Original Article

Early growth velocities and weight gain plasticity improve linear growth in Peruvian infants

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Abstract

Growth velocity patterns have the potential to signal unhealthy responses to environmental insults with long-term consequences. We aimed to investigate velocities in Peruvian infants ($n = 259$) in relation to attained anthropometric outcomes at 12 months and to identify determinants of velocities during critical periods of infancy. From 1995 to 1997, a randomised controlled trial of maternal zinc supplementation was conducted in a peri-urban slum area of Lima. Infants were followed monthly through 1 year on a range of anthropometric measures. Three types of velocity variables were studied: (1) *incremental velocity* (1 months and 3 months); (2) *proportional changes* (% of total size gained/month); and (3) *individual velocity variability* [standard deviation (SD) of individual child incremental velocities]. Mean individual child SD of weight velocity was 417 g (± 126). In multivariate ordinary least squares regression analyses, growth velocities in month 1 and individual weight velocity variability positively predicted attained length and weight by 12 months. Panel regression by generalised least-squares with random effects of length and weight velocities confirmed the exponentially decelerating pace of growth through infancy and the importance of birth size in driving this trajectory. This study contributes evidence to support the importance of early growth velocities and greater degrees of weight gain plasticity for attained length and weight.

Keywords: infant, growth velocity, anthropometry, Peru.

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Introduction

Growth velocity may be defined as the rate of change in physical size over a specified time interval. It is biologically driven by both hyperplasia (cell proliferation) and hypertrophy (increases in cell size) arising from endocrine system influences and nutrition pathways (Tanner 1990). Patterns of growth velocity may be interpreted as an early signal of healthy or unhealthy responses to environmental conditions. In recent years, growth velocity has been studied during childhood in relation to later obesity outcomes

(Monteiro *et al.* 2003; Botton *et al.* 2008). This study investigated velocity patterns in a context of under-nutrition, previously studied in Peru (Piwoz *et al.* 1994; Lee *et al.* 2012) and other developing countries (Walker & Golden 1988; Lartey *et al.* 2000; Xu *et al.* 2001; Maleta *et al.* 2003; Dewey *et al.* 2005; Eckhardt *et al.* 2005; Olusanya & Renner 2011; McGrath *et al.* 2012).

Growth velocity patterns are thought to arise from evolutionary processes preserving survival and reproduction (Rosenfeld 2003). The tremendous plasticity of growth in the short term also seems to indicate

adaptive responses to the environment and survival mechanisms (Lampl 2009). Growth retardation that may be associated with infection, for example, is generally followed by periods of 'catch-up' or rapid growth. The alternating periods of deceleration and acceleration return the child to its original growth trajectory, a process referred to as 'canalization' (Prader *et al.* 1963). Considerable evidence supports the health and developmental advantages of early growth during the first 2 years of life, though the pace of growth within particular periods of this time has been studied to a lesser extent (Victora *et al.* 2008). Understanding growth responses during critical periods may allow for early intervention to protect later health and development.

From 1995 to 1997, a randomised controlled trial was conducted in Peru to examine the effects of maternal zinc supplementation on birth outcomes and later offspring morbidity and growth outcomes (Caulfield *et al.* 1999; Iannotti *et al.* 2008, 2010). The anthropometric and body composition measures taken longitudinally during infancy offered an opportunity to undertake the growth velocity analyses for this study. Growth velocities for the Peruvian infants were explored to evaluate temporal aspects of different growth velocities in relation to each other and to attained size at 1 year of age.

Methods

This trial has been described elsewhere (Caulfield *et al.* 1999; Zavaleta *et al.* 2000). Overall, 1295 women living in Villa El Salvador, a peri-urban settlement area of Lima, Peru, were invited to enroll in the study when they initiated prenatal care between 10 and 24 weeks' gestation. The mothers were randomised to

receive treatment (15 mg zinc + 60 mg iron + 250 µg folic acid) or control (iron + folic acid only). In a separate follow-up study of their offspring, 579 infants were enrolled, meeting the criteria of: singleton birth; healthy infant; and residence in the study community (Iannotti *et al.* 2008, 2010). The study was funded for a specific time period, so children enrolled first were followed the longest. Due to inconsistencies in the sample size across analyses, we decided to limit the sample here to those infants completing 10 or more visits ($n = 259$). The excluded infants ($n = 320$) showed small differences compared with those included, in birth length (49.7 ± 1.9 vs. 50.1 ± 2.0 cm, $P = 0.01$), arm muscle area (597.4 ± 99.8 vs. 617.5 ± 109.3 mm², $P = 0.04$) and maternal age (23.8 ± 4.7 vs. 24.9 ± 5.3 years, $P = 0.02$). These variables were examined in all analyses and not found to be associated with outcomes with the exception of birth length, which was negatively associated with length velocity through infancy. Thus, the findings for the birth length effect may represent a slight underestimation. All other characteristics were comparable.

Signed consent for the follow-up study was obtained from mothers after an explanation of the protocol. Approval of this study was granted by the Ethics Committee of the Instituto de Investigación Nutricional, and the Committees for Human Research at The Johns Hopkins Bloomberg School of Public Health and Washington University in St Louis.

Anthropometric measures and other data collected

Anthropometric measures were taken for mothers at enrollment, 28–30 and 36–38 weeks' gestation, and for infants at birth and monthly through age 1 year.

Key messages

- Length and weight velocities in month 1 of life were significant positive determinants of attained growth by age 12 months.
- Higher levels of weight gain fluctuations for individual children throughout infancy enabled greater attained length.
- Accumulation rates of muscle and fat mass were associated with concomitant monthly weight and length gains, respectively.
- Size at birth influenced growth velocity in both weight and length during infancy and attained size at 1 year.

Standard procedures were followed by a trained nutritionist. Weight was collected to the nearest 100 g for mothers and to the nearest 10 g for infants (SECA, Hamburg, Germany). Height was measured with a stadiometer for mothers and recumbent length was measured using a length board, both to the nearest 0.1 cm. For newborns, skinfold thicknesses of the biceps, calf and subscapular region were measured using Lange precision calipers (Cambridge Scientific Instruments, Cambridge, MD, USA), and circumferences of the head, chest, calf and mid-upper arm were measured using a non-stretchable tape. At enrollment, socio-economic and demographic information was collected from mothers on a range of characteristics. For funding reasons, morbidity and infant feeding data were collected primarily during the second half of infancy. Fieldworkers visited households weekly to inquire about any illnesses experienced by infants over the previous week. Morbidities assessed included diarrhoea, respiratory illnesses, skin conditions and fever. Mothers were asked to report which complementary foods infants had received and whether the infant was still breastfed.

A series of standardised variables were created from the information described previously. Length-for-age (LAZ), weight-for-age (WAZ) and weight-for-length (WLZ) were generated and used to define stunting [LAZ < -2 standard deviation (SD)], underweight (WAZ < -2 SD) and wasting (WLZ < -2 SD) [World Health Organization (WHO) 2006]. Two kinds of attained anthropometry indicators were created: size (measure of the infant at each of 12 months); and change in size (measures at 1 year – measure at birth). A newborn weighing <2500 g at birth was classified as low birthweight (LBW), and those weighing less than the 10th percentile for gestational age as small-for-gestational-age (Alexander *et al.* 1996). Fat and muscle areas were derived from formulae incorporating circumferences and skinfold thickness (Frisancho 1981).

Three types of growth velocity markers were generated to be examined as both outcomes and determinants of attained growth. They were the following: (1) *incremental velocities*: monthly (1 month) and quarterly (3 months); (2) *proportional changes* (% of total size at 1 year that was gained/month); and

(3) *individual velocity variability*. *Incremental velocities* were calculated by subtracting size from the previous interval (1 month increment = 1 month – birth; 2 months – 1 month; etc.); (3 months increments = 3 months – birth; 6 months – 3 months). This is a standard approach to measuring velocity (WHO 2009). The exact number of days between intervals was included in panel and ordinary least squares (OLS) regression modelling to adjust for small differences across children in the time interval between measures. Quarterly incremental velocities were assessed in order to compare findings with previous evidence (Dewey *et al.* 2005). *Proportional changes in anthropometry* were calculated by dividing the incremental gain by the attained size variable. *Individual velocity variability* was indicated by the SD of the distribution of an individual child's monthly growth velocities. This indicator allowed for computation of dispersion from mean growth velocity through infancy with consideration of degrees of freedom, or number of growth measures taken on each child. Precision can be high for anthropometric measures of weight and height with proper training and protocols applied (Ulijaszek & Kerr 1999). Weight measures in the same child, however, may fluctuate depending on recent food intake, bowel habits, hydration status and time of day when measurements are taken, though standardised protocols as followed in this study may minimise these risks. To further ensure the precision of the indicator that might arise from missing data, only children with 10 or more measures through infancy were included in the analysis.

Variables reflecting the socio-economic and environmental conditions, infant health and feeding practices, as well as maternal characteristics, were considered as potential determinants of growth velocities and mediating factors in the pathway from velocity to attained size. Principal components analysis (PCA) was used to generate two indexes (Vyas & Kumaranayake 2006; Iannotti *et al.* 2008); one represented household wealth and included housing material, electricity in the home and type of cooking facility used, and the other indicated hygiene and sanitation conditions including type of toilet facility, total number of persons in the household and source of water for the household. Assessment of infant mor-

bidities and diet was undertaken through weekly home visits during which caregivers were asked to report on symptoms (cough, respiratory illness, fever, diarrhoea, appetite and skin conditions) and diet (breastfeeding practices and complementary food consumption) since the last visit. A broad set of variables was developed and examined in these analyses. In particular, longitudinal prevalence of diarrhoea was defined as the number of days with acute diarrhoea (≥ 3 liquid or loose stools in the previous 24 h) divided by the number of days of observation per child (Morris *et al.* 1996). A child was reported to be receiving *complementary foods* if solid foods (cereal, meat or fish, mixed or blended foods, stews, bread or other cereal products, and purees) were reported consumed in addition to breastmilk, and *animal source foods* if meat, fish, eggs or other milks besides breast milk were reported.

Statistics

Variable distributions were first examined and normalised by natural logarithmic transformation as necessary (e.g. skinfold thickness measures). Lowess curves, derived from non-parametric, locally weighted regression, were generated to graphically illustrate the sex-based differences and velocity patterns across anthropometric measures (Cleveland & Devlin 1988). This smoothing technique allowed us to explore the data outside a functional form with few assumptions necessary (Yatchew 1998). Kernel density estimation plots were applied to graphically represent the distribution of individual weight velocity variability. Chi-squared and *t*-tests were applied to statistically compare baseline characteristics of boys and girls.

OLS regression modelling was used to examine growth velocities during infancy as determinants of attained size at 12 months. The intent was to identify intervals showing greater predictive significance for attained size than other intervals. Longitudinal modelling was then conducted with panel regression by generalised least-squares with random effects (Diggle *et al.* 2002; Hamilton 2004). These models allowed us to study influences on growth velocity throughout infancy and partition the within and among individual variances. Functional forms for the age variable

(quadratic, natural logarithm) were considered to provide the best fit for the typical pattern of decelerating growth velocity during infancy. Socio-economic, demographic, dietary pattern and morbidity variables were entered into regression models to develop a comprehensive model of influences on infant growth. The exact age in days of the infant at each monthly follow-up visit was adjusted for in all models. Lagged and concomitant growth associations for different anthropometric measures were explored in the panel regression models. Independent variables that were highly correlated ($r \geq 0.7$) were not included in the same regression model to avoid the problem of collinearity. The full set of covariates was tested in all regression models, and only those found to be significant ($P < 0.05$) or trending towards significance ($P < 0.10$) are presented. Regression diagnostics were also conducted to assess goodness-of-fit for covariates (Hamilton 2004). As this was an intervention trial to study the efficacy of maternal zinc supplementation on birth outcomes and subsequently on infant health, we adjusted all models for allocation to prenatal supplement type. Data analyses were performed with STATA software (version 11.1; StataCorp, College Station, TX, USA).

Results

Baseline characteristics by sex of the infant were shown to be comparable with the exception of gestational age at birth and birth head circumference (Table 1). Male infants were born earlier and with larger head circumferences by 0.44 cm (± 0.12) when compared with female infants. All children were breastfed, and between 85% and 90% were still breastfed at 12 months with no differences observed by sex. Other socio-economic, water and sanitation factors represented in the PCA variables were found to be similar among male and female infants.

Monthly growth velocities in length and weight were normally distributed throughout infancy. The mean individual weight velocity variability throughout infancy was 417 g (± 126), and for length velocity variability was 1.6 cm (± 0.4). The marker, used to indicate plasticity through infancy, was normally distributed; boys, however, showed greater fluctuations

Table 1. Baseline characteristics of Peruvian infants by sex

	Boys* (<i>n</i> = 132)	Girls* (<i>n</i> = 127)	<i>P</i> -value [†]
Gestational age at birth (week)	39.3 (1.9)	39.8 (1.5)	0.01
Birth weight (kg)	3.30 (0.44)	3.27 (0.37)	0.43
Low birth weight (%)	3.8	2.4	0.51
Birth length (cm)	50.1 (2.0)	49.7 (1.8)	0.13
Birth MUAC (cm)	10.0 (0.9)	9.9 (1.0)	0.75
Birth chest circumference (cm)	33.0 (2.0)	32.9 (1.6)	0.81
Birth head circumference (cm)	34.5 (1.5)	34.0 (1.2)	0.003
Birth arm muscle area (mm ²)	612 (105)	599 (108)	0.33
Birth arm fat area (mm ²)	186 (54)	195 (56)	0.24
First-born (%)	47.7	55.1	0.23
Maternal age (years)	24.3 (5.0)	24.2 (5.3)	0.85
Maternal height (cm)	151.8 (4.9)	151.5 (5.5)	0.68
Maternal arm muscle area (mm ²)	3578 (782)	3462 (687)	0.20
Maternal fat muscle area (mm ²)	1758 (587)	1701 (720)	0.49

MUAC, mid-upper arm circumference. *Mean of measure (SD) or percentages. [†]Boys vs. girls, by chi-square or *t*-test.

Fig. 1. Monthly weight velocity plasticity, by sex. Kernel density plots, for boys in the solid line and girls in the dashed line, graphically illustrate the distribution of weight velocity plasticity in the Peruvian sample. Weight velocity plasticity is indicated by the mean SD of individual child monthly weight velocities for infants with 10 or more measures through infancy (*n* = 259).

in weight across infancy than girls by 57 g (95% CI: 27–88, $P < 0.001$) (Fig. 1). Length velocity in one period for an individual child was consistently negatively correlated with the previous period, with estimates ranging from -0.23 to -0.40 ($P < 0.05$). No associations were found for weight velocity, except at month 5 for which the correlation with month 4 was 0.20 ($P < 0.05$).

The shapes of velocity trajectories for length and arm fat area (AFA), and weight and arm muscle area

(AMA), were similar (Fig. 2); velocities in length and AFA, and weight and AMA, also showed significant correlations through infancy ($P < 0.05$). Weight and AMA showed a small increase in velocity between months 1 and 2, followed by a comparable pattern to length and fat area of rapidly decelerating velocity through 8 or 9 months, then a plateau until 1 year. In all four measures, boys grew faster than girls in the first 6 months of life, showing greater differences especially for weight and AMA accumulation. The rate of growth in boys was significantly greater than girls for weight, AMA and length in month 1, and for weight in month 2 and AFA in month 3 ($P < 0.01$). After 6 months, the sex-based curves converge with the exception of AFA that accumulates at a slightly faster rate in girls compared with boys. Girls showed significantly greater growth velocities in month 8 for length and AMA ($P < 0.05$). There were no differences observed between girls and boys in terms of the proportion of total weight or length gained by month. On average, month 1 increases in length were 19.7% of attained length by 12 months, and 16.4% of attained weight by 12 months. During month 1, girls gained 19.4% of their attained length, and 15.7% of attained weight at 12 months, and the corresponding values for boys were 19.7% for length and 17.0% for weight ($P > 0.05$).

Growth velocity in month 1 positively predicted attained length and weight at 12 months of age

Fig. 2. Lowess curves for growth velocities by sex. Patterns of monthly growth rates through infancy are graphically displayed for length (a), weight (b), arm fat area (c) and arm muscle area (d) among boys in solid lines and girls in dashed lines. The patterns are presented using lowess curves derived from non-parametric, locally weighted regression.

(Table 2). Individual weight velocity variability was also found to be strongly and positively associated with attained size. Being female or born LBW was negatively associated with size at 12 months. Maternal height showed a trend towards a positive association with both infant length and weight at 12 months. The socio-economic index indicated that infants from wealthier households were more likely to be taller.

Panel regression models were applied to examine influences in growth velocities throughout infancy (Table 3). Size at birth was a determinant of both length and weight velocities; birth weight showed a trend towards positively predicting monthly weight gains, whereas birth length was negatively associated with monthly length gains. Different functional forms of the age variable, such as the age quadratic for length and the natural logarithm of age for

weight, were found to improve the adjusted R^2 and model fit. Weight velocity positively predicted length velocity in the same month of infancy, and length velocity was significantly associated with weight velocity. Growth in head circumference was positively associated with both length and weight gains, whereas growth in chest circumference was significant only in the weight velocity model. AMA in the same month was positively associated with weight velocity. Child prevalence of diarrhoea in months 10 and 11 was significantly negatively correlated with length at 12 months (Pearson product-moment correlations -0.17 and -0.15 , respectively), but the variable was not significant in the panel regression models. Prenatal zinc treatment was also not significantly associated with monthly growth velocity in either length or weight.

Table 2. OLS regression models for attained length and weight at 12 months ($n = 178$)*

	Regression coefficient	Standard error	P-value	Adj. R^2
Length at 12 months (cm)				0.42
Female child	-0.65	0.29	0.03	
Birth length (cm)	0.61	0.07	<0.001	
Length velocity month 1 (cm)	0.55	0.10	<0.001	
Arm fat area velocity month 1 (mm ² per month)	-0.01	0.002	0.001	
Weight velocity variability (kg per year)	5.00	1.30	<0.001	
Maternal height (cm)	0.05	0.03	0.07	
SES index	0.25	0.14	0.07	
Weight at 12 months (kg)				0.29
Female child	-0.32	0.13	0.02	
Low birthweight	-1.34	0.37	<0.001	
Weight velocity month 1 (kg per month)	0.38	0.16	0.02	
Weight velocity variability (kg per year)	2.64	0.57	<0.001	
Maternal height (cm)	0.02	0.01	0.06	

OLS, ordinary least squares; SES, socio-economic status as indicated by principal components analysis. *Models were adjusted for zinc treatment and exact age of the infant at 1 and 12 months.

Table 3. Panel regression for growth velocities across infancy ($n = 259$)*†

Variables	Regression coefficient	Standard error	P-value	Adj. R^2
Length velocity (cm per month)				0.58
Child exact age at follow-up (month)	-0.64	0.03	<0.001	
Age quadratic (month)	0.04	0.002	<0.001	
Birth length (cm)	-0.03	0.01	0.001	
Weight velocity (kg per month)	1.04	0.07	<0.001	
Head circumference velocity (cm per month)	0.17	0.03	<0.001	
Weight velocity (kg per month)				0.66
Child exact age at follow up (month)	-0.07	0.00	<0.001	
Natural logarithm age (month)	0.17	0.03	<0.001	
Female child	-0.03	0.01	0.01	
Birth weight (kg)	0.02	0.01	0.09	
Length velocity (cm per month)	0.07	0.004	<0.001	
Arm muscle area velocity (mm per month)	0.02	0.01	<0.001	
Chest circumference velocity (cm per month)	0.06	0.003	<0.001	
Head circumference velocity (cm per month)	0.09	0.01	<0.001	

*Generalized least-squares with random effects. †Models adjusted for zinc treatment and exact age of the infant at each monthly interval.

Discussion

This study examined growth velocity in Peruvian infants across measures of size and body composition and their association with attained size at 1 year of age. We found that growth rates during month 1 positively predicted size in weight and length at 1 year of age, and that children with greater individual variability in monthly weight gain achieved greater length

and weight by 12 months. Boys grew more rapidly than girls, but not in proportion to the total incremental gain. Longitudinal modelling of length and weight velocities confirmed an exponentially decelerating pace of growth through infancy. Birth size influenced both growth velocity during infancy and attained size at 1 year of age. Regarding temporality, we found evidence for concomitant growth rather than lagged growth associations among anthropometric measures.

The growth of Peruvian infants and young children has been the subject of previous studies, though velocities have been studied to a lesser extent in this context (Piwoz *et al.* 1994; Marquis *et al.* 1997; Penny *et al.* 2005; Arsenault *et al.* 2008; Roche *et al.* 2011; Lee *et al.* 2012). One earlier study was conducted in another peri-urban slum of Lima with more limited access to safe water and health care than in our setting (Piwoz *et al.* 1994). Investigators also showed that early weight change patterns were predictive of later growth trajectories; infants with slow weight gain during months 1 and 2 were less likely to achieve catch-up growth later in infancy (Piwoz *et al.* 1994). Further, they demonstrated that diarrhoea and fever impaired catch-up growth in months 8 and 9 of infancy. We also found that child prevalence of diarrhoea in months 10 and 11 was associated with reduced length gain during month 12, though this variable was not significant in the panel models. Breastfeeding practices and consumption of animal source foods have been shown in Peru to be important determinants of young child growth (Piwoz *et al.* 1994; Marquis *et al.* 1997; Penny *et al.* 2005; Roche *et al.* 2011). In general, reported breastfeeding practices in these studies were comparable with our population, but our sample had greater access to animal source foods which may have masked any associated growth effects.

Our study revealed important aspects of growth velocity which confirm and build on the findings from previous studies. To begin, the pace of growth during particular periods of infancy matters for later outcomes. A study in Ghana carried out as part of a complementary feeding trial also showed the importance of month 1 velocities for attained weight and length at 1 year (Lartey *et al.* 2000). This study demonstrated the importance of diarrhoea and fever morbidity in negatively impacting both growth velocity and attained size at 12 months, which is also revealed in findings from the Kingston Project in Jamaica (Heikens *et al.* 1993). Month 1 velocities were shown to be important predictors of attained size, in part because proportionally, infants gain more in this month than any other during infancy. Thus, the quantitative effects should be considered together with any physiological explanations for this finding.

We found little evidence for lagged growth effects as revealed in other studies (Dewey *et al.* 2005; Lampl *et al.* 2005). This was likely because our time intervals were longer between measures, concealing and attenuating any lagged growth within the month period. Lampl *et al.* (2005) used 1-week time increments and showed that length growth in US boys was associated with both previous and concomitant weight gain, whereas weight gain among infant girls was coupled with saltatory length growth in the same week (Lampl *et al.* 2005). The study also found that abdominal fat (abdominal-to-suprailiac skinfold) significantly predicted length growth spurts in boys. In our study, although arm fat mass did not correlate with subsequent month length gains, it did show positive associations in the panel regression models for the same month throughout infancy. Similarly, we found that chest circumference growth rate was significant for weight velocity in the same month, but not length velocity. Overall, it may be smaller than monthly time intervals are needed to examine these types of lagged growth effects.

However, Dewey *et al.* (2005) found evidence of lagged growth effects using quarterly intervals. They examined the effects of weight gain preceding length gains in four samples of infants from the United States, Ghana and Honduras, and found that initial weight-for-length and prior weight change over the previous 3 months of infancy correlated with increased length gain in the subsequent 3-month interval. The study also showed that initial skinfold thickness at months 3 and 4 predicted length gain. We repeated these analyses in our sample, but found no evidence of lagged growth effects. Thus, the length of the interval does not explain the difference in our results. It may be, however, that the infants in our Peruvian sample were better off nutritionally at birth, as indicated by the higher birth weights when compared with three of the samples from Ghana and Honduras.

We also explored sex-based differences in the rates and patterns through infancy. We showed that girls and boys follow similar patterns of growth velocities across anthropometric measures (Fig. 2). On an absolute scale, boys grew markedly faster than girls early in infancy, but the differences were no longer signifi-

cant when proportional velocities were compared. In the panel regression models, sex of the child was a significant predictor for weight velocity, but for length velocity, the addition of the weight velocity removed the variance explained by child sex. This suggested that weight velocity was mediating the effects of sex on changes in length in the infants, and highlights the importance of early weight gain regardless of child sex.

We explored relationships between growth velocities and body composition; gains in AFA and length were positively correlated in the same month, while AMA velocities positively predicted weight velocities in the panel regression models. Endocrine influences on early growth may provide the physiological explanation for the positive fat mass-length association. Insulin-like growth factor (IGF)-1 is thought to be the primary driver of fetal and infant growth from late in gestation through 6 months of age, when control of growth is then taken over by the growth hormone (Gluckman & Pinal 2003). In animal models, it is glucose or insulin that controls IGF-1 concentrations, and not amino acids (Oliver *et al.* 1993). Glucose is more readily available from fat tissue than lean muscle, and may therefore enable faster growth rates in these infants. Our panel regression model for monthly weight velocity, in fact, revealed a positive association for arm muscle area velocity. Zinc is also important for insulin metabolism (Ghafghazi *et al.* 1981). We previously showed that maternal zinc was associated with greater attained weight and some body composition outcomes among the Peruvian infants (Iannotti *et al.* 2008). The association of prenatal zinc with infant growth velocities was not evident in these analyses, possibly due to the smaller sample size and lack of power to detect an effect. Size at birth was associated with infant growth velocities in this analysis, but did not differ by prenatal zinc treatment (Caulfield *et al.* 1999).

Variability in individual weight velocity was shown to have a positive influence on attained length and weight. This factor was represented by the mean SD of monthly weight velocities through infancy for each individual child, 417 g (± 126). In terms of magnitude of effect, we applied the regression coefficient from the attained length model to determine that for a

126 g difference (1 SD) in weight velocity fluctuation, there would be a 0.61 cm increase in length at 1 year or 26% of length SD for the Peruvian children. In principle, variability in this indicator can be driven by both gains and losses in weight. In this relatively healthy sample, however, the greater values of the indicator appeared to be driven by increases in weight gain, in month 2 especially, rather than weight loss. Episodic growth is thought to be a purposefully flexible system, responsive to environmental conditions (Lampl 2009). Our data suggest that an overall pattern of larger monthly weight gains leads to greater attained size in weight and length at 1 year of age.

In terms of study limitations, the monthly time interval between when the anthropometric measures were taken in these Peruvian infants could have been problematic in detecting temporal effects or even the variability of growth velocity. Weekly or even daily measures may have helped identify more precise temporal effects (Lampl *et al.* 2005). Another limitation may have been the level of detail for the dietary intake and morbidity data. More comprehensive information about maternal diet and the complementary feeding diet could have yielded more findings with regard to nutritional determinants of growth velocity and on attained size.

This study contributes to the evidence base around growth velocities in a resource-poor context where undernutrition is a prevalent condition (Iannotti *et al.* 2009). Panel data allowed us to examine determinants of growth velocity through infancy, with limited residual confounding. Our research confirms and deepens the understanding about the importance of early growth, in particular, that the pace of growth in month 1 significantly drives attained length and weight by month 12. Further, the work gives evidence for a growth advantage associated with greater weight fluctuations by individual children during infancy. Our findings reinforce that growth processes are complex, arising from an intricate interplay of genetics, biology and environmental conditions (Lampl 2009). The speed and variability with which these processes unfold may be one additional key to understanding later health outcomes.

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Conflicts of interest

The authors declare that they have no conflicts of interest.

Contributions

Conceptualization of the study and design of this analysis was completed by LEC, NZ, CH, ZL and LLI. Data were collected by LEC, NZ, CH, and ZL. Analyses, interpretation and drafting of the paper were undertaken by LLI with contributions from LEC.

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