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Is there a remnant signature of obstetric dilemma in modern pregnant women?

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Running title: obstetric dilemma in modern women

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Abstract

Objective: The aim of this study was to analyse the correlations between maternal size, neonatal size, the dimensions of the maternal pelvis and gestational variables.

Methods: In this study 131 mother-infant pairs were recruited. We investigate correlation between maternal traits (height, BMI, uterus height), neonatal traits (gestational age, birthweight, head, suboccipito-bregmatic and abdominal girth) and pelvic variables (conjugate diameter, inter-spinous diameter, sub-pubic angle) collected from computed tomography pelvimetry.

Results: We found that the five neonatal traits are significantly inter-correlated. Among maternal traits, height is highly correlated with conjugate and inter-spinous diameters. Subpubic angle is correlated with inter-spinous diameter. Uterus height is correlated with the four neonatal growth traits. Gestational age is correlated with birthweight, head and abdominal girth. Among neonatal and pelvimetry correlations, conjugate diameter is highly correlated with suboccipito-bregmatic girth.

Discussion: Matches between gestational age and neonatal traits, and between uterus height and neonatal traits could be related to the process of fetal maturation, orchestrated by the pregnancy clocks. Indeed, the triggering of parturition is supposed to result from the coordination and initiation

of 4 clocks (endocrine, fetal membrane, decidual and myometrial) implying fetal organ maturation and fetal membrane senescence. Obstetric dilemma is an evolutionary tradeoff resulting from the conflicting pressures between bipedal locomotion efficiency and the selection for bigger brain size at birth. Correlation between suboccipito-bregmatic girth and conjugate suggests that the more the inlet is sagittally reduced, the smaller suboccipito-bregmatic girth is. Moreover, acquisition of the adult birth canal morphology causes minimal variation at the inlet, compare to the fetus morphology, suggesting that suboccipito-bregmatic girth follows the size of the inlet, but in one-way. Therefore, our interpretation of this pelvic-fetal correlation suggests that the pelvic size seems to be also a constraint to the fetal growth process. This adjustment of fetus size to the birth canal dimensions limits the risk of dystocia and could be interpreted as a remnant signature of the obstetric dilemma in our obstetrical sample.

Introduction

The physiology of birth process, timing of the pregnancy or the mechanism of fetal growth process remain unclear in many aspects. Among these aspects, the relationship between pelvic size, birthweight, and pregnancy length has been the source of many discussions. Most authors widely assumed that modern human birth has been shaped by evolutionary stresses (Washburn, 1960; Berge *et al.* 1984; Häusler and Schmid, 1995; Rosenberg and Trevathan, 1996; 2002; Trevathan, 2011; Lovejoy, 2005; Wells, 2009), such as bipedal locomotion (Berge *et al.* 1984; Rosenberg and Trevathan, 1996; 2002), ecological stresses (Wells, 2009), genetic drift (Betti *et al.*, 2014; Betti and Manica, 2018), thermal environment (Weaver and Hublin, 2009; Betti *et al.*, 2014), or encephalization (Tague and Lovejoy, 1986; Häusler and Schmid, 1995; DeSilva and Lesnik, 2008). When compared with others hominoid, the patterns of modern human birth are markedly distinct (Berge *et al.*, 1984; Tague and Lovejoy, 1986; Franciscus, 2009). These evolutionary stresses are supposed to generate a complex parturition in modern human: a higher risk of difficult labor *i.e.* dystocic labor (Wittman and Wall, 2007; Franciscus, 2009), and a complex and lengthy way to give birth vaginally with the emergence of obstetrical mechanism (Malinas and Favier, 1979; Frémondrière *et al.* 2017), which includes rotational birth. For this reason, some authors suggested that human neonate shows specific neurological and growth patterns (Martin, 2007). Indeed, human infant is supposed to be unusually dependent for the first year of life (Martin, 2007). According to this observation, Portmann (1941) suggests that human embryonic development lasts 21 months and is divided in two periods: intrauterine (9 months) and extrauterine (12 months). As a result human neonate retains fetal pattern of brain growth when delivered (Washburn, 1960). When considering several eutherian species, brain growth rate during fetal development is conserved, and humans share brain growth patterns with other eutherian species. For example, they are born after the peak of brain growth acceleration, as well as macaques, marmosets, guinea pigs, sheeps, pigs and oxen (Hallen *et al.*, 2017). But primates (Hallen *et al.*, 2017) and more specifically humans (Martin, 2007) exhibits slow rates of body growth that increases brain size/body size ratio (encephalization) *in utero*.

After birth, substantial brain growth relative to body growth continues in humans but not in other primates where a switch in brain growth relative to body growth occurs (Martin, 2007). Slowing post-cranial growth could be an adaptation for reallocating resources to sustain brain development (Martin, 2007; Hallen et al., 2017). For the neonate, this implies a unique aspect of brain growth sharing precocial and altricial characteristics. As precocial species, humans have an extended gestational period, a large adult brain size, and usually give birth to a single offspring whereas they have a small neonate/adult brain size ratio and a helpless newborn typical to altricial species. This unique mosaic of neonate patterns is referred to as “secondary altriciality” (Portmann, 1969; Coqueugniot and Hublin, 2007). For parents, this requires a higher investment, which has cultural and biological consequences: the task of child care could be supported by other members of the family (Bogin, 1997), and the mother’s milk is also designed for sustaining a rapid brain growth during the infancy (Hinde and Milligan, 2011).

Evolutionary tradeoffs reflect necessary compromises among competing biological functions. For the reproductive function, Washburn (1960) uses the term “dilemma” to point out the tradeoff between bipedal demands and the selection for larger brains. Some authors suggest that the pelvic size is a critical factor that adjusts the brain size at birth to limit the risk of fetal-pelvic disproportion (Leutenegger, 1972; Häusler and Schmid, 1995; Frémondrière *et al.*, 2017; Wells *et al.*, 2017). For others, the pelvic size plays a minor role and the fetal growth arrest is due to metabolic limitations (Dunworth *et al.*, 2012). The “obstetric dilemma” refers to a hypothesis with several limitations that inevitably has weak assumptions. For example, humans have absolutely long gestation, large bodysize and brain at birth compare to non-human primates (Kuzawa, 1998; Dunsworth, 2018). Moreover, human is not the only primate that exhibits a tight fit between pelvis and fetal size (Dunsworth, 2018). Small bodied primates usually show a tight fit (Leutenegger, 1979) and among them, squirrel monkey or marmoset have often smaller sagittal dimension of the maternal pelvis than the length of the neonatal cranium (Leutenegger, 1982; Rosenberg, 1992). Moreover, the transversally wider female pelvises are as efficient as male pelvises concerning the locomotor performance (Warrener *et al.*, 2015). However, bipedalism and erected posture are supposed to deeply reshape the birth canal. Figure 1 summarises these changes according to the comparative anatomy between humans and non-human primates. There are strong evidences that bipedalism has indirect consequences on the human birth process. However, its influences about the timing of parturition are still unclear. From a recent work analyzing the correlation between body size, pelvic and neonatal traits, Wells *et al.* (2017) suggest that pelvic dimensions are better predictors of neonatal size rather than nutritional status. This analysis of the correlations between maternal and neonatal traits is a reliable and innovative approach to understand how selective pressure impact fetal growth patterns. However, this work suffers from two limitations: the consideration of the head girth which does not correspond to the relevant cross-sectional area in human birth, and the use of clinic pelvimetry, *i.e.* external pelvimetric measurements, where variables are only proxy variables of the birth canal. The aims of this study are two-fold: first to investigate whether pelvic dimensions of the mother predicted birth size of the offspring, with the consideration of nutritional status and maternal height, but also with variables of the birth canal measured from computed tomography pelvimetry, and obstetrically relevant neonatal variables. We hypothesize that pelvic dimensions predict obstetrically relevant neonatal variables. These associations would reduce the risk of fetal-pelvic disproportion, and represent a remnant signature of obstetric dilemma in our sample. Second,

we want to check if uterus size mediates a potential correlation between pelvic traits and size of the offspring.

Materials and Methods

One hundred and thirty-one (131) women at Saint Joseph Hospital, March 29, 2011 to December 10, 2013 Marseille, France, were included in this single center study. The women were recruited from 10597 deliveries in the hospital. Inclusion criteria were birth at term with a fetus in cephalic presentation and computed tomography pelvimetry prior to labor. Exclusion criteria were maternal pre-eclampsia, twin pregnancies, caesarean deliveries performed in case of abnormal fetal heart rate, or before 2 hours of arrest of labor, in case of abnormal uterine contraction or iterative caesarean delivery. Newborns were also excluded if they had congenital infections, malformations or genetic syndromes. All the 131 women had epidural anesthesia during labor. The center has three protocols for the pelvic scanning based on patient adiposity: low (100kV, 25mA); standard (100kV, 35 mA) and high adiposity (120kV, 35mA). These three protocols produce low level irradiation ranging from 15 mGy/cm to 35 mGy/cm. Indications for computed tomography pelvimetry were scar at uterus, breech presentation (during the pelviscan but cephalic presentation at the beginning of labor), suspicion or history of fetal-pelvic disproportion. Computed tomography pelvimetry was performed with a 16 Siemens Definition Flash strips scanner located in the Medical Imaging Department of the hospital. Intersection gap was 0.6-1 mm. Pelvises were reconstructed and measured using Amira 5.0.0 software (FEI Visualization Sciences Group / Zuse Institute Berlin). The three pelvic variables were the conjugate, interspinous diameters and the sub-pubic angle (figure 1). The newborn measurements were performed during the postpartum period using anthropometric tools (cephalometric compass, tape measure, newborn scale). Newborn measurements were birthweight, head girth, suboccipitobregmatic girth, abdominal girth (figure 1). The same operator (PF) measured all the pelvises and newborns. Suboccipito-bregmatic girth is a relevant obstetrical variable since it correspond to the presenting dimensions of the well-flexed head. Since flexion is a cardinal movement of labor (Walrath, 2003), well-flexed presentation represents the most common presentation in human birth (Malinas and Favier, 1979). Maternal age (years) and gestational age (weeks) were recorded. Maternal weight and height were measured and Body Mass Index (BMI, kg/m²) calculated. Uterus height was measured with a plastic tape measure from the symphysis to the uterus fundus at the onset of labor. This study was approved by the South Mediterranean II Ethical Committee for Protection of Persons (1d-RCB 2011-A00072-39) and written informed consent was obtained from all the participants. Correlation analyses were performed with SPSS Statistics 17.0. A correlation was significant with a p-value <0,05. For statistics, we followed the method described in Wells *et al.* (2017). 1) Crude associations between maternal and neonatal traits were investigated. 2) Potential confounding effects of birth order and offspring sex in maternal and neonatal traits association were tested by ANOVA with birth order models correcting for multiple comparisons using the Bonferroni method. 3) Associations of maternal body size and BMI with neonatal traits were tested with multiple regression models. 4) To test if pelvic dimensions mediated these associations, we first added single pelvic dimension in the models, then we included all three pelvic dimensions and uterus height. 5) Associations of pelvic traits and uterus height with birthweight, and mediation of head girth in these associations were tested in additional models. All models were adjusted where relevant for offspring sex and birth order.

Results

The table 1 shows the descriptive analysis of the sample of the 131 mother-infant pairs. The mean maternal age is 31.9 years, ranging from 22 to 42 years. At the beginning of the pregnancy, the mean weight is 64.1 kg, ranging from 40 to 142 kg., the mean neonate weight at birth is 3433 g, ranging from 2300 to 4600 g. There are 62 male and 69 female infants. Twenty seven mothers are primipara, 97 are 2ndpara and 7 are thirdpara or more. Table 2 shows crude correlations between maternal and neonatal traits. Among neonatal traits, the three neonatal variables are significantly inter-correlated with coefficients between 0,45 and 0,77. Among maternal traits, height is highly correlated with conjugate and inter-spinous diameters ($r=0,424$ and $0,299$). Subpubic angle is correlated with inter-spinous diameter ($r=0,591$). Among neonatal and pelvimetry correlations, conjugate diameter is highly correlated with suboccipito-bregmatic girth ($r=0,235$). Uterus height is correlated with BMI ($r=0,387$) and all the four neonatal traits ($r=0,394-0,403$).

There is no significant association by ANOVA of birth order or offspring sex with maternal height or pelvic measurements. Concerning neonatal traits, there is no significant association of birth order or offspring sex with gestational age, birthweight or abdominal girth. Primiparas have a 1,5 cm higher uterus height compared to secondparas (95% CI 0,2-2,7). Female infants have a 7,5 mm larger head girth (95% CI 1,5-13,5), and a 7 mm larger suboccipito-bregmatic girth (95% CI 0,4-13,6) compared to male infants. Then, offspring sex and order are considered in subsequent regression models.

Table 3 provides multiple regression models for the prediction of neonatal size with maternal nutritional statut and pelvic measurements. When adjusted for birth order and infant sex, gestational age is a predictor of all neonatal traits but not the suboccipito-bregmatic girth. These associations remain when uterus height alone or all maternal traits are added to the model. Among pelvic measurements, conjugate diameter is a predictor of head girth and suboccipito-bregmatic girth. In the combined model, conjugate remains independent predictor of suboccipito-bregmatic girth. Among maternal traits, uterus height is significantly associated with neonatal traits in simple and combined models.

Table 4 shows additional multiple regression models, testing whether associations of maternal pelvic dimensions with birth weight are mediated by maternal height or neonatal head girth. Maternal height is a predictor of birthweight in simple models, but these associations disappear after adjusting for neonatal head girth. Uterus height remains significantly associated with birthweight in simple and combined models.

Discussion

Conjugate diameter represents the antero-posterior enlargement of the pelvic inlet. According to Schaal and Riethmuller (2007), the inlet is a rigid bony ring where the effect of pelvic relaxation is minimal. The inter-spinous diameter corresponds to the midplane breadth whereas the subpubic angle represents the anterior space of the outlet. Contrary to the inlet, dimensions of midplane and outlet can increase during the birth process thanks to the backward displacement of the 5th sacral vertebra with nutation and counternutation movements (Borell and Fernström, 1957a). Therefore, these latter two pelvic planes are not as critical during the fetal head descent than the inlet level. These different obstetric significances should explain the close relationship between the conjugate diameter and the suboccipito-bregmatic girth. Moreover, the suboccipito-bregmatic girth represents the circumference of a cross-section of the well-flexed presentation, which is the most common presentation in eutocic deliveries, while it enters the birth canal. It thus closely reflects the size of the

presenting part at the inlet level. This may explain why correlation between conjugate diameter and head girth is absent in this work since head girth rarely represents the size of the presenting part (*i.e.* in case of deflexed presentation).

According to Wells *et al.* (2017), we do not find correlation between BMI of the mother and the rest of the neonatal variables. The nutritional status seems to be a weak predictor of neonatal traits. We find correlations between maternal height and maternal pelvic size. Previous studies demonstrate the allometric relationship between the pelvic size and other anthropometric measures among females (Holland *et al.*, 1982; Ruff *et al.* 1997; Tague, 2000). This relationship may explain the dystocic outcome for women less than 1,60 m (Mahmood, 1988). Stature is positively correlated with the size of the inlet (Holland *et al.*, 1982; Tague, 2000). Bi-iliac breadth is used as a proxy of body mass (Ruff *et al.*, 1997). However, the correlation between stature and pelvic size could be different depending on the variable considered. In accordance with Holland *et al.* (1982), we find a positive association between maternal height and bipinnous diameter. Conjugate is positively correlated with maternal height, but also with femoral length, used as a proxy of stature, and not with femoral head diameter, a proxy of weight (Tague, 2000). Moreover, subpubic angle is not correlated with BMI or height, and the percentage of variance of this variable is independent of body size (Tague, 2000). Correlation between maternal height and birthweight, but not BMI, may reflect a selection on fetal growth adaptation to maternal phenotype rather than external ecological conditions (Wells *et al.*, 2017). The maternal height and conjugate diameter are highly correlated, as well as the sub-occipitobregmatic girth and conjugate diameter. Our findings suggest that the inlet size may drive the fetal growth process to adjust the birthweight to the size of birth canal. This process may reduce the risk of fetal-pelvic disproportion, increase the chance of mother-infant survival rate in a non-medicalized context, and appears to be a strong selection force as suggested by Wells *et al.* (2017). However, the mechanism explaining the limitation of the fetal growth process is still unclear. Dunsworth *et al.* (2012) suggest that the limitation from the maternal metabolism is the primary constraint of fetal growth. But this hypothesis does not explain the correlation between the pelvis and the fetal size. The metabolic hypothesis could be a consequence of a physical process that induces the onset of labor and limits the gestation length and the fetal growth. In this work we consider the symphyseal fundal height, a proxy of uterus size. As well, the uterus height is highly correlated with birthweight since it is used to assess the risk of intrauterine growth restriction in modern obstetrics practice (Ducarme *et al.* 2012). However, we do not find a correlation between the pelvic and uterus size. Our work brings new highlights in the complex relationship between gestational age, fetal size, uterus size and pelvic dimensions.

According to the obstetric dilemma hypothesis, pelvic dimensions and fetal size have to be strongly correlated since birthweight is a predictor of neonatal mortality (Kramer, 1987). Pelvic dimensions would act as a « bottleneck » that restricts birthweight and neonatal size with a mechanism of down-regulation: the smaller the pelvis, the smaller the neonate. This mechanism would be a crucial solution to protect the mother and her offspring from the risk of obstructed labor (Krogman, 1951; Washburn, 1960; Schultz, 1969; Rosenberg, 1992; Rosenberg and Trevathan, 1996; Wittman and Wall, 2007; Walsh, 2008; Franciscus, 2009; Trevathan, 2011). Yet, the relationship between pelvic dimensions and neonatal size could be more complex than previously described in the obstetric dilemma hypothesis. Pelvic dimensions partially predict neonatal dimensions in clinical practice (Ferguson *et al.* 1998). In this study, we investigate crude correlations among maternal and neonatal traits. We find that neonatal dimensions are strongly predicted by gestational age and uterus height.

According to Fournié *et al.* (2007), uterus height and gestational age are correlated since uterus height (minus 4, 3, 2, 1 cm or plus 1 cm) is equal to the gestational age (in weeks of amenorrhea). This correlation helps clinicians to predict fetal growth retardation or abnormality in amniotic fluid volume. Gestational age and neonatal traits are correlated because the timing of human parturition stops the growth process at a specific age of maturation. The volume of the gravid uterus increases during the pregnancy until it reaches a critical size where parturition is induced (Menon *et al.* 2016). However, uterus height and gestational age are not correlated in this study. Two main causes could explain this result: 1) symphyseal-fundus height cannot reliably estimate the volume of the gravid uterus, or 2) gestational age, in a broad sense the timing of parturition, is independent of maternal traits and is the only independent factor explaining the neonatal size. The reproducibility of symphyseal-fundus height was investigated in few studies: the interobserver coefficient of variation is 6.4% but the sample sizes are small (two groups of 6 patients) (Calvert *et al.* 1982, Jacobsen *et al.* 1990). Timing of parturition is a complex process implying inflammatory (Behnia *et al.* 2015) and mechanical factors (Shynlova *et al.* 2013). According to the pregnancy clock theory, the coordination of several signals orchestrates the parturition triggers (Menon *et al.*, 2016). Among these signals, fetal membrane senescence and more specifically the increase of telomere fragments in amniotic fluid near the term are supposed to be major initiators of the process of parturition (Poletini *et al.* 2015). This process is related to fetal maturation and ageing (Campisi *et al.*, 2007), which in turn corresponds to a stage where growth process is achieved. This reveals a close relationship between gestational age and neonatal traits, and between neonatal traits and uterus height. All of these variables are related to the same process that fits the pregnancy clock adjustments, but this process is independent of pelvic traits. Among neonatal traits, suboccipito-bregmatic girth is not correlated with gestational age in multiple regression models. This exception could be explained in regard to the crucial role of the suboccipito-bregmatic girth in the course of delivery.

Bipedal locomotion has dramatically reshaped the pelvis. This locomotion is supposed to be the source of many humanlike pelvic patterns such as 1) the reduction of the sacro-cotyloid distance (between the sacro-iliac joints and the hip-joints) (Berge *et al.* 1984), 2) the angulation of 90° between the inlet and outlet (Borell and Fernstrom, 1957b) (3) the anterior projection of the 1st sacral vertebra (also called the promontory) (Abitbol, 1996). Human locomotor and obstetrical constraints seem to be contradictory (Krogman, 1951; Berge *et al.* 1984; Franciscus, 2009). The obstetric conjugate is the distance between the anterior part of the promontory and the upper and posterior part of the pubic symphysis. Yet, it also represents the antero-posterior dimension of the inlet. Therefore, this variable reflects the adjustment between obstetric and locomotor demands. In our work, obstetric conjugate is correlated to suboccipitobregmatic girth. This head perimeter represents the dimension of the head in the birth canal in case of well-flexed presentation. The flexion of the head is a necessary condition for a safe delivery since deflexed head could lead to relative cephalo-pelvic disproportion (Maharaj, 2010). Moreover, head flexion is crucial for the rotation of the head during its descent in the birth canal. Head flexion has the advantage of increasing the rotational momentum created by the strength of contractions on the presentation and the resulting reaction force of the anterior border of the pelvic brim (Malinas and Favier, 1979). Rotation of the head permits that fetal head and the maternal pelvic dimensions line up at all pelvic planes during the birth process (Rosenberg and Trevathan, 2002). Indeed, in humans the inlet is longer in the oblique dimensions whereas the midplane and the outlet are longer in the sagittal (antero-posterior) dimensions (Rosenberg and Trevathan, 2002; Maharaj, 2010). According to the

obstetric dilemma hypothesis, rotational birth is an adaptation of the fetal head descent to the twisted shape of the birth canal that has been attributed to selection for increased biomechanical efficiency during bipedal locomotion (Rosenberg, 1992; Rosenberg and Trevathan, 1996; 2002; Franciscus, 2009; Trevathan, 2011). Rotational birth mechanism also appears because of the increase of neonatal head volume (Wittman and Wall, 2007) according to the increase of adult cranial capacity *i.e.* encephalization process, during the course of human evolution (DeSilva and Lesnik, 2008; DeSilva, 2011). Flexion of the head is a simple mechanism that minimizes the presenting cross-sectional diameter of the head. Indeed, the suboccipitobregmatic diameter is *c.a.* 9,5 cm whereas the occipito-frontal diameter, corresponding to the neutral presentation, is *c.a.* 11.5 cm (Maharaj, 2010). The correlation between obstetric conjugate and suboccipito-bregmatic girth could be explained by the close fitting between bipedal demands and the conflicting increase of neonatal head volume occurring during human evolution. This unique correlation between a pelvic and a neonatal trait could be the signature of the obstetric dilemma.

Conclusion

Maternal height is associated with pelvic traits following the allometric relationships previously described by many authors (Holland *et al.*, 1982; Ruff *et al.*, 1997; Tague, 2000). Fetal growth is more sensitive to inflexible component of maternal phenotype (height) rather than external ecological conditions and nutritional status proxied by BMI. Fetal growth process and maturation are independent of pelvic traits. However, the relationship between neonatal and pelvic traits is not uniform among the dimensions of the neonate. The close fitting between obstetric conjugate and suboccipitobregmatic girth appears obstetrically efficient. This might be a signature of the adaptation of human parturition to alleviate the obstetric dilemma.

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Figure 1 Maternal and neonatal traits

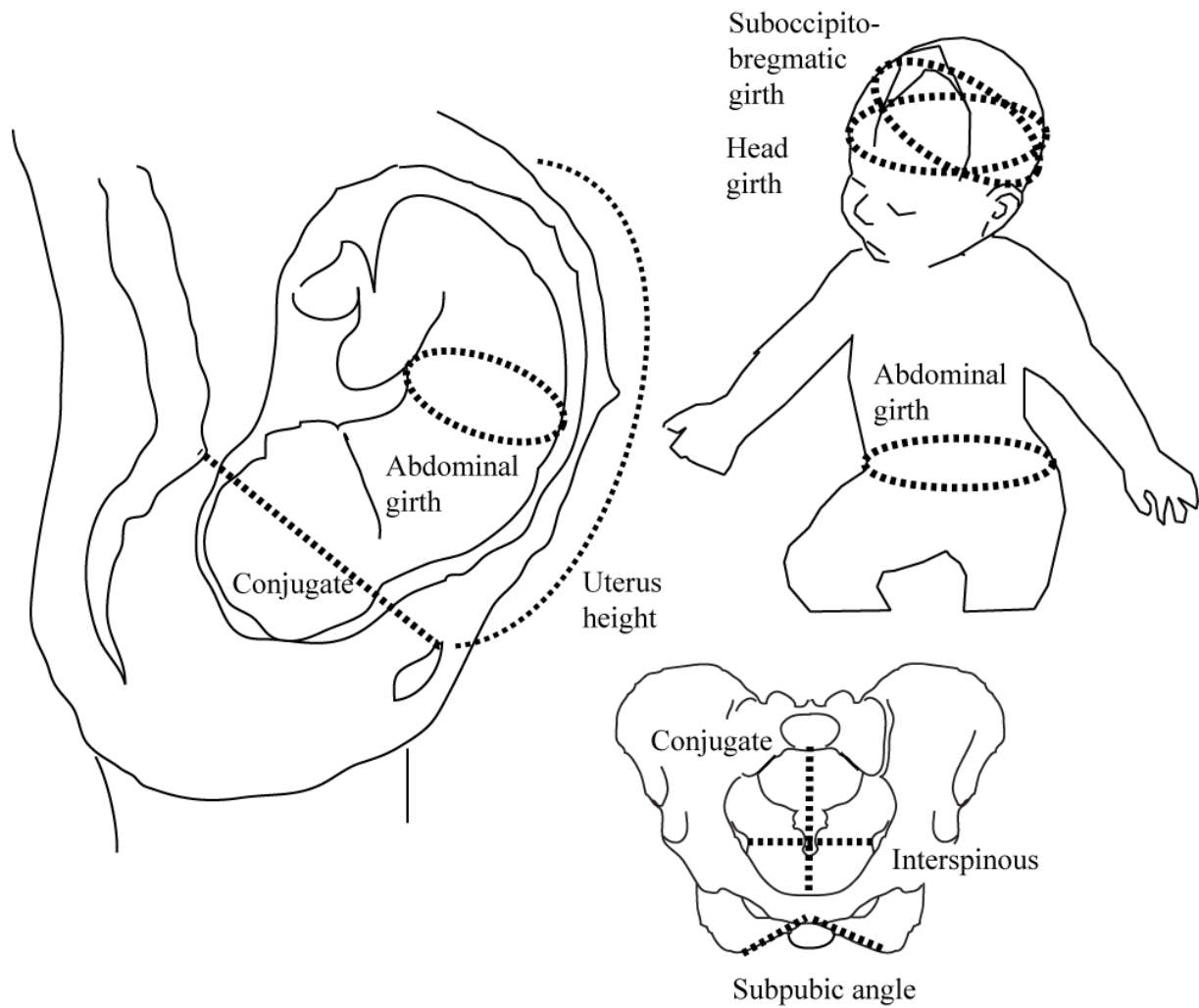


Table 1 Description of maternal and infant variables

Trait	Mean	SD	Range
Age (y)	31.9	4.5	22-42
Weight (kg)	64.1	14.1	40-142
Height (cm)	162.1	6.5	149-178
BMI (kg/m ²)	24.2	5.8	17-49
Conjugate diameter (mm)	121.1	9.2	95-142
Interspinous diameter (mm)	105.7	8.1	84-134
Subpubic angle (°)	83.7	6.9	68-100
Uterus height (cm)	33.2	2.4	29-41
Neonate			
Gestational age (wks)	39.5	1.1	37-41
Birth weight (g)	3433.3	489.9	2300-4600
Head girth (mm)	348.4	11.4	317-376
Suboccipito-bregmatic girth (mm)	327.8	11.4	299-355
Abdominal girth (mm)	330.6	22.4	270-396

SD, standard deviation

Table 2. Correlations among maternal traits and neonatal size

	Maternal trait				Neonatal trait				
	Conjugate	Inter-spinous	Sub-pubic angle	Uterus height	Gestational age	Weight	Head girth	Suboccipito-bregmatic girth	Abdominal girth
Maternal trait									
Height	0,424**	0,299*	-0,047	-0,030	0,060	0,220*	0,133	0,202*	0,193*
BMI	-0,101	0,073	-0,006	0,387*	0,003	0,106	0,120	0,029	-0,001
Conjugate		0,079	-0,170	-0,017	0,059	0,128	0,125	0,235**	0,132
Inter-spinous			0,591*	0,086	-0,121	0,127	0,101	0,085	0,146
Subpubic angle				0,052	-0,062	0,091	0,002	-0,004	0,058
Uterus height					0,120	0,527*	0,403*	0,449**	0,394**
Neonatal trait									
Gestational age						0,358*	0,360*	0,177*	0,287**
Weight							0,655*	0,645**	0,768**
Head girth								0,709**	0,449**
Suboccipito-bregmatic girth									0,447**

*. Correlation is significant at the 0.05 level. **. Correlation is significant at the 0.01 level.

Table 3. Multiple regression models of offspring traits on maternal BMI, uterus height and pelvic traits.

Predictor	Neonatal weight (g)				Neonatal head girth				Suboccipito-bregmatic girth				Abdominal girth			
	Beta	SE	P	r ²	Beta	SE	P	r ²	Beta	SE	P	r ²	Beta	SE	P	r ²
Constant	-4140.1	1693.5	0.016	0.16	185.6	36.3	<0.001	0.29	266.5	41.3	<0.001	0.08	30.3	80.2	0.706	0.11
Gestational age (w)	167.9	40.0	<0.001		3.6	0.8	<0.001		1.4	0.9	0.149		6.9	1.9	<0.001	
Maternal BMI (kg/m ²)	475.4	273.5	0.085		5.5	5.9	0.346		-1.1	6.7	0.873		22.4	12.9	0.086	
Constant	-5173.1	1775.1	0.004	0.18	159.6	37.8	<0.001	0.31	227.1	42.5	<0.001	0.13	-22.1	83.9	0.792	0.14
Gestational age (w)	166.6	39.6	<0.001		3.6	0.8	<0.001		1.4	0.9	0.151		6.9	1.9	<0.001	
Maternal BMI (kg/m ²)	569.3	276.2	0.041		7.9	5.9	0.182		2.5	6.6	0.704		27.2	13.1	0.039	
Congugate (mm)	7.9	4.4	0.076		0.2	0.1	0.037		0.3	0.1	0.005		0.4	0.2	0.057	
Constant	-5086.5	1770.5	0.005	0.18	163.4	37.9	<0.001	0.31	247.5	43.4	<0.001	0.09	-15.7	83.8	0.852	0.14
Gestational age (w)	172.4	39.8	<0.001		3.7	0.8	<0.001		1.5	0.9	0.125		7.2	1.9	<0.001	
Maternal BMI (kg/m ²)	378.0	277.4	0.176		3.2	5.9	0.584		-3.0	6.8	0.658		17.7	13.1	0.180	
Interspinous (mm)	8.6	5.1	0.092		0.2	0.1	0.065		0.2	0.1	0.166		0.4	0.2	0.083	
Constant	-5164.4	1778.6	0.004	0.16	187.2	37.8	<0.001	0.29	267.2	43.1	<0.001	0.07	16.1	83.5	0.848	0.12
Gestational age (w)	179.7	39.8	<0.001		3.6	0.9	<0.001		1.4	0.9	0.151		6.9	1.9	<0.001	
Maternal	377.1	278.1	0.177		5.7	5.9	0.342		-1.0	6.7	0.881		21.4	13.	0.105	

BMI (kg/m ²)														1		
Subpubic angle (°)	0.3	7.1	0.966		-0.2	0.1	0.872		-0.1	0.1	0.950		0.2	0.3	0.524	
Constant	-5807.4	1490.1	<0.001	0.39	155.3	33.9	<0.001	0.42	227.7	37.2	<0.001	0.29	-15.2	76.8	0.844	0.23
Gestational age (w)	134.6	35.2	<0.001		3.1	0.8	<0.001		0.7	0.9	0.419		5.6	1.8	0.002	
Maternal BMI (kg/m ²)	-147.0	253.6	0.563		-5.2	5.7	0.369		-15.0	6.3	0.019		2.7	13.1	0.837	
Uterus height (cm)	109.6	16.3	<0.001		1.9	0.4	<0.001		2.4	0.4	<0.001		3.5	0.8	<0.001	
Constant	-7225.9	1626.8	<0.001	0.41	129.0	36.6	0.001	0.45	190.7	40.1	<0.001	0.33	-92.7	83.3	0.268	0.27
Gestational age (w)	135.3	35.0	<0.001		3.1	0.8	<0.001		0.7	0.9	0.415		5.7	1.8	0.002	
Maternal BMI (kg/m ²)	-138.2	262.7	0.6		-4.9	5.9	0.404		-12.9	6.5	0.048		2.2	13.4	0.867	
Conjugate (mm)	5.7	4.0	0.155		0.1	0.1	0.150		0.2	0.01	0.021		0.3	0.2	0.154	
Interspinous (mm)	5.6	5.8	0.336		0.2	0.1	0.064		0.1	0.1	0.311		0.5	0.3	0.123	
Subpubic angle (°)	2.3	6.4	0.724		-0.2	0.1	0.231		-0.1	0.1	0.649		-0.1	0.3	0.901	
Uterus height (cm)	107.2	16.3	<0.001		1.8	0.4	<0.001		2.4	0.4	<0.001		3.4	0.8	<0.001	

Bold indicates predictors other than constant that are significant P<0.05.

Beta, untransformed B-coefficient; SE, standard error of B-coefficient.

Maternal BMI natural log-transformed.

All models adjusted for birth order and infant sex, by including (when significant P<0.1) dummy variables for second-born and infant sex.

Table 4. Multiple regression models of neonatal weight on maternal height, uterus height and pelvic dimensions

Predictor	Neonatal weight (g)							
	Beta	SE	P	r ²	Beta	SE	P	r ²
Constant	-5791.8	1776.7	0.001	0.20	-10051.1	1532.9	<0.001	0.48
Gestational age (w)	160.6	39.0	<0.001		68.1	33.6	0.045	
Maternal height (cm)	16.1	6.1	0.01		8.0	5.1	0.116	
Neonatal head girth (mm)					27.5	3.4	<0.001	
Constant	-5876.3	1784.8	0.001	0.20	-10052.0	1539.8	<0.001	0.48
Gestational age (w)	160.7	39.1	<0.001		68.1	33.8	0.046	
Maternal height (cm)	14.1	6.8	0.039		7.9	5.5	0.153	
Conjugate (mm)	3.3	4.8	0.494		0.1	3.9	0.985	
Neonatal head girth (mm)					27.5	3.4	<0.001	
Constant	-6226.7	1819.5	0.001	0.21	-10132.2	1560.2	<0.001	0.48
Gestational age (w)	165.1	39.2	<0.001		69.6	34.1	0.043	
Maternal height (cm)	13.9	6.4	0.031		7.5	5.3	0.155	
Interspinous (mm)	5.7	5.2	0.277		1.3	4.3	0.755	
Neonatal head girth (mm)					27.3	3.4	<0.001	
Constant	-6402.9	1859.6	0.001	0.21	-10646.4	591.8	<0.001	0.49
Gestational age (w)	161.4	39.0	<0.001		68.9	33.5	0.042	

Maternal height (cm)	16.4	6.1	0.008		8.4	5.1	0.100	
Subpubic angle (mm)	6.3	5.7	0.272		6.2	4.6	0.184	
Neonatal head girth (mm)					27.4	3.4	<0.001	
Constant	-8327.8	1548.8	<0.001	0.44	-10582.1	1421.2	<0.001	0.56
Gestational age (w)	128.2	33.7	<0.001		69.4	31.4	0.029	
Maternal height (cm)	16.5	5.3	0.002		10.1	4.8	0.036	
Uterus height (cm)	106.8	14.8	<0.001		70.2	14.5	<0.001	
Neonatal head girth (mm)					20.5	3.5	<0.001	

Bold indicates predictors other than constant that are significant $P < 0.05$.

Beta, untransformed B-coefficient; SE, standard error of B-coefficient.

Maternal BMI natural log-transformed.

All models adjusted for birth order and infant sex, by including (when significant $P < 0.1$) dummy variables for second-born and infant sex.

Annexe

Table: Comparaison of p-values of multiple regression models between our study and Wells *et al.* (2017)

Predictor	Neonatal weight (g)		Neonatal head girth	
	P (our study)	P (wells et al 2017)	P (our study)	P (wells et al 2017)
Constant	0.016	<0.0001	<0.001	<0.0001
Gestational age (w)	<0.001	<0.0001	<0.001	<0.0001
Maternal BMI (kg/m ²)	0.085	0.012	0.346	0.3
Constant	0.004	<0.0001	<0.001	<0.0001
Gestational age (w)	<0.001	<0.0001	<0.001	<0.0001
Maternal BMI (kg/m ²)	0.041	0.6	0.182	0.4
Congugate (mm)	0.076	0.004	0.037	0.009
Constant	0.005	0.002	<0.001	<0.0001
Gestational age (w)	<0.001	<0.0001	<0.001	<0.0001
Maternal BMI (kg/m ²)	0.176	0.6	0.584	0.5
Interspinous (mm)	0.092	<0.0001	0.065	0.003
Constant	0.004	0.012	<0.001	-
Gestational age (w)	<0.001	-	<0.001	-
Maternal BMI (kg/m ²)	0.177	-	0.342	-
Subpubic	0.966	-	0.872	-

angle (°)				
Constant	<0.001	-	<0.001	-
Gestational age (w)	<0.001	-	<0.001	-
Maternal BMI (kg/m ²)	0.563	-	0.369	-
Uterus height (cm)	<0.001	-	<0.001	-
Constant	<0.001	0.028	0.001	<0.0001
Gestational age (w)	<0.001	<0.0001	<0.001	<0.0001
Maternal BMI (kg/m ²)	0.6	0.18	0.404	0.2
Conjugate (mm)	0.155	0.6	0.150	0.2
Interspinous (mm)	0.336	0.006	0.064	0.079
Subpubic angle (°)	0.724	-	0.231	-
Uterus height (cm)	<0.001	-	<0.001	-