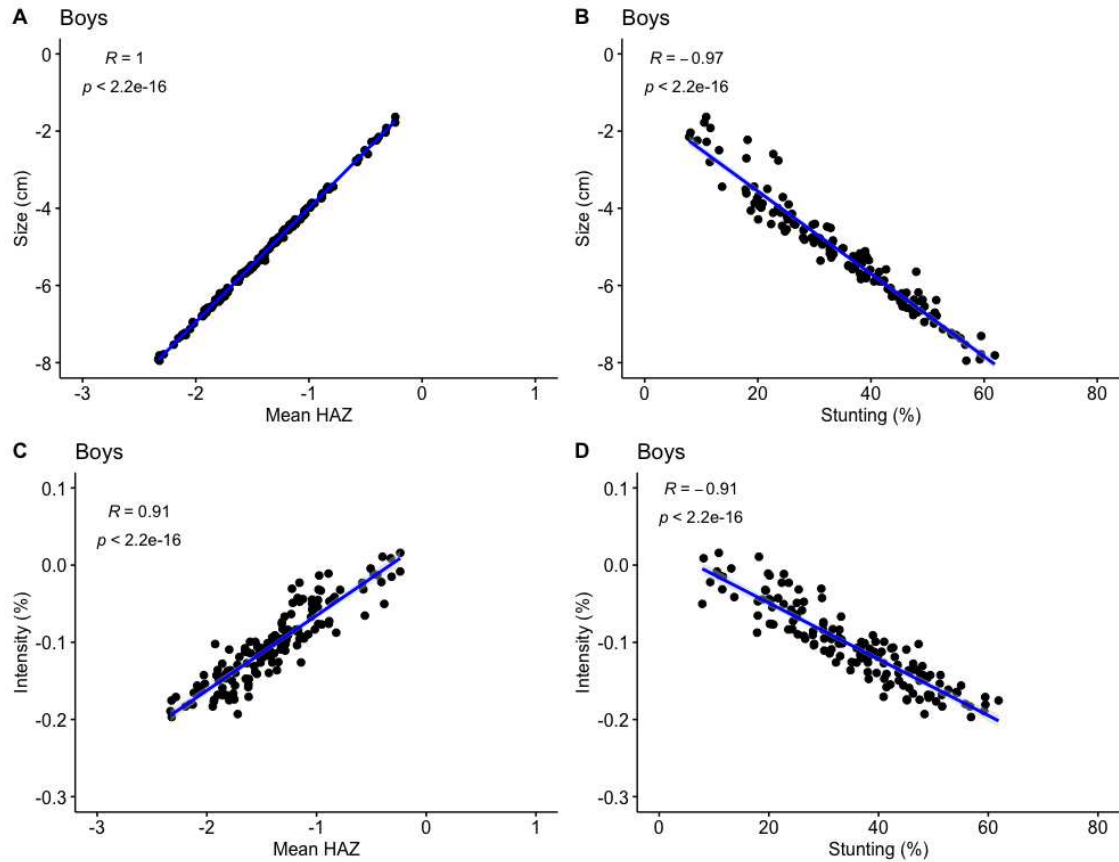

Difference = Without WHO data - With WHO data

42

Supplementary File 7: Scatter plot, correlation, and line of best fit (95% CI; shaded region) between SITAR size and intensity random effects (excluding WHO) for 145 Demographic and Health surveys from 64 countries for boys and girls
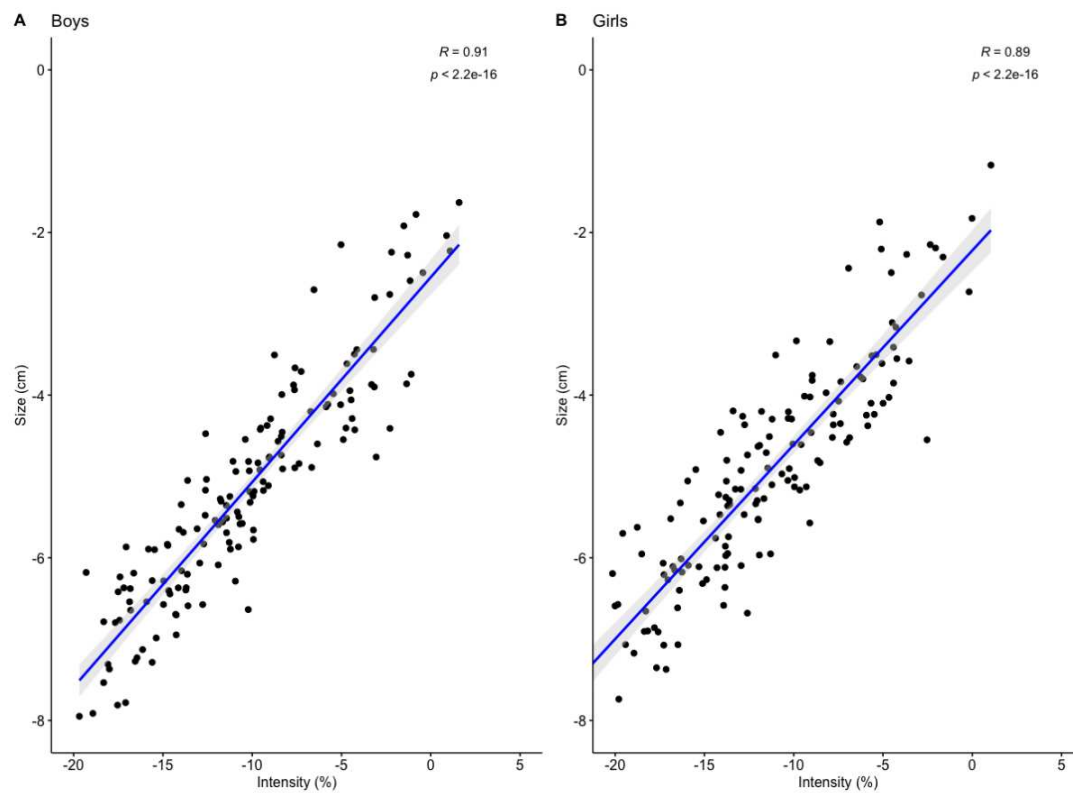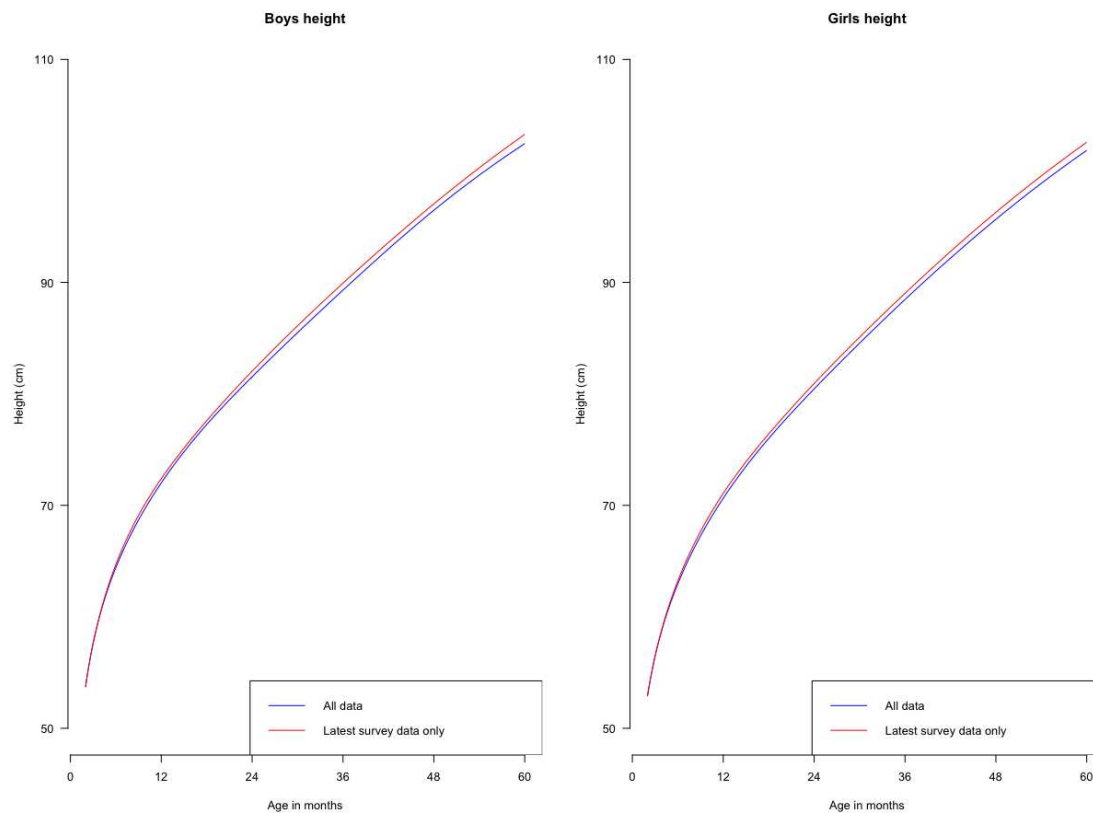
Supplementary File 8: Scatter plot, correlation, and line of best fit (95% CI; shaded region) between SITAR size and intensity random effects (excluding WHO) with stunting prevalence and mean height-for-age z-scores (HAZ) for boys

Supplementary File 9: Scatter plot, correlation, and line of best fit (95% CI; shaded region) between SITAR size and intensity random effects (excluding WHO) with stunting prevalence and mean height-for-age z-scores (HAZ) for girls
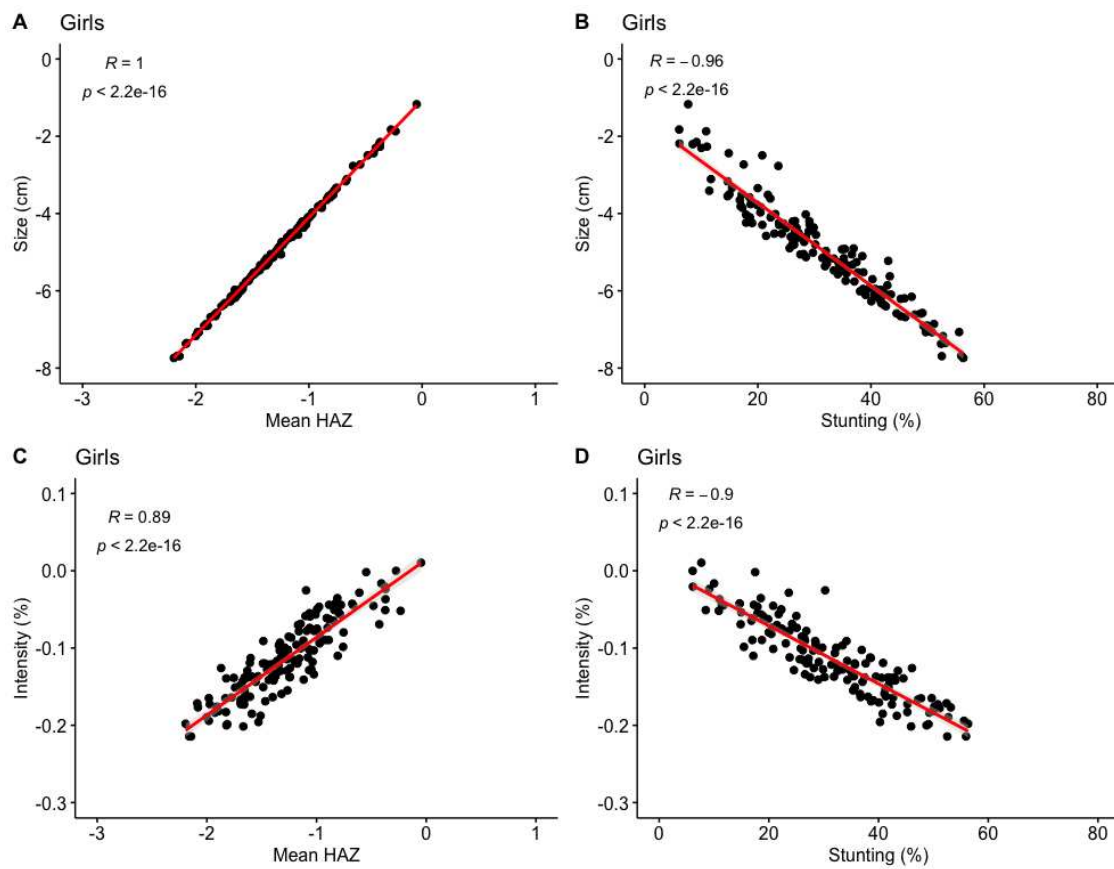
Supplementary File 10: Sensitivity analysis comparing the mean population growth curve using all surveys (n=145 surveys) compared to using only the latest survey in each country (n=64 countries): Boys (left panel) and girls (right panel)

Supplemental material

BMJ Publishing Group Limited (BMJ) disclaims all liability and responsibility arising from any reliance
placed on this supplemental material which has been supplied by the author(s)

BMJ Global Health

Supplementary File 11: A sensitivity analyses of SITAR models fitted to the Demographic Health Survey data of 145 surveys (64 countries) from 2000 to 2018 classified according to the World Bank regions

World Bank region classification	Percentage of variance explained by the fitted SITAR model	
	Boys (%)	Girls (%)
Sub-Saharan Africa (n=83)	70.3	69.0
East Asia and Pacific (n=7)	No convergence	No convergence
Europe and Central Asia (n=10)	No convergence	No convergence
Latin America and the Caribbean (n=21)	80.6	81.8
Middle East and North Africa (n=11)	83.9	80.7
South Asia (n=13)	70.0	71.3

Supplemental material

BMJ Publishing Group Limited (BMJ) disclaims all liability and responsibility arising from any reliance placed on this supplemental material which has been supplied by the author(s)

BMJ Global Health

Supplementary File 12: Correlation and linear regression analyses of the SITAR size and intensity parameters with average starting height from birth to 2-months of age (proxy of fetal growth)

Model specification	Coefficient (95% CI)	Correlation	Adjusted R-squared
Boys			
Postnatal size vs Starting height at 2-months	0.56 (0.36 - 0.76)	0.41	0.165
Postnatal intensity vs Starting height at 2-months	0.67 (-0.11 - 1.44)	0.14	0.013
Postnatal size at 2-months vs Postnatal intensity	0.26 (0.24 - 0.28)	0.91	0.826
Postnatal size vs Starting height at 2-months + Postnatal intensity			
Starting height at 2-months	0.39 (0.32- 0.46)	N/A	0.903
Postnatal intensity	0.25 (0.23 - 0.26)		
Girls			
Postnatal size vs Starting height at 2-months	0.64 (0.41 – 0.86)	0.43	0.177
Postnatal intensity vs Starting height at 2-months	0.84 (-0.04 – 1.72)	0.16	0.017
Postnatal size vs Postnatal intensity	0.24 (0.22 – 0.27)	0.89	0.791
Postnatal size vs Starting height at 2-months + Postnatal intensity			
Starting height at 2-months	0.44 (0.35 – 0.53)	N/A	0.876
Postnatal intensity	0.23 (0.22 – 0.25)		