Perinatal factors associate with vertebral size and shape but not lumbar lordosis in 10-year-old children

Anastasia V. Pavlova[1,2], Janet E. Jeffrey[1], Rebecca J. Barr[1,3], Richard M. Aspden[1]*

[1] Centre for Arthritis and Musculoskeletal Health, School of Medicine, Medical Sciences and Nutrition, University of Aberdeen, Aberdeen, UK.

[2] Current address: School of Health Sciences, Robert Gordon University, Aberdeen, UK.

[3] Current address: Medicines Monitoring Unit (MEMO), Division of Molecular & Clinical Medicine, School of Medicine, University of Dundee, Dundee, UK

Short title: Antenatal factors and spine shape in children

***Corresponding author**

Professor Richard M. Aspden
Centre for Arthritis and Musculoskeletal Health,
University of Aberdeen,
School of Medicine, Medical Sciences and Nutrition,
IMS Building
Foresterhill
Aberdeen, AB25 2ZD
UK
E-mail: r.aspden@abdn.ac.uk

Abstract

The intrauterine environment is known to influence foetal development and future health. Low birthweight has been linked to smaller vertebral canals in children and decreased adulthood spine bone mineral content. Perinatal factors affecting lumbar spine curvature have not yet been considered but could be important for adult spinal health as lumbar movement during lifting, a risk factor for backpain, is associated with lordosis. To investigate this, lumbar spine magnetic resonance images at age 10 years and perinatal and maternal data (birthweight, placental weight, gestation length, crown-heel length, maternal age, height, weight and smoking status) from 161 children born in Aberdeen in 1988-1989 were acquired. Statistical shape modelling, using principal component analysis, quantified variations in lumbar spine shape and resulting modes of variation were assessed in combination with perinatal data using correlations and analyses of covariance, adjusted for potential confounders. Spine modes 1-3 (SM1-SM3) captured 75% of the variation in lumbar spine shape. The first and third modes described the total amount (SM1) and evenness of curvature distribution (SM3). SM2 accounted for variations in antero-posterior vertebral diameter relative to vertebral height; increasing positive scores representing a larger relative diameter. Adjusting for gestation length and sex, SM2 positively correlated with birthweight (r=0.25, P <0.01), placental weight (r=0.20, P=0.04), crown-heel length (r=0.36, P<0.001) and maternal weight (r=0.19, P=0.04) and negatively with maternal age (r=-0.22, P=0.02). SM2 scores were lower in girls (P<0.001) and in the low birthweight group (P=0.02). There were no significant differences in SM1 and SM3 scores between birthweight groups, boys and girls or children of smokers (31%) and non-smokers (69%). In conclusion, **s**ome perinatal factors were associated with vertebral body morphology but had little effect on lumbar curvature.

Keywords: Lumbar spine, perinatal factors, antenatal, lordosis, statistical shape modelling

Introduction

The antenatal period is a crucial time for a developing foetus and, as hypothesized by Barker for ischaemic heart disease (Barker, 2007), disruptions to the processes occurring during this period can have long lasting consequences (Bagnall et al., 1977, Strauss, 1997). Although antenatal factors and intrauterine environment are suggested to have short- and long-term effects on musculoskeletal health (Javaid and Cooper, 2002, Pasco et al., 2008), little is known about their influence on the spine. We previously demonstrated, in a study of lumbar magnetic resonance images (MRI) in children, that low birthweight and maternal smoking were associated with a reduced vertebral canal size (Jeffrey et al., 2003), which is related to spinal stenosis, leg and back pain later in life (Porter et al., 1980). In other studies using vertical MRI we have shown that each individual has a characteristic lumbar spine shape that is present to some degree in all positions of flexion and extension (Meakin et al., 2009a, Pavlova et al., 2014). This intrinsic shape affected the way the same individuals chose to lift a weight from the ground (Pavlova et al., 2018a); those with ‘curvier’ spines preferred to stoop whereas those with straighter spines found stooping difficult and chose to squat. The relationship between lumbar lordosis and low back pain is unclear but some studies have found that those with chronic low back pain were less lordotic (Chaleat-Valayer et al., 2011). A study of 13-year-olds found that increasing backpack load did not change lumbar lordosis in either those with idiopathic low back pain or controls but they noted that children with low back pain experienced significantly less lumbar lordosis with backpack load compared with controls but that it was unclear whether this related to their back pain (Shymon et al., 2013). These uncertainties indicate the need for a better understanding of the factors affecting the development of the lumbar lordosis.

One of the greatest contributors to low birthweight is short gestational length (<37 weeks (Mohsin et al., 2003)). Low maternal height and weight are suggested to place physical limitations on placental and foetal growth, either genetically or environmentally (Kramer, 1987, Spencer and Logan, 2002). Other factors associated with low birthweight include female sex, maternal age (both low (12-19 years) and high (>35 years)), maternal smoking and socioeconomic status, which can itself influence some of the aforementioned maternal factors (Kramer, 1987, Mohsin et al., 2003, Spencer and Logan, 2002). Furthermore, at age 10 years, a child’s height is around 78% of their adult standing height for boys and 83% for girls (Dimeglio et al., 2010) and sex differences in spine morphology might be expected. The relationship between perinatal factors and pre-pubertal spinal shape and curvature is unknown but could be important for load bearing capability and future back health (Aspden, 1988, Livshits et al., 2011, Meakin and Aspden, 2012, Stone et al., 2015).

Comparisons of spinal curvature are often done from measures of the lumbar spine angle (usually between the first lumbar to first sacral vertebrae, L1-S1) or intersegmental angles between vertebrae (Cil et al., 2005, Masharawi et al., 2012). However, statistical shape modelling (SSM) provides a simpler yet more effective way to quantify spine shape and enable analysis of relationships with other factors (Meakin et al., 2009b, Meakin et al., 2008). Statistical shape modelling (SSM) uses Principal Component Analysis to describe variation in complicated shapes (Cootes et al., 1995). SSMs have previously been applied to images taken from a number of different sites within the human body using a variety of different imaging modalities; these include the heart (Cootes et al., 1995), brain (Cootes and Taylor, 2004), spine (Meakin et al., 2009b, Pavlova et al., 2014), hip (Barr et al., 2012, Goodyear et al., 2013) and leg (Varzi et al., 2015). In the context of this study SSM is a relatively new methodology and was not available at the time of the original Jeffrey et al. (2003) study.

We hypothesised that spinal shape would be associated with birthweight and possibly maternal smoking or other antenatal factors. The primary objective of this study, therefore, was to characterise lumbar spine shape using SSM in a cross-section of 10-year-old children, then relate these shape characteristics to perinatal factors and compare spine shapes between normal and low birthweight children (as defined by the World Health Organisation (Wardlaw, 2004)). A secondary objective was to explore potential differences in the shape of the lumbar spine between pre-pubertal girls and boys.

Materials and Methods

The cohort for this cross-sectional study comprised children born in 1988-1989 at the Aberdeen Maternity Hospital (United Kingdom) and included normal- and low-birthweight children. This was an existing cohort so recruitment and data collection are described in detail elsewhere (Jeffrey et al., 2003). In brief, two cohorts of children, born during 1988 or 1989 and aged 10 (standard deviation (SD) 0.6) years, were invited to take part in an MRI study to investigate antenatal factors affecting the development of the lumbar vertebral canal (Jeffrey et al., 2003). The first cohort were children born to mothers taking part in a study investigating dietary advice on pregnancy nutrition and living within Aberdeen (Anderson et al., 1995). The second cohort was recruited using the Aberdeen Maternity and Neonatal Databank. Children were identified by birthweight and gestational age; two thirds of the children classed as “small for gestational age” (standardised birthweight score < -2SD) as defined in Jeffrey et al. (Jeffrey et al., 2003). In the current study all children were reclassified using current World Health Organisation (WHO) reference values and placed into low (<2500 g) or normal (≥2500 g) birthweight groups (Wardlaw, 2004).

Magnetic resonance images (MRI) of the lumbar spine and retrospective antenatal data were available for all 161 children (77 male, 84 female) who took part in the original study. Supine, sagittal images of the lumbar spine were obtained using a 0.2 T Open Magnetom Viva MRI Scanner (Seimens, Erlangen, Germany). Historical data included birthweight and placental weight measured at birth; crown-heel length measured supine at birth from crown to sole (Fok et al., 2003); gestation period; maternal age, height, weight and smoking status (smoker/non-smoker). The children’s sex, age, height and weight at the time of imaging were also available.

The detailed methodology of statistical shape modelling (SSM) has been described in detail elsewhere (Cootes and Taylor, 2004, Cootes et al., 1995) and its application to the spine, including a sensitivity analysis, has been described by Meakin et al. (Meakin et al., 2009b, Meakin et al., 2008). Briefly, marker points were placed on mid-sagittal images according to a 168-point lumbar spine template (Meakin et al., 2009b) constructed using the Active Appearance Modelling software tools from the University of Manchester (http://personalpages.manchester.ac.uk/staff/timothy.f.cootes/software/am_tools_doc/index.html); a software program that runs within MATLAB (The Math Works Inc, Natick, United states) software environment. Further analysis was done using custom made software (SHAPE, Aberdeen University, Aberdeen, UK) and involved Procrustes transformation, to remove the overall effects of size, before principal components analysis generated a set of orthogonal modes that describe the variations in shape found within that set of images. Mode scores for the whole image set are scaled to have a mean of zero and unit standard deviation. Each image then received a score for each mode quantifying, in standard deviations, how much the shape in that image deviated from the mean. A lumbar lordosis angle was calculated between lines tangential to the superior vertebral endplates of L1 to S1 using a custom programme written in MATLAB 2008a (The MathWorks Inc., Natick, Massachusetts). Intra-rater repeatability was tested on 10 images, marked up by the same observer (AVP) on two separate occasions.

Statistical analyses were performed in SPSS 22 (SPSS, Inc., Chicago, IL, USA). Intra-rater repeatability for point placement was assessed by calculating intra-class correlation coefficients (ICC) from a two-way random effects (absolute agreement) analysis of variance (ANOVA) model (Bland, 2000). Data normality was tested using Shapiro-Wilk statistics and statistical significance was taken as $P < 0.05$. Where historical data were missing, correlations and other tests were performed by omitting the individual from that analysis.

Descriptive statistics are presented as mean values (standard deviations), with differences in group means assessed using Student's *t*-test. Associations between mode scores and other measures were first explored using Pearson correlation (Spearman correlation where data were not normally distributed). Since birthweight is strongly associated with gestation length and sex (Lesiński, 1962) we performed further, partial, correlations to account for these factors. Analysis of covariance (ANCOVA) was used to test for differences in mode scores between low and normal birthweight groups, adjusting for sex, gestation length, and maternal height and weight. Differences in mode scores between children of smokers and non-smokers were also explored using ANCOVA, with birthweight as a covariate. Modes scores are presented in units of standard deviations (SD). Differences in mode scores between boys and girls were assessed using the independent samples *t*-test in the first instance and ANCOVA was used to check whether adjusting for potential confounders (infant bodyweight, crown-heel length, maternal weight, child weight and height at 10 years) would attenuate any results.

Results

The cohort characteristics are presented in Table 1. The ICC's for *x* and *y* coordinates of repeated point placements in SSM were 0.99, demonstrating good intra-rater point placement repeatability.

A scree plot of the variance explained by each mode versus the mode number (Cattell, 1966) was used to select the first three modes for further analysis, as the point at which the slope of the curve changes markedly. These first three spine modes (SM1-SM3) explained 75% of the overall variance in shape (Fig 1 and supporting information). SM1 (54% of total variance) described the overall curvature within the lumbar spine, from straight spines with little lordosis (positive scores) to curvy lordotic spines (negative scores). SM2 (13% variance) captured differences in vertebral morphology, positive scores describing vertebrae with greater anterior-posterior diameters relative to vertebral height (aspect ratio) and negative scores indicating smaller aspect ratios. Finally, SM3 (8% variance) described the distribution of sagittal curvature along the lumbar spine, whether evenly distributed throughout (C-shaped curve, positive scores) or uneven (S-shaped curve, negative scores). Subsequent modes each explained less than 5% of the total variance.

No correlations were found between SM1 or SM3 with any of the maternal or perinatal variables, including birthweight. Partial correlations controlling for sex and gestation length revealed positive associations between SM2 scores and birthweight, placental weight, crown-heel length and maternal weight and a negative association with maternal age (Table 2). This suggests that children with smaller vertebral aspect ratios at age 10 were overall smaller at birth and were born to lighter and older mothers. Adjusting for potential confounders, ANCOVA results revealed significant differences in SM2 scores between normal and low birthweight groups (*P*=0.02); children with a lower birthweight having smaller vertebral aspect ratios at age 10.

Data on maternal smoking were available for 150 (93%) of the participants, of whom 31% were born to mothers who smoked during pregnancy. Mode scores were not different between children of smokers and non-smokers (difference(non-smoker – smoker): SM1 -0.13, *P* = 0.48, SM2 0.10, *P* = 0.58, SM3 -0.03, *P*= 0.86).

No significant differences were found in SM1 or SM3 scores between boys and girls, even though lumbar lordosis angle was, on average, 3° (±1°) greater in girls than boys (*P*<0.01) (Table1). Boys had higher SM2 scores (0.119) than girls (-0.109) with the difference between the means being 0.228 [95%CI: 0.190, 0.226] indicating larger vertebral aspect ratios (Fig 2 and Supporting Information). This difference in SM2 remained significant (*P*<0.001) after accounting for possible confounders. Partial correlations controlling for sex and gestation period revealed a negative association between SM3 and height at age 10 (*r*=-0.21, *P*=0.02), taller children having a more uneven curvature in their lumbar spine (Table 2).

Discussion

Perinatal factors, including low birthweight and maternal smoking, have previously been associated with the presence of a narrow spinal canal in childhood (Jeffrey et al., 2003), thus increasing susceptibility to back pain, sciatica and spinal stenosis in adulthood. Here we used SSM to characterise lumbar spine shape and found associations between perinatal and maternal factors and the shape of individual vertebrae, but not overall lumbar curvature, in sagittal MR images of the lumbar spine from 10-year-old children.

The primary three modes identified by SSM were similar to those found in SSM studies of healthy adult spines (Meakin et al., 2009b, Pavlova et al., 2014, Pavlova et al., 2017). SM1 describes the overall 'curviness' of the lumbar spine and, in this study, SM3 describes the 'evenness' of the curvature; whether the curvature is located lower in the spine or distributed along the lumbar region (Meakin et al., 2008). The order of modes is in descending order of variance explained and may vary between studies, reflecting the variation between different models. Accordingly, in adults we have found the order of SM2 and SM3 is sometimes reversed but the features identified are very similar (Meakin et al., 2009b, Pavlova et al., 2017). In this study, associations between SM3 and height at age 10 years indicated that taller children had a more uneven lumbar curvature. However, overall lumbar spine shape (SM1 and SM3) at age 10 was not related to perinatal factors and not significantly different between low and normal birthweight groups. Thus, the intrauterine environment appears to have little influence on lumbar lordosis, perhaps because curvature has a greater capacity to change with the advent of walking and rapid spinal growth between 0-5 years of age and again from 10 years until adulthood (Dimeglio et al., 2010).

Lumbar lordosis has a heritability of 42-72% (Stone et al., 2015) and although Moore and colleagues (2011) proposed that curvature is primarily influenced by genetics they suggest that it is exaggerated by mechanical stimuli. The primary cervical and thoracic curves of the spine develop in the foetal period but less is known about secondary lumbosacral curves (Been and Kalichman, 2014) which develop during childhood. The spine starts to form *in utero* in the third week of gestation and at around 6 weeks the foetus begins to move (Birnholz et al., 1978, Moore et al., 2011), which is known to play a mechanical role in the formation of tissue, including bone, (Andrew and Bassett, 1971) and joints (Pitsillides and Ashhurst, 2008). Nowlan has reviewed the effects of mechanical stimulation on multiple aspects of skeletal development and showed that reduced foetal movement leads to altered shapes of limb rudiments, abnormal ossification patterns and loss of tissue definition in joint regions (Nowlan, 2015). Recent studies of the developing chick spine from that group, in which paralysis was produced for short or prolonged periods during gestation, resulted in fusion of vertebrae and gross alterations in spinal curvature (Levillain et al., 2019, Rolfe et al., 2017). The variations we found were much more subtle, as might be expected, but these laboratory studies do show that the foetal environment can play an essential role in spine formation. Interestingly, Stone et al. (2015) found no differences in lumbar lordosis between different zygosities of twins. The relative contributions of environmental (especially mechanical) and genetic factors on lumbar curvature remain unclear and pose a challenge for future research.

Vertebral body shape (SM2) appeared to be under some influence from ante- and perinatal factors. Heavier babies grew to have larger vertebral a-p diameters relative to vertebral height at age 10 years while a lighter birthweight was associated with narrower vertebrae. Shorter babies and those with lighter and older mothers also tended to have relatively narrower vertebrae in childhood. These results agree with our previous findings in adults, showing that shorter and lighter individuals had smaller vertebral aspect ratios (Pavlova et al., 2017) and results from an adult cohort in which high BMI throughout the life-course was associated with larger aspect ratios (Pavlova et al., 2018b). This could prove important for future spine health as we recently found smaller aspect ratios to be associated with lower spine bone mineral density (BMD) at age 60-64 (Pavlova et al., 2017). In this same cohort, a separate study showed that later age at walking was associated with lower BMD and smaller bone area in later life (Ireland et al., 2017). Although not strong, these associations suggest that antenatal factors may have some influence on the processes involved in vertebral growth and ossification. Vertebrae begin to ossify at around 8 weeks (Moore and Dalley, 1999) and Bagnall and colleagues (1977) argue that mechanical stimuli could affect osteoblast and osteoclast activity in the spine, determining the course and sequence of ossification. Since intrauterine environmental factors, including smoking, have been associated with reduced foetal movement (Birnholz et al., 1978, Manning et al., 1975) and growth retardation (Strauss, 1997), these may also have consequences for the dimensions and shape of individual vertebrae (Vialle et al., 2005).

Studies comparing lumbar curvature in boys and girls have produced conflicting results (Cil et al., 2005, Lee et al., 2012, Mac-Thiong et al., 2007, Mac-Thiong et al., 2011, Masharawi et al., 2012, Poussa et al., 2005). Here we found that although girls were, on average, 3° more lordotic than boys this difference was not reflected in SM1 or SM3 scores, describing overall and distribution of lumbar curvature. The boys did, however, have a larger vertebral aspect ratio. These results compare with a study of over 1500 adults in which significant differences were found between men and women in overall lumbar curvature, which then disappeared on adjusting for the height of the individual. Men also had larger vertebral aspect ratios than women, although evenness was not related to sex (Pavlova et al., 2017).

Whereas smoking was previously associated with a smaller lumbar spine canal (Jeffrey et al., 2003), in this study we found no relationships between smoking and lumbar spine shape modes. Expanding on previous work (Jeffrey et al., 2003) we investigated relationships between spine shape modes and dimensions of the lumbar spine canal (midsagittal diameter, interpedicular diameter, canal shape, cross-sectional area and perimeter), but only found a few weak correlations (not reported here) which might be explained by effects of multiple testing. The lack of association with SM2, vertebral aspect ratio, was somewhat surprising but may indicate that load bearing is a key driver of vertebral body dimensions whereas other factors control the morphology and size of the posterior elements and, hence, the canal size.

The imaging in this study was limited to MRI scans of individuals in a supine posture, which are less representative of natural weight bearing postures. On average the lumbar spine angle (L1-S1) is smaller in supine lying than during standing (Lee et al., 2014) and this might be why our sample had a smaller average lordosis angle (38±6°) compared with other cohorts (41 to 54°, (Lee et al., 2012, Mac-Thiong et al., 2007, Mac-Thiong et al., 2011, Masharawi et al., 2012)). While a supine posture is a limitation, imaging children is not easy and imaging them in a standing posture is even harder and the technology to do this was not available at the time. Here we make use of an existing resource and, while there are differences in spine shapes between standing and supine postures, we have shown previously that these shapes are highly correlated and that each individual has an intrinsic shape that is detectable in all postures (Meakin et al., 2009b, Pavlova et al., 2014). All the participants were imaged in the same supine posture and comparisons, therefore, should still be informative. Pelvic incidence, measured from radiographs, is useful in describing sagittal spine alignment (Roussouly et al., 2005) but this was not possible here due to its absence from the images available to us. The pitfalls of using low birthweight in association studies have been discussed at length (Joseph and Kramer, 2004, Wilcox, 2001), especially that a strong association does not imply causality or that low birthweight is preventable (Wilcox, 2001). We do not wish to add to the long list of risk variables related to low birthweight or to encourage interference with foetal growth during pregnancy but to improve our understanding of the relationships between factors during growth and the structure of the spine.

To the best of our knowledge, this is the first study of its kind to investigate relationships between perinatal and maternal factors and lumbar spinal shape in childhood. Contrary to our hypothesis, perinatal and maternal factors appear to have no relationship with overall lumbar curvature, although there is some relationship with lumbar vertebral body size at age 10 years. Sex differences were seen in sagittal vertebral shapes but not the amount or distribution of lumbar curvature.

Further investigation is warranted into the roles of mechanical stimuli and environmental factors on spinal curvature development.

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Author Contributions

Anastasia V. Pavlova contributed to the concept and design of the study, to the formal analysis of the data, drafted the manuscript, and contributed to critical revision of the manuscript and approval of the final article.

Janet E. Jeffrey contributed to the concept and design of the study, the acquisition of data, to the formal analysis of the data and approval of the final article.

Rebecca J. Barr contributed to the concept and design of the study, to the formal analysis of the data, to critical revision of the manuscript and approval of the final article.

Richard M. Aspden contributed to the concept and design of the study, the acquisition of funding for the project, the acquisition of data, to the formal analysis of the data, to drafting of the manuscript, to critical revision of the manuscript and approval of the final article.

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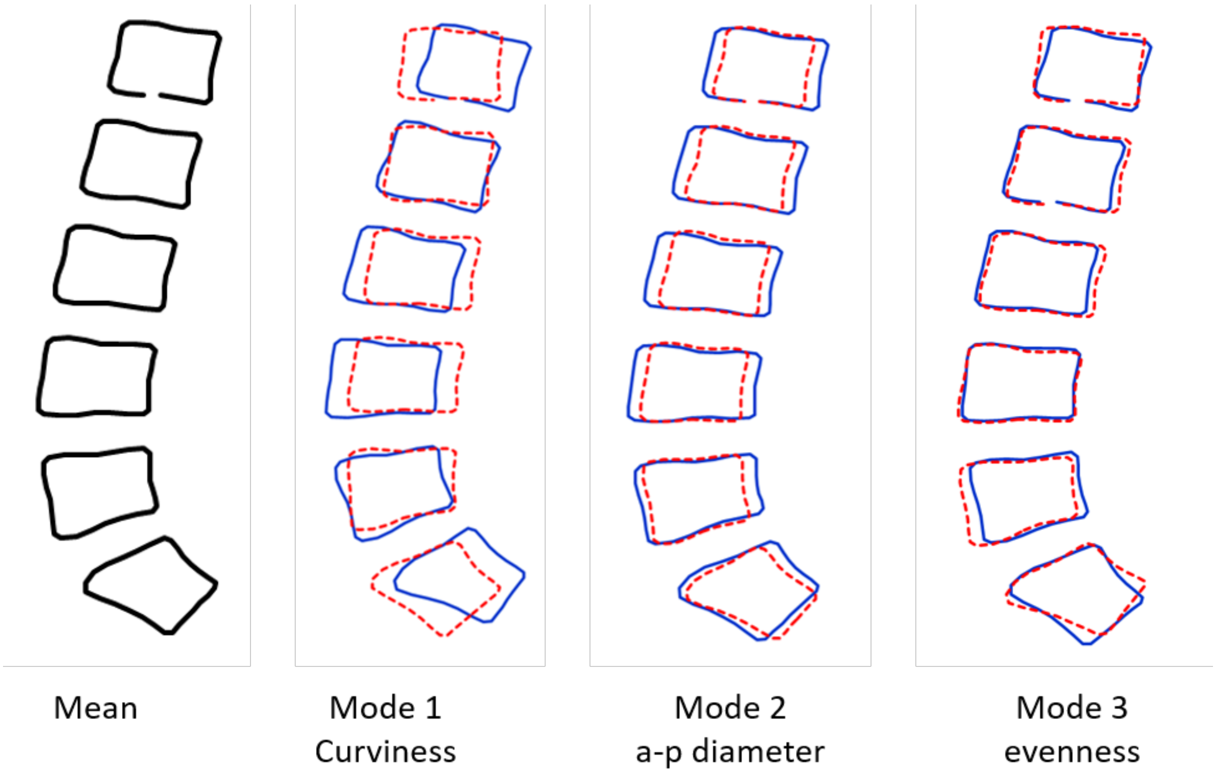
Table 1. Characteristics of the study sample, by birthweight and sex. Shown as mean (SD) except for the sample size, *n*, where brackets indicate the percentage of the cohort).

	All	Low Birthweight	Normal Birthweight	Boys	Girls
n (%)	161	39 (24)	122 (76)	77 (48)	84 (52)
Birthweight (*g*)	3072 (644)	**2227 (276)**	**3342 (469)****	3048 (704)	3094 (585)
Low birthweight (*n*)	39	39	-	22	17
Normal birthweight (*n*)	122	-	122	55	67
Gestation period (*weeks)*	38.8 (2.3)	**37 (3)**	**39 (1)****	38.5 (2.5)	39.1 (2.1)
Placenta weight (*g*)	591 (133)	**456 (92)**	**635 (113)****	580 (146)	602(120)
Crown to heel length (*cm*)	48.5 (2.7)	**45.5 (2.4)**	**49.5 (2.1)****	48.7 (3.0)	48.4 (2.5)
Child weight at scan (*kg*)	37.8 (8.9)	38.3 (7.8)	37.6 (9.3)	37.2 (8.4)	38.4 (9.4)
Child height at scan (*cm*)	143.5 (7.4)	144.5 (6.9)	143.2 (7.6)	143.4 (6.9)	143.7 (7.9)
Lumbar angle at scan (°)	38 (6)	38.4 (6.5)	38.3 (6.3)	**37 (6)**	**40 (6)***
range (°)	25-54	26 - 53	25 – 54	25-49	27-54
Maternal age (*years*)	28 (5)	28 (6)	29 (5)	29 (5)	27.9 (5.4)
Maternal weight (*kg*)	61.7 (9.4)	62.3 (10.5)	61.5 (8.9)	62.8 (9.9)	60.6 (8.7)
Maternal height *(cm)*	160.9 (5.9)	161.8 (7.0)	160.6 (5.5)	161.1 (6.3)	160.6 (5.4)
Maternal smoking	(11 missing)	(5 missing)	(6 missing)	(6 missing)	(5 missing)
- smokers (*n (%)*)	46 (31)	15 (44)	85 (73)	21 (30)	25 (32)
- non-smokers (*n (%)*)	104 (69)	19 (56)	31 (27)	50 (70)	54 (68)

Bold text denotes significant differences between group means (low/normal birthweight, male/female) at *P*<0.05 (*) and *P*≤0.001 (**).

Table 2 Partial correlations and *P*-values between infant and maternal data and sagittal spine shape mode scores at age 10 years, adjusting for gestation length and sex of baby, except [a]controlled for sex only. Mode 1 (curviness), mode 2 (aspect ratio) and mode 3 (evenness). Significant associations shown in bold.

	Mode 1	Mode 2	Mode 3
	r (P)	*r (P)*	*r (P)*
Birthweight (g)	0.06 (0.51)	**0.25 (<0.01)**	0.02 (0.85)
Placenta weight (g)	0.07 (0.47)	**0.20 (0.04)**	-0.01 (0.94)
Gestation length (weeks)	0.001 (0.99)[a]	0.11 (0.27)[a]	0.03 (0.80)[a]
Crown-heel length (cm)	-0.02 (0.86)	**0.36 (<0.001)**	-0.11 (0.26)
Weight at scan (kg)	-0.01 (0.89)	0.09 (0.35)	-0.18 (0.06)
Height at scan (cm)	0.01 (0.95)	0.08 (0.40)	**-0.21 (0.02)**
Lumbar angle at scan (°)	**-0.83 (<0.001)**	-0.09 (0.32)	0.01 (0.93)
Mother's weight (kg)	-0.1 (0.31)	**0.19 (0.04)**	-0.03 (0.75)
Mother's height (kg)	0.13 (0.16)	0.12 (0.21)	-0.05 (0.62)
Mother's age (years)	0.12 (0.22)	**-0.22 (0.02)**	-0.07 (0.45)



Mean

Mode 1
Curviness

Mode 2
a-p diameter

Mode 3
evenness

Fig 1. Statistical shape model of the lumbar spine (L1-S1) in 161 children, showing the average spine shape (Mean) and when each mode separately is varied by plus (solid, blue line) and minus (dashed, red line) two standard deviations (2 SD). These modes describe variations in overall lumbar curvature (SM1), anteroposterior vertebral diameter relative to height or ‘vertebral aspect ratio’ (SM2) and the distribution of curvature along the lumbar spine (SM3).

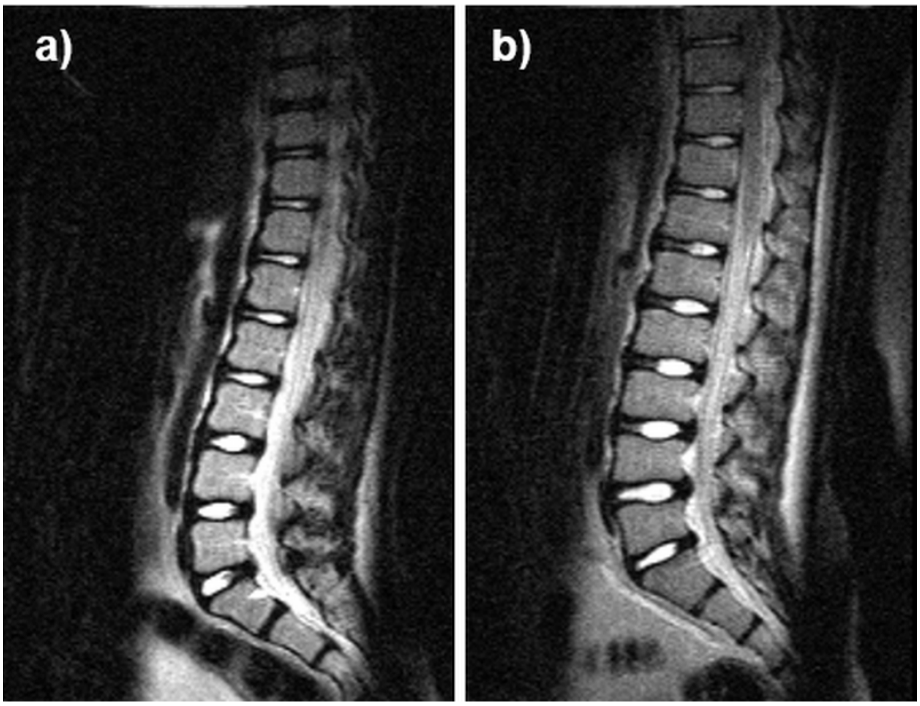


Fig 2. Supine magnetic resonance images demonstrating the shape variation described by mode 2 (vertebral aspect ratio) in two 10-year-old children with the lowest (a) and highest (b) mode 2 scores. Lower scores had relatively narrower vertebral bodies (image (a)) compared with the relatively wider vertebrae in image (b).