Associations between birth size and later height from infancy through adulthood: An individual based pooled analysis of 28 twin cohorts participating in the CODATwins project

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Background: There is evidence that birth size is positively associated with height in later life, but it remains unclear whether this is explained by genetic factors or the intrauterine environment.

Aim: To analyze the associations of birth weight, length and ponderal index with height from infancy through adulthood within mono- and dizygotic twin pairs, which provides insights into the role of genetic and environmental individual-specific factors.

Methods: This study is based on the data from 28 twin cohorts in 17 countries. The pooled data included 41,852 complete twin pairs (55% monozygotic and 45% same-sex dizygotic) with information on birth weight and a total of 112,409 paired height measurements at ages ranging from 1 to 69 years. Birth length was available for 19,881 complete twin pairs, with a total of 72,692 paired height measurements. The association between birth size and later height was analyzed at both the individual and within-pair level by linear regression analyses. Results: Within twin pairs, regression coefficients showed that a 1-kg increase in birth weight and a 1-cm increase in birth length were associated with 1.14–4.25 cm and 0.18–0.90 cm taller height, respectively. The magnitude of the associations was generally greater within dizygotic than within monozygotic twin pairs, and this difference between zygosities was more pronounced for birth length.

Conclusion: Both genetic and individual-specific environmental factors play a role in the association between birth size and later height from infancy to adulthood, with a larger role for genetics in the association with birth length than with birth weight.

1. Introduction

Height is inversely related to all-cause mortality but shows heterogeneous relationships with cause-specific morbidity and mortality [1–3]. For example, there is a well-established association with incidence of cardiovascular diseases (CVD) [1,3]; shorter individuals both in childhood and adulthood have a higher risk of coronary heart disease [4–6]. In contrast, taller people are at a greater risk of death from several specific cancers [3,7]. Epidemiological studies have shown a positive association between size at birth (i.e. birth weight or birth length) and height in childhood [8], adolescence [9,10] and adulthood [11–13]. Similar findings have been observed in studies restricted to children of low birth weight or born small for gestational age [14–16]. The mechanisms underlying this association are, however, still poorly understood. One explanation involves the critical role of intrauterine environment in childhood growth [17,18], but it is unclear to what extent the associations between birth size and later height reflect early developmental factors in the intrauterine environment or whether they are explained by common genetic factors affecting body size already in fetal life.

Twins provide a natural experimental design that offers an opportunity to shed light into the mechanisms underlying the association between birth size and later height [19,20]. Twins come from the same family, share the same maternal environment, have the same gestational age, and in the case of monozygotic (MZ) twins, they share the same genomic sequence, whereas dizygotic (DZ) twins share, on average, 50% of genes identical-by-descent. However, each fetus has its own fetoplacental environmental conditions, such as supply of nutrients and oxygen, which may differ substantially from that of its co-twin [21]. The association between the intra-pair differences in birth size and intra-pair differences in later height cannot be attributed to shared family factors, such as maternal nutrition, smoking during pregnancy, parental education or socio-economic status. Further, differences within MZ pairs cannot be attributed to genetic factors. The comparison of intra-pair associations in MZ and DZ twins is, thus, a strong design to distinguish within-family effects, that is, the non-shared environment and genetic differences between co-twins. Differences in birth size and later height within MZ pairs can only be influenced by environmental factors that are unique to individuals (i.e. the individual-specific intrauterine environment), while differences within DZ pairs can also be
influenced by genetic factors [19,20]. Thus, a stronger association within DZ than MZ twin pairs is taken as evidence that the relationship between birth size and later height is explained, at least in part, by genetic factors [19].

Twin studies in late adolescence and adulthood have shown that intra-pair differences in birth size are positively associated with intra-pair differences in later height [22–27]; i.e. the heavier or longer co-twin at birth will also be the taller one later in life. These associations between birth size and height were generally greater in DZ than in MZ twins, suggesting that both the individual-specific intrauterine environment and genetic factors are involved [23–26]. However, it is not known whether these effects vary in their importance by sex or age, particularly in childhood. Moreover, studies in singletons have shown that height is more strongly associated with birth length than with birth weight [12,13], suggesting that part of the association with birth weight is driven by birth length. Whether these associations are differently affected by genetic and environmental factors is not clear [24,26]. To address these questions, we analyzed the association between birth size (weight, length and ponderal index (PI)) and later height from infancy to adulthood in MZ and DZ twins of both sexes, at both the individual and within-pair level, in a multinational database of 28 twin cohorts from 17 countries.

2. Material and methods

2.1. Sample

This study is based on the data from the Collaborative project of Development of Anthropometrical measures in Twins (CODATwins), which aims to pool data from all twin projects in the world with information on height and weight [28]. Information on birth weight and length was available in 28 and 15 cohorts, respectively. The participating twin cohorts are identified in Table 1 (footnote) and were previously described in detail [28,29].

In the original database, there were 124,475 twin individuals with information on birth weight and later height measurements from ages 1 to 69 years. After excluding 80 individuals with extreme birth weight of $<0.5$ or $>5$ kg, there were 124,395 individuals with a total of 378,796 height measurements throughout the life course. Age was classified to single-year age groups from age 1 to 19 years (e.g. age 1 refers to 0.5–1.5 years range) and one adult age group (20–69 years); height measurements at ages $\geq70$ years were excluded because individuals in old age are more likely to develop osteoporosis leading to shorter height. Implausible values and outliers were checked by visual inspection of histograms for each age and sex group and were removed (<0.2% of the measurements) to obtain an approximately normal distribution, resulting in 378,284 measurements. To confirm that all analyses are based on independent observations, we selected one height measure per individual in each age group by keeping the measurement at the youngest age (removing 10% of the measurements), which left 339,097 observations from 124,041 individuals. We next excluded unmatched pairs (without data on their co-twins) resulting in 156,084 paired observations. Because of the effects of sex differences within pairs on both birth size and height, opposite-sex dizygotic twin pairs were excluded (43,409 paired observations). Intra-pair differences in birth weight and later height were checked by visual inspection of histograms; we removed extreme intra-pair differences (implausible values/outliers) of birth weight $>1.7$ kg (92 paired observations) and

| Table 1 |
| Descriptive statistics of birth size and later height by zygosity, age and sex. |
| Males | | | Fema | | |
| MZ | N | Mean | SD | N | Mean | SD | N | Mean | SD |
| Birth weight (kg) | 20,804 | 2.53 | 0.55 | 20,124 | 2.61 | 0.57 | 23,240 | 2.42 | 0.53 | 19,536 | 2.52 | 0.55 |
| Birth length (cm) | 10,720 | 46.9 | 3.49 | 10,172 | 47.4 | 3.49 | 10,510 | 46.3 | 3.49 | 8360 | 46.8 | 3.46 |
| Ponderal index (kg/m$^3$) | 10,594 | 24.4 | 3.05 | 10,034 | 24.5 | 3.07 | 10,378 | 24.3 | 3.24 | 8218 | 24.5 | 3.22 |
| Height (cm) | | | | | | | | | |
| Age | N | Mean | SD | N | Mean | SD | N | Mean | SD | N | Mean | SD |
| 1 | 2098 | 127.6 | 6.24 | 1598 | 129.1 | 6.47 | 2190 | 127.0 | 6.39 | 1352 | 127.9 | 6.74 |
| 2 | 2002 | 133.0 | 6.94 | 1566 | 134.0 | 6.93 | 2044 | 132.0 | 6.88 | 1352 | 133.7 | 7.06 |
| 3 | 3986 | 151.1 | 8.18 | 3122 | 152.2 | 7.76 | 4204 | 152.2 | 8.04 | 3078 | 153.0 | 8.10 |
| 4 | 1294 | 158.0 | 9.40 | 1150 | 158.4 | 9.24 | 1306 | 157.4 | 7.41 | 956 | 158.6 | 7.92 |
| 5 | 2168 | 165.5 | 8.99 | 1956 | 166.0 | 8.79 | 2556 | 161.9 | 6.68 | 2010 | 162.6 | 6.76 |
| 6 | 1334 | 172.2 | 8.43 | 1192 | 172.5 | 8.46 | 1318 | 165.0 | 6.83 | 1100 | 164.7 | 7.00 |
| 7 | 1660 | 175.9 | 7.54 | 1596 | 176.2 | 7.48 | 2066 | 164.5 | 6.47 | 1774 | 165.4 | 6.59 |
| 8 | 1872 | 178.0 | 7.27 | 1950 | 178.2 | 7.01 | 2524 | 165.7 | 6.57 | 2040 | 166.3 | 6.41 |
| 9 | 2028 | 179.1 | 6.89 | 1696 | 179.2 | 6.76 | 1382 | 166.5 | 6.54 | 1144 | 166.6 | 6.58 |
| 10 | 814 | 179.3 | 6.90 | 780 | 180.3 | 6.87 | 996 | 166.4 | 6.56 | 738 | 168.0 | 6.40 |
| 11–19 | 5290 | 178.6 | 6.89 | 4220 | 179.6 | 6.57 | 6860 | 164.2 | 6.40 | 5006 | 165.2 | 6.26 |

Names list of the participating twin cohorts in this study: Australian Twin Registry, Boston University Twin Project$^a$, Carolina African American Twins Study of Aging, Child and Adolescent Twin Study in Sweden$^a$, Colorado Twin Registry, East Flanders Prospective Twin Survey, FinnTwin12$^a$, FinnTwin16$^a$, Gemini Study$^a$, Guinea-Bissau Twin Study$^a$, Hungarian Twin Registry, Italian Twin Registry$^a$, Japanese Twin Cohort$^a$, Korean Twin-Family Register, Longitudinal Israeli Study of Twins, Michigan Twins Study, Minnesota Twin Family Study, Minnesota Twin Registry, Mongolian Twin Registry, Norwegian Twin Registry, Peri/Postnatal Epigenetic Twins Study$^a$, Qingdao Twin Registry of Children, Quebec Newborn Twin Study$^a$, Swedish Young Male Twins Study of Adults$^a$, Swedish Young Male Twins Study of Children$^a$, Twins Early Developmental Study$^a$, West Japan Twins and Higher Order Multiple Births Registry$^a$ and Young Netherlands Twin Registry$^a$. All twin cohorts were used in the analyses on the association between birth weight and later height (total sample). $^a$Twin cohorts used in the analyses involving birth length. MZ, monozygotic twins; DZ, dizygotic twins.
height in each age group (179 paired observations). Taken together, we had 224,818 observations (112,409 paired observations), 55% MZ and 45% same-sex DZ, from 83,704 twin individuals (41,852 complete twin pairs). For analyses of birth length, we additionally removed twins without information on birth length (43,487 individuals), birth length < 25 or > 60 cm (25 individuals), unmatched pairs (410 individuals) or intra-pair difference in birth length > 12 cm (10 twin pairs), resulting in 72,692 paired observations (19,881 complete twin pairs). Finally, we calculated PI [weight (kg)/height (m^3)] as a measure of relative weight at birth; we additionally removed those individuals with PI < 12 or > 38 or intra-pair difference in PI > 15 kg/m^3 resulting in 71,881 paired observations (19,612 complete twin pairs).

All participants were volunteers and they or their parents gave informed consent when participating in their original studies. A limited set of observational variables and anonymized data were delivered to the data management center at University of Helsinki. The pooled analysis was approved by the ethical committee of Department of Public Health, University of Helsinki.

2.2. Statistical analyses

Statistical analyses were conducted using the Stata statistical software package (version 12.0; StataCorp, College Station, Texas, USA). First, all height measurements were adjusted for exact age within each age and sex group using linear regression (height was used as the dependent variable and age as a continuous independent variable) and the resulting residuals were used as the input variables for the following analyses. Since all analyses were carried out separately for birth weight,

![Fig. 1. Regression coefficients with 95% confidence intervals for the associations between birth size and later height, with monozygotic (MZ) and dizygotic (DZ) twins treated as individuals (individual level). Birth size (weight, length or PI) was used as the explanatory variable, height as the outcome, and birth year and twin cohort as additional regressors. For birth weight and length, associations are significant at p < 0.001 with the following exceptions (**p < 0.01, *p < 0.05): a (MZ6**), b (DZ9**), c (DZ13*, DZ14**), d (DZ6**, DZ9*). For birth PI, p-values are provided in Appendix Table 7.](image-url)
length and PI, in the description of the methods we refer to birth size for simplicity.

Even though the primary focus is on within-pair analyses, we studied the association between birth size and height residuals at both the individual and within-pair level for comparison. At the individual level, linear regression models for each age, sex and zygosity group were used with birth size as the explanatory variable and height residuals as the outcome. Associations were adjusted for birth year and twin cohort (treated as continuous and categorical variables, respectively). The non-independence within twin pairs was taken into account by using the cluster-option available in Stata [30]. This method takes into account that twin pairs rather than independent individuals are sampled and accordingly corrects the standard errors to be larger because of the less informative sample design. For the within-pair analyses, intra-pair differences in birth size were calculated by randomly subtracting the twin with the smallest size at birth from the co-twin with the largest size at birth or vice versa; the twin order was the same for the calculation of intra-pair differences in later height. This guarantees an approximately normal distribution of the new variables. We then performed linear regression models for each age, sex and zygosity group with intra-pair birth size difference as the explanatory variable and intra-pair height residuals difference as the outcome. The associations were also adjusted for birth year and twin cohort. Next, we ensured that the regression lines passed through the origin by checking that the intercept was not different from zero.

An interaction analysis was performed to investigate whether zygosity influenced the associations between birth size and height residuals by introducing a product term of zygosity and birth size (weight or length) into the regression model. At the individual level, linear regression models for each age and sex group were used with height

![Fig. 2. Regression coefficients with 95% confidence intervals for the associations of intra-pair differences in birth size with intra-pair differences in later height, in monozygotic (MZ) and dizygotic (DZ) twin pairs (within-pair level). Intra-pair birth size (weight, length or PI) difference was used as the explanatory variable, intra-pair height difference as the outcome, and birth year and twin cohort as additional regressors. For birth weight and length, associations are significant at \( p < 0.001 \) with the following exceptions (**\( p < 0.01 \), *\( p < 0.05 \), #NS): a (DZ13**, DZ15#), b (DZ12**, DZ13*), c (MZ14**, MZ15**, DZ15**), d (DZ6**, DZ13**). For birth PI, p-values are provided in Appendix Table 7.](attachment://image.png)
residuals as the outcome, and birth size, zygosity, the product term of zygosity and birth size, birth year and twin cohort as the regressors. At the within-pair level, linear regression models for each age and sex group were performed with intra-pair height difference as the outcome, and intra-pair birth size difference, zygosity, the product term of zygosity and intra-pair birth size difference, birth year, and twin cohort as the regressors. Further, the quadratic effect of birth size was investigated by introducing the term in the regression models for the association between birth size and height residuals, that is, by introducing the quadratic term of birth size (weight or length) in the individual level analyses and the quadratic term of intra-pair birth size differences in the pair-wise analyses. Finally, since all analyses were based on height residuals, we refer to “height residuals” as “height” for simplicity, except in statistical methods section.

3. Results

3.1. Descriptive statistics

Descriptive statistics for birth size and height by zygosity, sex and age are provided in Table 1. Mean birth weight and length were slightly greater in males than in females and in DZ than in MZ twins. The SD of birth weight was also greater in males and DZ twins, but the SD of birth length was similar in the four sex and zygosity groups. PI showed a very similar mean across sex and zygosity groups and a slightly greater SD in DZ twins. Regarding height, sample size for each zygosity, age, and sex group ranged between 662 and 6860 measurements. The age 6 and 19 years groups had the smallest sample sizes. Mean height was expectedly greater with age in both sexes, with the exception of the slightly shorter mean height observed at age 20–69 years, which reflects differences in the distribution of different cohorts within each age group. Mean values were greater in males than in females; only at the age of 11 and 12 years were girls somewhat taller than boys, reflecting the earlier onset of pubertal growth in girls. The SD of height was generally greater with age until it peaked at 12 years in girls and at 13 years in boys, and then lower with age. DZ twins had slightly greater mean height than MZ twins in both sexes, but the SD of height did not show any clear zygosity pattern.

3.2. Test for quadratic effect

We first tested the quadratic effect of birth size on the associations. At the individual level, a quadratic effect of birth weight was observed only at age 1 (Appendix Table 1); the quadratic term of birth length was significant at several ages, but the effect size was very small (Appendix Table 2). In the pair-wise analyses, only 7 and 10 of 80 tests for birth weight and length, respectively, reached nominal significance (p < 0.05), but after Bonferroni correction for multiple testing, none were significant (\( p_{\text{corrected}} < 0.001 \)) (Appendix Tables 3 and 4). Since the primary focus of the present study is on within-pair analyses, the quadratic effect of birth size was not included in the models.

3.3. Individual level analyses

At the individual level, birth weight was positively associated with later height at all ages in both sexes; each 1-kg increase in birth weight was associated with 1.30 (95% CI 0.51–2.09) to 4.01 (95% CI 3.24–4.78) cm taller height (Fig. 1). Birth length was also positively associated with later height: a 1-cm increase in birth length was associated with from 0.21 (95% CI 0.13–0.29) to 0.82 (95% CI 0.70–0.93) cm greater height. In contrast, PI at birth was not generally associated with later height. For both birth weight and length, the magnitude of the associations was similar in males and females and was somewhat more pronounced in late adolescence and adulthood than in childhood. Supported by the lack of interaction between zygosity and birth weight or length (only 3 and 2 of 40 tests had p-value < 0.05, respectively) (Appendix Tables 1 and 2), the magnitude of the associations was similar in MZ and DZ twins.

3.4. Within-pair level analyses

Within twin pairs, intra-pair differences in birth size were also positively associated with intra-pair differences in later height: each 1-kg difference in birth weight and 1-cm difference in birth length was associated with 1.14 (95% CI 0.59–1.69) to 4.25 (95% CI 2.81–5.70) and 0.18 (95% CI 0.05–0.31) to 0.90 (95% CI 0.71–1.09) cm taller height, respectively (Fig. 2). Supported by the zygosity interaction effects found at several ages (Appendix Tables 5 and 6), particularly for birth length, the magnitude of the associations in DZ twins was greater than in MZ twins at several ages. This difference in the magnitude between zygosities was more pronounced for birth length; the greatest differences were observed mainly in adolescence and adulthood for boys and in childhood for girls. Moreover, since some of the previous studies in twin pairs were based on samples that are also part of the CODATwins project, we repeated the analyses excluding those samples and obtained very similar results (data not shown). Finally, intra-pair PI differences were not generally associated with intra-pair height differences in DZ twins, but showed significant and positive associations at several ages in MZ twins.

4. Discussion

The present study, based on a multinational database of 28 twin cohorts, showed that birth weight and length are positively associated with later height in males and females from infancy to adulthood. Because the associations within DZ pairs were generally greater than within MZ pairs, our results support the role of genetic and individual-specific environmental factors in the relationship and refine previous findings by considering, in addition to adult age, childhood and adolescence using one-year age groups from 1 to 19 years of age.

At the individual level, our findings are in line with previous twin and singleton studies in adolescence and adulthood showing that an increase in 1-kg birth weight and 1-cm birth length was associated with 3.3–4.0 cm and 0.73–0.92 cm taller height, respectively [9,24,25,27,31]. At the within-pair level, intra-pair differences in both birth weight and length were associated with intra-pair differences in later height in both zygosity groups. The relationships in MZ twin pairs showed that individual-specific environmental factors are important in the association between birth size and later height. Our results are comparable with those from other studies of MZ twin pairs in adolescence and adulthood, which reported regression coefficients ranging 1.9–3.3 cm height/kg birth weight [23–27] and 0.45–0.73 cm height/cm birth length [24,26]. The magnitude of associations between PI and later height observed at some ages within MZ pairs (up to 0.2 cm/PI unit) is similar to that reported for Finnish twins [26]. These individual-specific environmental factors could be related to intrauterine differences experienced by twin pairs who are discordant for birth size, for example differences in delivery of nutrients to the fetus. It has been suggested that intrauterine programming in response to fetal malnutrition induces permanent changes in structure and function of the body, which may cause shorter height in later life [17]. This is in accordance with a randomized trial in East Java showing that energy supplementation during pregnancy increased postnatal growth and reduced malnutrition in preschool children [32].

As in our multinational database, the previous studies on birth weight and length also found greater associations in DZ twin pairs ranging 3.6–4.4 cm height/kg birth weight [23–26] and 0.84–0.96 cm height/cm birth length [24,26], suggesting that genetic factors are involved in the relationship between birth size and later height. This is supported by the strong genetic correlation (0.41) observed between birth weight and adult height in European ancestry samples using linkage-disequilibrium score regression based on information from...
The development of twins, especially in the intrauterine environment, influences later growth and development. This is evident in the data from Finnish twins, where a high kappa value of 0.89 was observed in birth weights (in singletons) [28]. The correlations between measured and self-reported heights have commonly been over 0.90 [39,40]. Moreover, there are many potential sources of error both for birth weight and birth length. It is not likely that they would explain the observed associations, i.e. the measurement errors of birth size would correlate with the measures of later height, but they may make the observed associations weaker. Finally, it has been questioned whether differences in birth size in twins are a suitable model for differences in birth size in general, because intrauterine growth in twins is different from that in singletons and fetal growth may be particularly compromised in MZ twins [41]. However, the magnitude of the relationship between birth weight and height in twins was similar to that reported in singletons [9], and thus there is no reason to suggest that data from twins cannot be used to shed light on causal pathways underlying these associations also in the general population.

In conclusion, our findings showed that both genetic and individual-specific environmental factors influence the association between birth size and later height from infancy to adulthood. Although the magnitude somewhat differed by sex and age at height measurement, genetic factors were in general more importantly involved in the association with birth length than with birth weight. The influence of individual-specific environmental factors on the association supports the role of the intrauterine environment in the development of later height, and suggests that improvement of the intrauterine delivery of nutrients may in part prevent growth problems during childhood and adolescence leading to shorter stature in adulthood.

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Appendix A. Supplementary data

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References