Fetal growth is determined by both genetic and environmental factors. Evidence for genetic regulation comes from intergenerational studies that have shown parental birthweight, growth in childhood, and adult anthropometry to be associated with offspring birthweight. There is some evidence to suggest that paternal height is a more important determinant of offspring birth length (neonatal skeletal size) than maternal height, while maternal weight, or BMI, has the greater influence on offspring birthweight. However, the statistical methods used in these earlier studies did not test formally the (in)equality of coefficients between maternal and paternal influences. Similarly, while the intrauterine environment and post-natal period are important for growth and subsequent obesity risk, few studies have examined the contribution of parental size to infancy weight gain and whether maternal or paternal size exerts a greater influence on birthweight or weight gain.

We used data from the UK Millennium Cohort Study to examine the contribution of parental height and weight to birthweight and infant weight gain.
offspring birthweight and weight gain in infancy. We tested the differential contributions of each parent to these outcomes using a novel reparameterization of the regression model.

**Methods**

We investigated birthweight and weight gain of 8053 infants. These infants were members of the Millennium Cohort Study, comprising 18819 children born in the UK between 2000 and 2002 (overall response rate: 72%). Cohort members were excluded if they were from multiple conceptions (156), or multiple births (522), not born at term (37–41 weeks) (3342), were not living with their natural mother (30) or father (3289), if they were not white (3298), or if their last weight was not measured between 8 and 10 months of age (4318). We excluded all infants from ethnic minority groups to obtain a homogeneous sample, and this study is, therefore, representative of the UK white population only.

Parental report of infant birthweight and child’s last weight was obtained at interview when the children were ~9 months old. We have previously shown a high level of agreement between MCS reported birthweights and birth registration data, and the child’s last weight was confirmed by 85% of the mothers by referring to the personal child health record, a booklet used by mothers and health professionals in the UK to monitor a child’s early growth and development. Parents also reported their current height and weight (including pre-pregnancy weight for mothers). Data were missing for maternal height (23), maternal weight (272), paternal height (936), and paternal weight (1002). It was assumed that the 15% missing parental data were missing at random. Owing to this and the large sample size, the missing data were not imputed. Complete data were, therefore, available for 6811 infant–parent triads.

We calculated $z$-scores for birthweight and conditional weight gain to age 9 months, that is weight gain adjusted for the child's birthweight, using the British 1990 growth reference. We also calculated internal parental height and weight $z$-scores by subtracting the mean and dividing by the standard deviation. This was done to allow for the difference in standard deviations between the sexes in adult height and weight.

We used a novel reparameterization to provide regression coefficients that are the mean and difference of the separate parental contributions. To achieve this, two summary variables were constructed: the sum (maternal + paternal), and half difference (maternal − paternal)/2, of the two parental $z$-scores (see Appendix for rationale).

The contribution of parental size to birthweight and weight gain was tested using multivariable regression with allowance made for the survey design (Stata 8.2, StataCorp, College Station, TX). The Millennium Cohort study was approved by the South West Multicentre Research Ethics Committee.

**Results**

The mutually adjusted coefficients for maternal and paternal height and weight $z$-scores were all positively and significantly associated with birthweight and conditional weight gain (Table 1, model 1). For example, the coefficient of 0.18 for maternal weight is the increase in offspring birthweight $z$-score per unit increase in maternal weight $z$-score. The variation in birthweight was more than 5 times greater for the mother than the father. Adjusting for potential confounders such as parity, smoking and infant feeding practice made little difference to the results (data not shown). The $R$-squared values were 0.063 and 0.036 for the birthweight and weight gain regression models, respectively.

Model 2 in Table 1 presents the same coefficients as model 1, but rearranged as the difference in coefficients and mean coefficient for the two parents. Thus for birthweight the difference in weight coefficients is 0.15, reflecting the difference between the maternal and paternal coefficients in model 1 of 0.18 and 0.03. The advantage of the reparameterization is that the difference coefficient has its own standard error, confirming the highly significantly greater maternal influence on birthweight. Conversely the parental height contributions were similar and not significantly different (0.09 vs 0.06, difference coefficient 0.03). For infant weight gain, there were no differential parental contributions.

**Table 1 Regression coefficients for birthweight and conditional weight gain on maternal and paternal height and weight (model 1), and the same coefficients expressed as the mean and difference for the two parents (model 2)**

<table>
<thead>
<tr>
<th>Model</th>
<th>Variable</th>
<th>Birthweight</th>
<th>R-Squared</th>
<th>Conditional weight gain</th>
<th>R-Squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mother’s weight $z$-score</td>
<td>0.18 (0.15–0.21)</td>
<td>0.052</td>
<td>0.05 (0.01–0.08)</td>
<td>0.006</td>
</tr>
<tr>
<td></td>
<td>Father’s weight $z$-score</td>
<td>0.03 (0.00–0.06)</td>
<td>0.009</td>
<td>0.08 (0.04–0.12)</td>
<td>0.012</td>
</tr>
<tr>
<td></td>
<td>Mother’s height $z$-score</td>
<td>0.09 (0.07–0.12)</td>
<td>0.027</td>
<td>0.11 (0.08–0.14)</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td>Father’s height $z$-score</td>
<td>0.06 (0.03–0.10)</td>
<td>0.009</td>
<td>0.09 (0.05–0.13)</td>
<td>0.012</td>
</tr>
<tr>
<td>2</td>
<td>Difference in weight coefficients</td>
<td>0.15 (0.10–0.20)</td>
<td>−0.03 (−0.09 to 0.02)</td>
<td>0.03 (−0.02 to 0.07)</td>
<td>0.02 (−0.03 to 0.07)</td>
</tr>
<tr>
<td></td>
<td>Difference in height coefficients</td>
<td>0.03 (−0.02 to 0.07)</td>
<td>0.06 (0.04–0.08)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mean parental weight coefficient</td>
<td>0.11 (0.09–0.13)</td>
<td>0.10 (0.08–0.12)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Adjusted for other variables in table and infant’s sex.

* For univariate unadjusted associations.

* Mother’s weight = pre-pregnancy weight.

* Difference = maternal − paternal.
Discussion
Our findings suggest that there are important paternal genetic and environmental effects on birthweight and weight gain, independent of maternal influences. By using a novel approach to formally compare parental contributions with birthweight and weight gain, we have shown that maternal weight exerts a greater influence than paternal weight on birthweight. In contrast, we did not find any differential parental height contributions to birthweight, or weight and height contributions to weight gain, in this large cohort study of nearly 7000 infants. These observations confirm findings of other smaller studies, which have reported maternal and paternal size to be significant and independent determinants of offspring birthweight.10,13

Although based on maternal report, we have previously confirmed that accuracy of birthweight in this cohort is high,9 and 85% of mothers were able to verify reported infant weight in their child’s personal child health record.10 Measurements of infant length were not obtained, so we were unable to examine parental influences on infant skeletal size and growth. Maternal and paternal self-reported weights and heights are thought to be generally reliable but differential systematic errors in reporting of maternal and paternal weight remain possible. In particular, any overestimation of maternal but not paternal weight might attenuate the effect sizes reported and, hence, the estimate of maternal relative to paternal contributions to birthweight and infant weight gain.

We have, in addition, proposed a novel statistical method for comparing the contribution of parental anthropometry to infant size and growth, which can be applied to examining these influences at other stages in the life course.

In conclusion, both maternal and paternal height and weight exert independent and significant influences on offspring birthweight and weight gain in infancy. There are important paternal effects on birthweight and weight gain, independent of maternal genetic and environmental influences, although maternal weight has a far greater influence on birthweight than paternal weight. The interaction between these maternal and paternal genetic, and environmental, influences is complex. Under the conflict theory,14 fathers try to ensure maximal growth of the child, while mothers maximize their chance of survival by limiting fetal growth. These results make clear that the mother wins this conflict in that her genome has a much greater influence than the father’s on offspring birthweight. Further research is needed to understand both the genetic and epigenetic15 mechanisms involved and to determine the relevance of these intergenerational influences to future health and weight gain.

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KEY MESSAGES
- Maternal and paternal height and weight exert independent and significant influences on offspring birthweight and weight gain in infancy.
- There are no differential parental height contributions to birthweight or weight and height contributions to weight gain.
- Maternal weight has a greater influence on birthweight than paternal weight.

References
Appendix

Consider the regression equation

$$z_{ch} = a + \beta z_{ma} + \gamma z_{pa} \quad (1)$$

where $z_{ch}$, $z_{ma}$, and $z_{pa}$ are z-scores for the child, mother, and father, respectively. The aim is to reparameterize (rearrange) the equation so that the first regression coefficient is the mean of the two parental regression coefficients, $(\beta + \gamma)/2$, while the second is the difference between the two coefficients, $(\beta - \gamma)$. This is achieved by constructing a new equation in this form, with unknown weightings for $z_{ma}$ and $z_{pa}$, and the weightings are obtained by equating coefficients. The rearranged equation is:

$$z_{ch} = a + \left(\frac{\beta + \gamma}{2}\right)(A z_{ma} + B z_{pa}) + (\beta - \gamma)(C z_{ma} - D z_{pa}) \quad (2)$$

where $A$, $B$, $C$ and $D$ are the unknown weightings to be derived. Equating coefficients for $z_{ma}$ in (1) and (2) gives

$$\beta = \left(\frac{\beta + \gamma}{2}\right)A + (\beta - \gamma)C$$

so that $\beta = \frac{\gamma}{2}A + BC$ and $0 = \frac{\gamma}{2}A - \gamma C$. From this $C = \frac{A}{2}$, $A = 1$ and $C = \frac{1}{2}$.

Equating coefficients for $z_{pa}$ in (1) and (2) gives

$$\gamma = \left(\frac{\beta + \gamma}{2}\right)B - (\beta - \gamma)D$$

so that $\gamma = \frac{\beta}{2}B + \gamma D$ and $0 = \frac{\beta}{2}B - \beta D$. From this $D = \frac{\beta}{2}$, $B = 1$ and $D = \frac{1}{2}$.

Substituting $A$, $B$, $C$, and $D$ into (2) gives

$$z_{ch} = a + \left(\frac{\beta + \gamma}{2}\right)(z_{ma} + z_{pa}) + (\beta - \gamma)\left(\frac{z_{ma} - z_{pa}}{2}\right) \quad (3)$$

which is in the required form and simplifies to (1). Thus constructed variables consisting of the sum and half-difference of the parental z-scores lead to coefficients that are, respectively, the mean and difference of the separate parental coefficients.

Note that since Equations (1) and (3) are algebraically equivalent, other variables can be added to the regression without affecting the reparameterization. This means that further regression adjustments can be included as necessary.