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Components of height and blood pressure in childhood

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Background In children being taller is associated with higher blood pressure (BP), but few studies have divided height into its components: trunk and leg length. We examined the associations of total height, trunk length and leg length with systolic BP (SBP), diastolic BP (DBP) and pulse pressure (PP) at early childhood and mid-childhood visits, as well as change between the two visits.

Methods We obtained five measures of SBP and DBP at the early childhood visit (N = 1153, follow-up rate = 54%) and at the mid-childhood visit (N = 1086, follow-up rate = 51%) respectively, in Project Viva, a US cohort study. We measured total height and sitting height (a measure of trunk length that includes head and neck) and calculated leg length as the difference between the two. Using mixed models, we adjusted the cross-sectional analyses for leg length when trunk length was the exposure of interest, and vice versa. We also adjusted for maternal race/ethnicity, child age, sex, overall adiposity and BP measurement conditions.

Results At the mid-childhood visit, total height was positively associated with SBP [0.34 (0.24; 0.45) mmHg/cm] but not with DBP [0.07 (−0.003; 0.15)]. In models examining trunk and leg length separately, each was positively associated with SBP [0.72 (0.52; 0.92) and 0.33 (0.16; 0.49) respectively]. In a fully adjusted model with both leg and trunk length, only trunk length remained associated with BP. For a given leg length, a 1-cm increment in trunk length was associated with a 0.63-mmHg (0.42; 0.83) higher SBP and a 0.17-mmHg (0.02; 0.31) higher DBP. For a given trunk length, however, the associations of leg length with SBP [0.13 (−0.03; 0.30)] and with DBP [0.002 (−0.11; 0.12)] were null. These patterns were similar at the early childhood visit.

Conclusions Children with greater trunk lengths have higher BPs, perhaps because of the additional pressure needed to overcome gravity to perfuse the brain.

Keywords Leg length, trunk length, blood pressure, child, longitudinal studies

Introduction

Greater height is correlated with higher blood pressure (BP) in childhood and young adulthood.[1–3] However, the associations of two components of height, trunk (upper body) and leg (lower body) length, with higher BP in childhood have seldom been studied.[4,5] Assessing the importance of each component independent of the other is possible given their moderate correlation.[6] To our knowledge, only one study investigated cross-sectional associations of leg length, but not trunk length, and blood pressure in children.[4,5] This study showed no association of leg length with systolic BP (SBP) or diastolic BP (DBP) in either high- or and low-socioeconomic status Indian adolescents.

A relatively longer trunk length might be associated with higher BP if the distance from the heart to the vertex of the head determines the arterial BP that ensures adequate perfusion of the brain.[7] In adults, the evidence argues against that hypothesis since most studies have shown a null or weak inverse association of trunk length with BP.[6,8–13] Alternatively, longer legs may be associated with higher BP. In adults, however, shorter leg length is associated with a higher BP.[6,8–13] Some studies have shown that shorter leg length could reflect less favourable conditions to attain optimal growth in childhood,[14,15] others have failed to show a similar association.[16–20] Early life factors may have an impact on both early somatic growth and physiological development of arterial structure and function.

Our aim was to examine the associations of components of height and BP at the early childhood and mid-childhood visits in a cohort of relatively privileged US children. We hypothesized that shorter legs and longer trunk would each be associated with higher BP, independent of the other. To our knowledge, this is the first study to assess these associations at two time points in childhood. This allows us to relate change in components of height with change in BP between the early and mid-childhood visits.

Methods

Study population

Project Viva is an ongoing prospective pre-birth cohort study in which we recruited pregnant women between April 1999 and July 2002 at their initial prenatal visit at Harvard Vanguard Medical Associates, a large multispecialty group practice in eastern Massachusetts. Details of recruitment and retention procedures are available elsewhere.[21] All mothers gave informed consent and institutional review boards of participating institutions approved the study. All procedures were in accordance with the ethical standards established by the Declaration of Helsinki. [22]

Of 2128 women who delivered a live infant, 1579 participants were eligible for the early childhood follow-up. Owing to a funding cut, we defined eligibility criteria to set up in-person visits for a smaller group but with a better response rate. Criteria for the early childhood visit eligibility in Project Viva were the availability of the information on maternal prenatal diet and the maternal agreement to enrol their child for follow-up beyond age 6 months.[23] We excluded 28 participants whose gestational age at birth was less than 34 weeks, 32 participants who refused the early childhood follow-up, 145 participants who were lost to follow-up, 102 who completed the early childhood assessment only by mail or phone and those with missing data on blood pressure (N = 97) or anthropometry (N = 22). Thus, our sample size for the analysis of the early childhood outcomes was 1153 mother-infant pairs (follow-up rate = 54%). Compared with the women who delivered a live infant in the study but were not included in this analysis, mothers of the children included in this analysis were more likely to be married or cohabiting at the time of pregnancy (48.7% vs 42.7%) but did not differ in terms of race/ethnicity, education, mean household income, smoking status during pregnancy, parity, pre-pregnancy BMI or offspring birthweight.

We conducted the analyses of the outcomes measured at the mid-childhood visit on a sample of 1086 participants, a subset of the 1116 we saw at that visit (follow-up rate = 51%). A total of 262 children attended the early childhood but not the mid-childhood examination and 195 attended the mid-childhood but not the early childhood examination. We carried out the analysis of change on the 891 participants who attended both examinations.

Data collection

We measured anthropometry and blood pressure at the early and mid-childhood visits [mean age at visit (SD, range): 39.4 (4.6, 33.6–74.7) and 95.5 (10.2, 78.8–131.1) months, respectively]. We have previously reported details of examinations up to the early childhood visit.[23–25]

Exposures. We measured height using a calibrated stadiometer (Shorr Productions, Olney, MD). The research assistant placed the stadiometer on top of a hard, flat seat against a flat door or wall to assess sitting height, a measure of trunk length. Each child was seated upright, as tall as possible, with his or her back against the board, the head in the Frankfort plane, knees directed straight ahead and feet hanging freely. We used total sitting height as a measure of trunk length. We did not measure the height of the neck and head and did not differentiate sitting height above and below the mid arm.We calculated leg length as the difference between standing and sitting heights. Research assistants followed standardized techniques[26] and participated in biannual in-service training to ensure measurement validity (Shorr Productions). Inter-rater and intra-rater measurement errors were well within published reference ranges for all of the measurements (example for height: rater 1, 0.22 cm; rater 2, 0.35 cm; rater 3, 0.19 cm; rater 4, 0.25 cm; and between raters, 0.29 cm).[27] Experienced field supervisors provided ongoing quality control by observing and correcting the measurement technique every 3 months.

Outcomes. Using biannually calibrated Dinamap Pro-100 oscillometric automated monitors (GE Medical Services, Tampa, FL), trained research assistants recorded BP on the child's upper arm up to five times at the early childhood and mid-childhood visits, at 1-min intervals. It has been suggested that compared with auscultation, the oscillometric devices may overestimate SBP and DBP, leading to misclassification of BP status.[28–32] However, in this study, we analysed blood pressure as a continuous variable and did not intend to classify children as hypertensive. Recorded measurement conditions included order of readings, cuff size, limb, body position (sitting, semi-reclining, reclining, standing), and state during measurement (at the early childhood visit: sleeping, quiet awake, active awake, crying; at the mid-childhood visit: still, moving, quiet, talking). We calculated pulse pressure (PP) as the difference between SBP and DBP measurements. Of the 1153 children included in the early childhood analysis, 1003 had 5 measurements of BP, 64 had 4, 25 had 3, 30 had 2 and 31 had 1, for a total of 5437 measurements. Of 1086 children included in the mid-childhood analysis, 1072 had 5 measurements of BP, 6 had 4, 3 had 3, 1 had 2 and 4 had 1, for a total of 5399 measurements.

Confounders and covariates. During pregnancy and at the early and mid-childhood visits, using a combination of questionnaires and interviews, we obtained information about maternal age, race/ethnicity, education, marital status, parity, smoking during pregnancy and household income. We collected information from prenatal medical records on serial pregnancy weights and BP readings, and infant birthweight and delivery date. Mothers reported their pre-pregnancy weight and height and paternal weight and height. We calculated gestational weight gain as the difference between pre-pregnancy weight and the last clinically recorded weight before delivery. We derived gestational age from the last menstrual period or from the second trimester ultrasound if the two estimates differed by >10 days. Based on US national natality data we determined sex-specific birthweight for gestational age z-scores.[33] At the early and mid-childhood visits, we measured children's weights using a calibrated scale (early childhood visit: Seca model 881, Seca Corp, Hanover, MD; mid-childhood visit: Tanita model TBF-300A, Tanita Corporation of America, Arlington Heights, IL). We calculated age- and sex-specific height, weight and BMI percentiles and z-scores using US national reference data.[34] We measured subscapular (SS) and triceps (TR) skinfold thicknesses using Holtain calipers (Holtain, Crosswell, Wales, UK). We calculated the sum of these two thicknesses (SS + TR) to estimate overall adiposity. We measured hip and waist circumferences to the nearest 0.1 cm using a Hoechstmass measuring tape (Hoechstmass Balzer GmbH, Sulzbach, Germany). Mothers reported the number of hours per day the children participated in active play (early childhood visit) or in light/moderate/vigorous activities (mid-childhood visit) for weekdays and weekend days. We calculated change in physical activity as the change of quintile of physical activity between the early and mid-childhood visits.

Statistical analysis

We used linear regression to investigate the adjusted associations of the components of height with sex and race. We did not find any evidence of effect modification by sex or race/ethnicity in the association of the components of height with BP (all *P*-values for interaction terms $\geqslant 0.15$), so we report adjusted rather than stratified analyses. To assess associations of parental and child characteristics with height, trunk length and leg length, we computed Spearman correlations, adjusting for child sex, age at examination and maternal race/ethnicity. To investigate the associations of height, trunk and leg length with BP, we used mixed-effects regression models that incorporated up to 5 BP measurements from each infant in two separate cross-sectional analyses, at the early and mid-childhood visits. We used a compound symmetry variance/covariance matrix in proc mixed (SAS version 9.2, SAS Institute, Cary, NC). All the covariates were fixed effects only, with one random effect for the individual. We tested the assumption of linearity in effects of leg and trunk length by adding quadratic and cubic terms in the models, and found that the linear assumption was reasonable. The choice of the covariates that we included in the analyses was based on the literature, in particular previous reports from Project Viva,[23–25, 35–37] and on the bivariate associations. We adjusted base models for age, sex, race/ethnicity and measurement conditions [child's state, arm, cuff size, body position and indicator for the measurement sequence number (1st through 5th)]. We then successively adjusted for parental anthropometry, child sum of skinfolds and socio-demographic variables. The socio-demographic variables did not significantly contribute to the model nor did they modify the association of the components of height with BP. Consequently, we did not include these variables in the final models.

Several approaches have been used to investigate the associations of components of height with a given outcome. They are illustrated in Supplementary Table 1 (available as Supplementary data at *IJE* online). Some studies have used 'absolute' leg length and trunk length adjusted or not for each other. Other studies have used ratios: the sitting height ratio (trunk to height), the leg-to-trunk, the trunk-to-leg or the leg-to-height ratios, adjusted or not for total height. These ratios are relevant when used in the clinical setting. However, in a regression, the interpretation of the coefficient associated with leg-to-trunk is challenging. Indeed, an increment of BP with an increment of leg-to-trunk can be due to an increase in leg length or a decrease in trunk length. This is why we based our conclusions on models that include 'absolute' leg length and trunk length. In the final models, we adjusted for leg length when trunk length was the exposure of interest, and vice versa. The rationale for this choice is detailed further in the online statistical Appendix 1 (available as Supplementary data at *IJE* online). Previous studies have also adjusted models for the other component of height.[6,38,39]

We performed a sensitivity analysis on the subsample of the 891 children who attended both the early and mid-childhood examinations. Because we found similar results, we present the cross-sectional analyses on the larger early and mid-childhood specific study samples.

To investigate the relations of change in linear growth with change in BP between the two visits, we calculated the change in each of the anthropometric measures between these two ages. We calculated the change in BP as the difference between the mean of the recorded measures at the mid-childhood visit and the mean of the recorded measures at the early childhood visit. We used multivariable linear regression adjusted for change in age, adiposity and physical activity between the two visits. We subsequently adjusted these models for the measure of height, trunk length or leg length at baseline.

Results

Descriptive statistics can be found in Tables 1 and 2. The partial correlations between leg length and trunk length, accounting for age at examination, were 0.31 at the early childhood visit and 0.46 at the mid-childhood visit (Supplementary Table 3, available as Supplementary data at *IJE* online) At the mid-childhoodexamination, boys were taller (129.2 vs 128.5 cm, $P = 0.05$) and tended to have longer legs than girls (60.6 vs 60.1 cm, $P = 0.04$) but trunk length was similar (68.6 vs 68.4 cm, $P = 0.22$). Black children had longer legs (43.5 vs 41.6 cm, $P < .0001$) but shorter trunks (55.3 vs 55.8 cm, $P = 0.03$) at 7 years of age than White children. Blood pressure at the early and mid-childhood visits did not differ by race/ethnicity or by sex (data not shown).

Table 1 Parental and child characteristics at birth and in infancy of the 1153 participants in Project Viva included in the analyses of the early childhood outcomes

Characteristic	Total N	N (%)
Socio-demographic characteristics		
Maternal race/ethnicity (White)	1153	834 (72.3%)
Mother married and/ or cohabitating[a]	1152	1064 (92.4%)
Household income[a] >US$70,000	1064	711 (66.8%)
Mother's education ⩾college graduate	1150	821 (71.4%)
Multiparity	1153	615 (53.3%)
Offspring sex: female	1153	573 (49.7%)
Maternal medical history		
Pre-existing hypertension	1125	17 (1.5%)
Pregnancy induced hypertension	1124	104 (9.2%)
Smoked during pregnancy	1120	120 (10.7%)
	Total N	**Mean (SD)**
Age at enrolment (years)	1153	32.5 (5.1)
Gestational age at delivery (weeks)	1153	39.7 (1.4)
Parental anthropometry		
Maternal pre-pregnancy BMI (kg/m^2)	1149	24.9 (5.1)
Maternal height (cm)	1153	164.1 (7.0)
Gestational weight gain (kg)	1137	15.7 (5.4)
Paternal BMI (kg/m^2)	1103	26.4 (3.9)
Paternal height (cm)	1130	179.3 (7.7)
Child anthropometry at birth		
Birthweight (kg)	1152	3.52 (0.51)
Birthweight for gestational age (z-value)	1152	0.22 (0.95)
Birth length (cm)	676	49.9 (2.0)

SD, standard deviation.
[a]At the early childhood visit.

Based on the magnitude of the correlation coefficients, height, trunk length and leg length at the two visits were not associated with the socio-demographic variables (correlations at the mid-childhood visit in Table 3, correlations at the early childhood visit not shown) but they were weakly associated with maternal pre-pregnancy body mass index (BMI) and paternal BMI ($r = 0.05$ to 0.15), and weakly to moderately with maternal and paternal height ($r = 0.21$ to 0.37). Height, trunk and leg length were positively associated with birthweight and birth length at both ages ($r = 0.19$ to 0.37). We showed weak to moderate cross-sectional associations of child adiposity (SS + TR) with height and trunk length at the two visits ($r = 0.08$ to 0.31) and with leg length at the mid-childhood ($r = 0.21$) but not at the early childhood visit ($r = 0.02$).

Table 4 presents the different models tested. Because model building was similar at both visits and for the three outcomes (SBP, DBP and PP), we show only the

Table 2 Anthropometry and blood pressure at the early and mid-childhood visits and change between the two visits. Data from participants in Project Viva

Measurement	Early childhood visit		Mid-childhood visit		Change between the two visits	
	N	Mean (SD)	N	Mean (SD)	N	Mean (SD)
Age (months)	1153	39.4 (4.6)	1086	95.5 (10.2)	891	55.0 (9.7)
Linear growth						
Height (cm)	1153	97.6 (4.8)	1086	128.8 (7.7)	891	30.8 (6.0)
Trunk length (cm)	1153	55.7 (2.7)	1086	68.5 (3.5)	891	12.7 (2.8)
Leg length (cm)	1153	41.9 (2.9)	1086	60.4 (5.0)	891	18.0 (3.9)
Leg-to-trunk ratio	1153	0.75 (0.05)	1086	0.88 (0.05)	891	0.12 (0.05)
Leg length (% of height)	1153	42.9 (1.5)	1086	46.8 (1.5)	891	3.7 (1.5)
Ponderal growth						
Weight (kg)	1153	15.8 (2.4)	1083	28.9 (7.7)	888	12.6 (5.7)
BMI (kg/m^2)	1153	16.5 (1.5)	1083	17.2 (3.1)	888	0.6 (2.3)
BMI z-score [a]	1153	0.47 (1.04)	1083	0.39 (1.00)	888	−0.09 (0.81)
SS + TR (mm)[b]	1129	16.7 (4.3)	1082	19.9 (10.1)	870	2.7 (7.8)
Blood pressure						
Systolic blood pressure (mmHg)	1153	92.3 (10.6)	1086	94.6 (8.6)	891	1.8 (11.4)
Diastolic blood pressure (mmHg)	1153	58.2 (8.1)	1086	54.4 (5.7)	891	−3.9 (8.7)
Pulse pressure (mmHg)	1153	34.1 (7.5)	1086	40.2 (7.4)	891	5.7 (9.0)

[a]Age- and sex-specific height, weight and BMI percentiles and z-scores use US national reference data.[34]
[b]Sum of subscapular (SS) and triceps (TR) skinfold thicknesses.

results for SBP at the mid-childhood visit. Height, trunk length and leg length were each positively associated with SBP in a model adjusted for age, sex, race and measurement conditions (Table 4, model 1; height: 0.40 mmHg/cm; 95% CI: 0.31, 0.49; trunk length: 0.84; 95% CI: 0.67, 1.01; leg length: 0.41; 95% CI: 0.27, 0.55; estimates are for increments in SBP (mmHg) for every 1-cm increment in height or its components) (Table 4). Additional adjustments for covariates (models 2 to 4), but not adjusting each component of height for the other, resulted in a moderate attenuation of the estimates (Table 4, model 4). In the final model that included both leg and trunk length in order to investigate their independent effects, the association of leg length with SBP was attenuated ($\beta = 0.13$; 95% CI: −0.03, 0.30), but the estimate for trunk length was minimally changed ($\beta = 0.63$; 95% CI: 0.42, 0.83) (Table 4, model 5).

Table 5 presents the fully adjusted cross-sectional models of height, trunk length and leg length with SBP, DBP and pulse pressure at both ages, as well as the association of change in linear growth with change in BP. In the cross-sectional analyses, the associations were fairly similar at both ages, and for all comparisons height and trunk length were associated with the BP outcomes. The associations of height and trunk length with DBP were weaker than the associations of these variables with SBP or PP. For example, at the mid-childhood visit, a 1-cm increment in height was associated with a 0.34-mmHg increment in SBP (95% CI: 0.24, 0.45) vs 0.07 mmHg in DBP (95% CI: −0.003, 0.15).We did not find evidence for an association of leg length with BP at the early or mid-childhood visit. Consistent with the cross-sectional analyses, change in trunk length was positively associated with change in SBP and DBP (Table 5. A 1-cm change in trunk length between the two visits was associated with an increment of 0.68 mmHg (95% CI: 0.25, 1.10) in SBP and 0.40 mmHg (95% CI: 0.08, 0.73) in DBP. We did not find evidence for the association of change in leg length with change in SBP (0.12, 95% CI: −0.22, 0.46), DBP (−0.14, 95% CI: −0.40, 0.12) or pulse pressure (0.26, 95% CI: −0.01, 0.52). Additional adjustment for trunk length or leg length at baseline, i.e. at the early childhood visit, did not materially change the results (data not shown). Change in total height between the two ages was associated with change in SBP (0.38, 95% CI: 0.10, 0.66) and pulse pressure (0.30, 95% CI: 0.08, 0.52) but not in DBP (0.08, 95% CI: −0.14, 0.30) (Table 5).

Discussion

In this study of over 1000 children, we showed that having a longer trunk for a given leg length was

Table 3 Correlations between components of height at the mid-childhood visit and socio-demographic characteristics, parental anthropometry and child adiposity at birth and at the mid-childhood visit, adjusted for child age, sex and maternal race/ethnicity. Data from participants in Project Viva

Characteristic	N	Spearman r		
		Height	Trunk length	Leg length
Socio-demographic variables				
Maternal age at enrolment (years)	1086	0.002	0.02	−0.02
Household income ($ categories)	1020	−0.03	0.03	−0.06
Mother's education (levels of schooling)	1080	−0.05	−0.001	−0.07
Parity	1086	−0.007	−0.03	0.02
Parental anthropometry				
Maternal pre-pregnancy BMI (kg/m^2)	1081	0.10	0.08	0.10
Maternal height (cm)	1086	0.37	0.27	0.35
Gestational weight gain (kg)	1070	−0.01	0.04	−0.04
Paternal BMI (kg/m^2)	1031	0.08	0.06	0.08
Paternal height (cm)	1061	0.31	0.26	0.29
Child's anthropometry at birth				
Birthweight (kg)	1083	0.22	0.19	0.20
Birthweight (z-score)	1085	0.25	0.22	0.22
Birth length (cm)	606	0.31	0.29	0.24
Child's adiposity at the mid-childhood visit				
BMI (kg/m^2)	1083	0.31	0.36	0.21
BMI age- sex-specific z-score	1083	0.31	0.35	0.20
Waist circumference (cm)	1083	0.49	0.46	0.40
Hip circumference (cm)	1073	0.59	0.57	0.47
SS + TR (mm)	1081	0.29	0.31	0.21

associated with a higher BP at the early and mid-childhood examinations. However, we found no evidence that having longer legs for a given trunk length was associated with BP. Consistent with these results, an increase in trunk length between the two visits, but not change in leg length, was associated with increases in SBP and DBP over the same period.

Our results thus suggest that trunk length is associated with BP in children. They are consistent with the 'hydrostatic column of blood hypothesis' formulated by Kahn and colleagues.[7] As demonstrated by Blaise Pascal in 1646, hydrostatic pressure at a given point increases in proportion to the height of a liquid column because of the increasing weight of fluid exerting downward force from above. As a consequence, to ensure adequate perfusion of a child's brain, BP at heart level must exceed the hydrostatic pressure induced by the vertical distance between the heart and the head. The giraffe provides a classic example. Giraffe arterial pressure is a consequence of a baroreceptor-regulated mechanism that results in the generation of sufficient hydrostatic pressure to overcome gravitational effects, and to supply the head with blood at a pressure of about 100 mmHg.[40] To generate this pressure, a giraffe's mean arterial BP is approximately 200 mmHg.[41] If humans are like giraffes (in this feature, anyway) the distance from the heart to the vertex of the head should determine BP level measured at the level of the heart. Thus, trunk length but not leg length should be associated with BP, as our data suggest. It has also been suggested that since the vertical distance between the heart and the head determines BP at heart level, vertex-corrected BP (ie BP corrected for cuff-to-vertex height) might be preferable to customary BPs for standardizing BP during childhood growth. Kahn ***et al***. showed that correction for cuff-to-vertex height reduced the effects of age and height.[7,42]

Our results differ from previous findings that showed an inverse association of leg length with cardiovascular outcomes in cross-sectional studies in adulthood.[6,8–13,43] The Boyd Orr study also suggested that leg length measured in childhood was inversely associated with adult mortality and cardiovascular disease.[11,44] One explanation is that, because leg length is the component of height responsible for

Table 4 Cross-sectional associations between components of height and systolic blood pressure at the mid-childhood visit. Separate multivariable random-effects regression models for each component. Data from participants in Project Viva

		Systolic blood pressure (mmHg)	
Exposure	Model	Estimate[a] (95% CI)	*P*
Height (cm)	1	0.40 (0.31, 0.49)	<.0001
	2	0.42 (0.31, 0.52)	<.0001
	3	0.34 (0.24, 0.45)	<.0001
	4	0.36 (0.25, 0.47)	<.0001
Trunk length (cm)	1	0.84 (0.67, 1.01)	<.0001
	2	0.84 (0.65, 1.03)	<.0001
	3	0.68 (0.49, 0.87)	<.0001
	4	0.72 (0.52, 0.92)	<.0001
	5	0.63 (0.42, 0.83)	<.0001
Leg length (cm)	1	0.41 (0.27, 0.55)	<.0001
	2	0.37 (0.20, 0.53)	<.0001
	3	0.30 (0.14, 0.46)	<.0001
	4	0.33 (0.16, 0.49)	0.0002
	5	0.13 (−0.03, 0.30)	0.12

[a]Increment in BP for each 1-cm increment in height component.

Model 1: adjusted for age, sex, race and measurement conditions (state, arm, cuff size, body position, indicator for the sequence number (1st through 5th)), N = 1086.

Model 2: model 1 + maternal and paternal height and BMI, N = 1028.

Model 3: model 2 + sum of SS + TR skinfold thickenesses measured at the mid-childhood visit, N = 1023.

Model 4: model 3 + maternal education, marital status and household income at the mid-childhood visit, maternal smoking during pregnancy, parity, N = 976.

Model 5: model 3 +the other component of current height (leg length for trunk length and vice versa), N = 1023.

the greater part of pre-pubertal height growth, relatively long legs in childhood could indicate better childhood circumstances.[45] It has also been suggested that the trend to increasing height is due almost entirely to an increase in leg length during the first 2 years of life, whereas sitting height changed very little.[46] Studies mostly showed a null or a weak inverse association of trunk length with cardiovascular outcomes. However, authors of the Boyd Orr study mentioned that their sample size was relatively small, limiting their power to detect small but possibly biologically important associations.[47] In addition, the context of these studies was very different from our study of relatively privileged children which probably explains in part these discrepancies. We suggest that whereas the hydrostatic hypothesis, a fundamental principle in physics, applies universally, the inverse association of leg length with BP could be observable only in settings where the early nutritional or emotional environment was not adequate.[14,15] Mothers included in our study were relatively well educated and the large majority had household incomes well above the poverty line. Our results might thus not be generalizable to other settings. The relative lack of children of low socioeconomic status in our cohort might mask any association of shorter legs with higher BP and prevented further stratification on socioeconomic status. Contemporary studies in populations with lower socioeconomic status could shed light on these discrepancies.

We analysed blood pressure in early to mid- childhood. Although BP at later pre-pubertal ages tracks better to adulthood, BP even at these ages is a reasonable predictor of later BP.[48] It is possible that the associations between components of height and BP change after puberty. In particular, early pubertal timing is associated with reduced adult height and leg length.[49] Follow-up of the children in Project Viva will allow investigation of these associations.

The strengths of this study include prospectively collected longitudinal data beginning in early pregnancy, detailed assessment of demographic, socioeconomic and biological family and child characteristics, and research standard measurements of both components of height and childhood BP. Within-person variability of BP is particularly high in childhood,[50] and we have previously highlighted the importance of measuring BP multiple times in epidemiological studies of children.[29,36] The use of the oscillometric devices rather than the sphygmomanometer has both advantages and disadvantages. Although not the gold standard in epidemiological studies in adults, oscillometric devices minimize observer bias, avoid the hazards of a mercury column, reduce the study's dependence on technicians with good hearing and require less training.[29–32] The only validation study of the oscillometric device we used (Dinamap Pro 100 Vital Signs Monitor) has been performed in middle-aged and older persons.[51] However, a study in healthy young persons, using the same device, showed good reproducibility.[52] Measurement variability was mostly due to the device and can be largely reduced when several measurements are performed as in the present study. Our findings should be cautiously interpreted as related only to oscillometric measurements. Future studies could assess whether similar associations are found using the conventional sphygmomanometer.

Limits of this study pertain to its observational nature. Results can be impeded by attrition, confounding and other biases.[53] We accounted for many potential confounders in the analysis but we cannot exclude residual confounding. We carried out a sensitivity analysis using multiple imputation in order to assess the impact of attrition, but the results were not materially changed (results not shown). For practical reasons, we had to assume that total height and sitting height provide sufficient information to

Table 5 Cross-sectional associations of the components of height with blood pressure at the early childhood visit (N = 1076) and the mid-childhood visit (N = 1023), and associations of change in height, trunk length or leg length with change in blood pressure between the early and mid-childhood visits (N = 774). Data from participants in Project Viva

	Systolic blood pressure (mmHg)		Diastolic blood pressure (mmHg)		Pulse pressure (mmHg)	
Exposure	Estimate (95% CI)	*P*	Estimate (95% CI)	*P*	Estimate (95% CI)	*P*
Linear growth and its components at the early childhood visit[a]						
Height (cm)	0.37 (0.20, 0.53)	<.0001	0.13 (0.008, 0.26)	0.04	0.24 (0.12, 0.36)	0.0001
Trunk length (cm)	0.59 (0.34, 0.85)	<.0001	0.26 (0.07, 0.46)	0.01	0.36 (0.17, 0.55)	0.0002
Leg length (cm)	0.12 (−0.14, 0.39)	0.37	−0.01 (−0.21, 0.19)	0.92	0.11 (−0.09, 0.31)	0.30
Linear growth and its components at the mid-childhood visit[b]						
Height (cm)	0.34 (0.24, 0.45)	<.0001	0.07 (−0.003, 0.15)	0.06	0.27 (0.18, 0.36)	<.0001
Trunk length (cm)	0.63 (0.42, 0.83)	<.0001	0.17 (0.02, 0.31)	0.02	0.46 (0.28, 0.64)	<.0001
Leg length (cm)	0.13 (−0.03, 0.30)	0.12	0.002 (−0.11, 0.12)	0.97	0.13 (−0.01, 0.27)	0.07
Change in linear growth and its components between the early and mid-childhood visits[c]						
Height (cm)	0.38 (0.10, 0.66)	0.01	0.08 (−0.14, 0.30)	0.47	0.30 (0.08, 0.52)	0.01
Trunk length (cm)	0.68 (0.25, 1.10)	0.002	0.40 (0.08, 0.73)	0.02	0.27 (−0.06, 0.61)	0.11
Leg length (cm)	0.12 (−0.22, 0.46)	0.49	−0.14 (−0.40, 0.12)	0.30	0.26 (−0.01, 0.52)	0.06

[a]Associations with BP measured at the mid-childhood visit.
[b]Associations with BP measured at the mid-childhood visit.
[a, b]Estimate is increment in BP for each 1-cm increment in height component.Estimates are adjusted for age, sex, race, measurement conditions, parental anthropometry, child's current SS + TR (similar to model 3 in Table 4) when the outcome is height, and additionally adjusted for the other component of height when the outcome is trunk or leg length (similar to model 5 in Table 4).
[c]Association with change in BP between the early and mid-childhood visits. Estimate is increment in change in BP for each 1-cm increment of change in height component. Estimates are adjusted for number of months, change in sum of subscapular and triceps skinfolds thickness and change in physical activity between the early and mid-childhood visits.

partition stature into trunk and leg length. We estimated leg length from total minus sitting height. As a consequence, measurement error in leg length (and change in leg length) is greater than that in trunk length because it includes measurement error both in trunk length and in height. Thus even if the associations between leg or trunk length and BP were equal, the estimated association between trunk length and BP would appear greater as the association with leg length would be more biased towards the null. This may in part explain the lack of association of leg length with BP in our study. Although we did not assess measurement error in sitting height at the early and mid-childhood visits, assessing measurement error in trunk length in future studies might shed light on how much of the difference in size of coefficients is likely to be due to measurement error. It has also been suggested that buttock fatness may lead to underestimation of leg length in the very subjects who have higher BP.[54] We assessed this possibility by including different measures of adiposity—in particular the sum of the subscapular and triceps skinfolds, and hip circumference—in the multivariable models and found similar results (data not shown). Although this bias is probably more of an issue in adult populations with severe overweight and obesity, we cannot exclude the existence of measurement error due to variability in buttock fat in our sample of pre-pubertal children. Future studies should consider using direct measures of leg length or record measurement error in sitting height.

Our data suggest that the distance from the heart to the top of the head may be the component of height most pertinent to BP level measured in the brachial artery. Yet, in our data, the change in BP between the two visits was rather small, given the fact that on average trunk length increased by 12.7 cm during this period. To further evaluate the hydrostatic contribution of the blood column, future studies in children could separate total stature into three components: sitting height above the mid arm, sitting height below the mid arm and leg length.

In conclusion, children with greater trunk length had higher BP, perhaps because of the need to overcome gravity to perfuse the brain. After taking trunk length into account, we found no evidence for an association of leg length with BP.

Supplementary Data

Supplementary data are available at *IJE* online.

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Conflict of interest: None declared.

KEY MESSAGES

- Height is positively associated with blood pressure (BP) in children, which itself predicts BP in adulthood.
- We show that, in a cohort of relatively privileged US children, those with greater trunk length (which includes head and neck) had higher BP at the early and mid-childhood visits. However, after taking trunk length into account, we found no evidence for an association of leg length with BP.
- Our data suggest that trunk length rather than leg length may explain the positive association of height with BP in childhood.
- To ensure adequate perfusion of a child's brain, BP at heart level must exceed the hydrostatic pressure induced by the vertical distance between the heart and the head. This distance may be the component of height that best predicts BP at heart level.

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