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# Maternal physical, socioeconomic, and demographic characteristics and childbirth complications in rural lowland Nepal: Applying an evolutionary framework to understand the role of phenotypic plasticity

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**Abstract**

**Objectives:** Evolutionary perspectives on human childbirth have primarily focused on characteristics of our species in general, rather than variability within and between contemporary populations. We use an evolutionary framework to explore how physical and demographic characteristics of mothers shape the risks of childbirth complications in rural lowland Nepal, where childbearing typically commences in adolescence and chronic undernutrition is widespread, though maternal overweight is increasing in association with nutrition transition.

**Methods:** We conducted secondary analyses of data from a cluster-randomized trial. Women aged 14–35 years were categorized by age, number of previous pregnancies, height, body mass index (BMI), husband's education, and household wealth. Multivariable logistic regression models tested whether these characteristics independently predicted risks of episiotomy and cesarean section (CS, $n = 14\,261$), and obstructed labor (OL, $n = 5185$).

**Results:** Risks were greatest among first-time adolescent mothers, though associations with age varied by outcome. Independent of age and parity, short stature and high BMI increased risks of CS and OL, whereas associations were weaker for episiotomy. Male offspring had increased risk of CS and OL but not episiotomy. Wealth was not associated with OL, but lower wealth and lower husband's education were associated with lower likelihood of episiotomy and CS.

**Conclusions:** At the individual level, the risk childbirth complications is shaped by trade-offs between fertility, growth, and survival. Some biological markers of disadvantage (early childbearing, short stature) increased the risk, whereas low socio-economic status was associated with lower risk, indicating reduced access to relevant facilities. Independent of these associations, maternal age showed complex effects.

# 1 | INTRODUCTION

From an evolutionary perspective, anthropologists have long approached the challenges of childbirth through the lens of the "obstetrical dilemma," a term coined by Sherwood Washburn (Washburn, 1960). According to this approach, human childbirth is subject to antagonistic selective pressures favoring reduced size of the bony birth canal to support bipedal locomotion, but larger dimensions of the fetal head. Washburn suggested that this antagonism was ameliorated by human babies being born at an earlier stage of development compared to other apes, reducing the fetal head dimensions attained at the typical time of delivery (Washburn, 1948; Washburn, 1960). The relatively tight fit between the maternal pelvis and the fetal head is considered to underlie the unique process of birth in our species, where the fetus typically rotates as it passes through the birth canal, and the near-universal need for social assistance at birth (Rosenberg & Trevathan, 2018).

Recently, however, Washburn's emphasis on antagonistic selective pressures has been critiqued from several angles (Dunsworth et al., 2012; Stone, 2016; Walrath, 2003; Warrener et al., 2015; Wells et al., 2012). Collectively, these authors have argued that the human obstetrical dilemma has been considered too much of a "given," and that women's pelvic variability is unrelated to the efficiency of locomotion (Warrener et al., 2015), that the short duration of pregnancy is linked with maternal energetic constraints on fetal growth (Dunsworth et al., 2012), that physical dimensions relevant to childbirth vary in association with local ecological conditions (Wells et al., 2012), and that childbirth complications could be reduced if traditional birthing positions and social strategies were more widely used (Rosenberg & Trevathan, 2018; Stone, 2016).

Therefore, further work is needed to explain the significant global burden of maternal and neonatal morbidity and mortality associated with childbirth (Ronsmans et al., 2006), and the variable epidemiological distribution of this burden (Rosenberg & Veile, 2019). In low- and middle-income countries (LMICs), for every mother who dies during childbirth an additional 30–50 suffer injury, infection, or disease (Islam, 2007).

While this burden of ill-health derives in part from inadequate medical facilities, other factors may also be important. First, birth outcomes may actually have worsened in association with a shift from traditional and socially supportive birthing practices to a more restrictive biomedical approach (Rosenberg & Trevathan, 2018; Veile & Kramer, 2018), representing the consequences of cultural change. Second, human morphological variability within and between populations may still be an important factor contributing to birth complication and injuries. To address this second issue, the evolutionary lens of the obstetrical dilemma may be shifted away from humans per se, and used instead to improve understanding of variability among individuals and populations in traits relevant to childbirth (Wells et al., 2012).

## 1.1 | An evolutionary perspective on individual variability in childbirth: The "coordination problem"

At a mechanistic level, childbirth may be considered as a "coordination problem" (Wells, 2015), whereby successful delivery requires a degree of matching between the physical dimensions of individual mother-infant dyads. There is increasing evidence that growth of the maternal pelvis as well as the fetus varies within and between populations (Betti & Manica, 2018; Ricklan et al., 2020; Shirley et al., 2020; Wells et al., 2012). An evolutionary perspective, therefore, remains very relevant to our understanding of how and why mothers experience variable outcomes to this coordination problem. Where variability in maternal or fetal phenotype reflects genetic factors, for example, the obstetrical dilemma could be considered to have been "re-negotiated" through the mechanism of natural selection (Wells, 2015).

Independently of genotype, however, coordination might also be improved or challenged through mechanisms of phenotypic plasticity, reflecting shorter-term exposure to environmental factors. From a broader perspective, human growth and development are understood to be subject to reaction norms shaped by competing selective pressures (Walker et al., 2006). On the one hand, the supply of energy constrains growth, and all other things being equal, growth and reproductive maturation are expected to occur at lower rates when the threat of malnutrition or food insecurity is higher. On the other hand, higher mortality risk during the juvenile period favors earlier maturation. In an analysis of 22 small-scale societies, both of these associations were supported, with several populations occupying high-risk environments demonstrating an average age at first female birth <18 years (Walker et al., 2006). These varying patterns of development across populations result in adult women showing different combinations of height, nutritional status, and the age of commencing reproduction.

Life history trade-offs between survival, growth, and reproduction may, therefore, be important in shaping childbirth outcomes. Specifically, maternal life history trade-offs may shape both the dimensions of the pelvis and levels of body fat stores, while maternal metabolism during pregnancy is the primary ecological factor impacting the offspring's size at birth (Wells, 2010).

For example, poor growth in early life may constrain dimensions of the maternal pelvis (Shirley et al., 2020). This may reflect exposure to an inadequate energy supply or an increased allocation of resources to immune function in early life (Urlacher et al., 2018), reducing the allocation of resources to skeletal growth. Many studies have shown that shorter mothers are at greater risk of obstructed labor (Amoa et al., 1997; Desai et al., 1989; Sokal et al., 1991; Wells, 2017). Early childbearing may itself contribute to such trade-offs, as early reproduction has been associated with shorter maternal stature in adulthood (Casanueva et al., 2006; Marphatia et al., 2021; Rah et al., 2008).

Fetal growth, also relevant to the risk of childbirth complications, is largely determined by maternal metabolic phenotype, as only around 30% of the variability in birth weight can be attributed to parental genotype (Lunde et al., 2007; Magnus et al., 2001). Consequently, higher maternal body mass index (BMI) may contribute to the risk of obstructed labor by promoting high levels of fetal growth (Liu et al., 2011; Mochhoury et al., 2013; Munim & Maheen, 2012; Wells, 2017; Wells et al., 2012). BMI often changes substantially within mothers over the reproductive career, hence the timing of reproduction may shape the trade-offs that underlie variability in birth weight (Prentice et al., 1987; Rosenberg, 1988).

Crucially, environmental factors that affect fetal growth are expected to act later than those affecting growth of the maternal pelvis (Wells, 2015), so that differences in ecological conditions across generations may raise the risk of "poor coordination" and childbirth complications. For example, while maternal short stature and maternal overweight are each associated with an increased risk of cesarean delivery (Wells, 2017), analysis of Demographic and Health Survey (DHS) data from India found that these risks were additive, and were greatest in dyads where maternal BMI and offspring birth weight were high while the mother was also short (Wells et al., 2018). Similar findings emerged from analysis of DHS data from several other LMICs (Mendez-Dominguez et al., 2020; Wells et al., 2020). Longitudinal analysis supports the hypothesis that rapid environmental change, generating different effects on female phenotype depending on age, may increase the risk of "poor coordination" (Wells et al., 2018).

### 1.2 | Applying an evolutionary approach to childbirth in low-income populations undergoing nutrition transition

The framework outlined above may be especially helpful for understanding childbirth complications in low-income settings, where a number of risk factors may co-exist. We focus here on three related issues: early childbearing, chronic undernutrition, and rapid nutrition transition which drives life-course exposure to the "double burden of malnutrition" in individual women (Wells et al., 2020).

The UN considers women's marriage before 18 years to be unlawful (United Nations, 1962), and this is supported by substantial evidence that under-age marriage is harmful to women's autonomy, education and general and reproductive health, while also adversely affecting health of the offspring (Marphatia et al., 2017). Despite this, early marriage remains common in many geographical regions, such as sub-Saharan Africa and South Asia (UNICEF, 2019). In Nepal, where the research described below was conducted, national legislation prescribes 20 years (18 years with parental permission) as the minimum acceptable age (Government of Nepal, 1971), yet according to recent data, about 40% of all women aged 20–24 years still married before 18 years (Nepal Ministry of Health, 2017). In such populations, norms for early marriage represent a cultural gateway to early reproduction.

A comprehensive analysis of data from 144 countries and territories found that adolescent mothers had only slightly greater mortality risk compared to mother's age 20–24 years (Nove et al., 2014). Nonetheless, early childbearing has been associated with high maternal morbidity during pregnancy and labor. For example, a survey on maternal and newborn health across 29 countries by the World Health Organization (WHO) found that, compared with mothers aged 20–24 years, adolescents under 16 years of age had higher risks of cesarean section, eclampsia, and uterine and systemic infections (Ganchimeg et al., 2014). The magnitude of these risks was generally higher for the youngest mothers, aged 15 years or below.

However, it remains unclear *how* early reproduction may contribute to childbirth complications in disadvantaged populations, independent of other risk factors. Potentially, adolescent mothers are still growing in height and pelvic dimensions, and early reproduction might constrain this skeletal development. For example, cross-sectional studies of women from India found that pelvic dimensions and height both increased in association with age through the 20s and into the earlier 30s (Sharma et al., 2016; Wells et al., 2018), while in three north American historical populations, pelvic growth likewise appeared to continue during the third decade (Tague, 1994). These studies suggest that skeletal traits relevant to childbirth might continue to grow long after adolescence in its conventional sense has completed, putting adolescent mothers at a relative disadvantage.

However, analyses of five large LMIC cohorts indicated that maternal reproduction before 20 years was associated with a 20–30% increased risk of low birth weight and preterm delivery (Fall et al., 2015), suggesting that in younger mothers the obstetrical dilemma may partly be resolved by producing smaller offspring. Such a response would be adaptive for both mothers and offspring, given that surgical solutions to childbirth complications were likely minimal until relatively recently. The low genetic contribution to birth weight may enable fetal growth to adapt to maternal skeletal dimensions (Wells, 2015). Consistent with that hypothesis, a study of Brazilian women found that adolescent mothers <20 years had smaller pelvic dimensions than those of older mothers (Alves et al., 2013), and this was associated with 125 g lower birth weight, equivalent to 4%. Moreover, even in the non-adolescent women in this sample, pelvic dimensions predicted birth weight better than did maternal BMI (Wells et al., 2017).

Where early reproduction and linear growth constraint in early life interact with rapid nutrition transition, the likelihood of "poor coordination" may be increased. This scenario has been reported previously for cesarean section (Mendez-Dominguez et al., 2020; Wells et al., 2018; Wells et al., 2020). However, a limitation of previous research is that data on obstructed labor itself are not collected in DHS surveys. Cesarean delivery is a challenging outcome to interpret, as the procedure is used for various reasons, some medically indicated but unrelated to cephalopelvic disproportion or other forms of obstructed labor, and others not associated with medical need (Boerma & Ronsmans, 2019; Neuman et al., 2014; Rosenberg & Trevathan, 2018; Rosenberg & Veile, 2019). There is widespread concern that the rate of cesareans is excessive in wealthier groups, reflecting factors such as wealth and defensive medicine (where clinical decisions are influenced by the aim of protecting clinicians from litigation), whereas in poorer settings the facilities required may be inadequate (Boatin et al., 2018). Therefore, other outcomes are needed to understand associations of environmental and maternal factors with childbirth complications.

In settings with fewer resources, delivery is often facilitated by a simpler form of surgery, episiotomy, where an incision is made in the perineum and posterior vaginal wall. A meta-analysis of 74 surveys from 41 LMICs estimated that 46% of all births involved episiotomies, while 25% involved birth injuries (Aguiar et al., 2019). These data are likely to come both from countries where episiotomy is routinely used, a practice discouraged by WHO, and from those that have a more restrictive policy (Jiang et al., 2017; WHO Reproductive Health Library, 2018). As with cesareans, there is concern that episiotomies are often undertaken beyond their medical need, and rates differ substantially between countries. For example, the frequency in India is around four times higher than in adjacent Nepal (Aguiar et al., 2019), suggesting either that there is a more restrictive policy on their use in Nepal, or that there are greater limits to their availability.

Our aim in this study was to apply the evolutionary framework described above to improve understanding of the multiple risk factors for selected childbirth complications in a vulnerable population where under-age marriage and early first reproduction are the norm, poverty and chronic undernutrition are widespread, but where maternal overweight is also becoming more common in association with the nutrition transition (Figure 1). These traits may be interconnected, for example in the same population we have recently shown that both early marriage and early childbearing are associated with shorter adult height (Marphatia et al., 2021). Using secondary analysis of data from a large randomized trial in lowland Nepal, we investigate here how four maternal traits (young age, low parity, short stature and high BMI) are associated with the risks of episiotomy, cesarean section, lengthy labor and obstructed labor, while also taking into account offspring sex and markers of socio-economic status that might affect access to medical facilities.

## 2 | METHODS

Our study focuses on the predominately Maithili-speaking Madhesi population, living across Dhanusha and Mahottari districts in Province 2 of the lowland Terai region of Nepal. The data come from the cluster randomized controlled (nonblinded) "Low Birth Weight South Asia Trial" (LBWSAT), conducted between 2013 and 2015 (Saville et al., 2016; Saville et al., 2018); Trial registration: ISRCTN75964374. This trial assessed the impact of pregnancy interventions on birth weight and weight-for-age $z$-score in children aged 0–16 months. The trial protocol and main results are described elsewhere (Saville et al., 2016; Saville et al., 2018; Style et al., 2017). Briefly, all married women aged 10–49 years residing in 80 Village Development Committees (VDC) in the two selected districts who had not had operative family planning, and whose husbands had not had vasectomy were eligible to participate in the trial. A total of 64 000 eligible women consented to menstrual monitoring, and 25 090 pregnant women were recruited into the trial (Saville et al., 2018). Population clusters were randomized to one of four arms: (a) Participatory Learning and Action (PLA) behavior change approach in Women's Groups, (b) PLA with unconditional cash transfers, (c) PLA with a fortified blended food supplement, or (d) a control

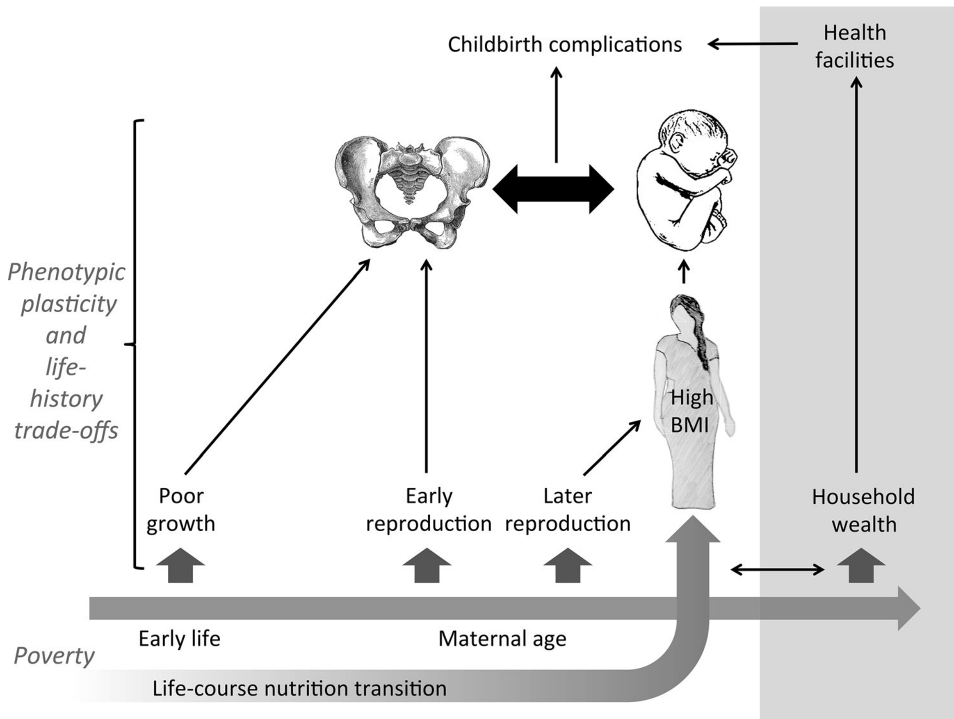


**FIGURE 1** Conceptual diagram illustrating a life-history perspective on the "obstetrical dilemma," whereby the physical traits of the mother and the fetus that are relevant to the risk of childbirth complications reflect plastic responses to ecological conditions at different stages of the life-course. The dimensions of the obstetric pelvis may be influenced by growth faltering in early life or adolescence, and may also not have reached their final size if the mother reproduces early in adolescence. Conversely, the size of the offspring at birth is shaped by maternal metabolism before/during pregnancy, proxied by maternal body mass index, which increases both with maternal age and with greater life-course exposure to nutrition transition. Finally, in a population with high poverty levels, household financial status may also influence access to medical facilities, should childbirth complications occur

group who had access to usual Government of Nepal health services.

Research ethics approval for the original trial was obtained from the Nepal Health Research Council (108/2012) and University College London (UCL) Research Ethics Committee (4198/001). Consent for inclusion of villages in the trial was obtained from VDCs. Written consent was obtained from women regardless of their age with guardians also consenting to participation of married adolescents (<18 years of age). Additional ethical approval for the secondary analysis was obtained from UCL (0326/015), the University of Cambridge (1016) and the Nepal Health Research Council (292/2018).

## 2.1 | Data collection

Questionnaires were administered verbally to pregnant women by trained fieldworkers, using smartphones. Data were collected on current age, age at marriage and first pregnancy, education level of the woman and her husband, caste and parity. Pregnancy refers to any conception that was detected by the woman, and included miscarriages, abortions, stillbirths, or livebirths. Data collection from each participant continued through the trial, and was scheduled to cover late pregnancy, delivery, and early infancy.

At the trial's endpoint, when children ranged in age from birth to 22 months, a cross-sectional endpoint study captured information on maternal and child anthropometry and details of the delivery. At birth or endpoint, data were obtained on place and type of delivery (including episiotomy and cesarean delivery), offspring sex, and birth outcomes. Our interest in these delivery outcomes was focused on childbirth itself, rather than future health issues. Data were also collected on where the birth occurred (home, health institution, or on the way to an institution). Obtaining data on childbirth complications by maternal self-report is not ideal, as it may not accurately reflect clinical diagnosis. Moreover, clinical criteria may themselves be problematic, due to an inherent overreliance on physical markers of labor. Inadequate attention has been directed to the fact that labor is also sensitive to the stress response, and may, therefore, vary according to the forms of social support available (Rutherford et al., 2019).

In this setting, women may receive assistance during delivery from a wide variety of sources. Nepal introduced a Skilled Birth Attendant (SBA) policy in 2006 to specifically address high maternal and neonatal mortality, as a minority of birthing women were attended by health workers (Paudel et al., 2019). To be considered a SBA in Nepal the health worker must have attended specific government-endorsed SBA training and usually auxiliary nurse midwives (ANMs) and staff nurses receive this. Compared with trained SBAs, more informally trained Maternal and Child Health Workers and ANMs were less effective in preventing maternal and neonatal deaths (Paudel et al., 2019). The delivery questionnaire therefore recorded the most skilled (or senior) health worker or family member that assisted during the delivery, and also asked the mothers whether they considered that a skilled health worker was present or not.

A household wealth score was derived using principal component analysis (see Supporting Information). Each household was assigned a score based on the ownership of 12 items, including a number of consumer goods (television, bike, and computer), and household infrastructure, including source of drinking water, facilities for toilets, materials for flooring, roof and walls, and access to electricity and nonbiomass fuel use. The first principal component had positive factor loadings for all 12 variables and accounted for 30.2% of the variability, compared to 10.5 and 8.5% from the second and third principal components, thus this score was taken as the marker of wealth.

Maternal weight was measured both in early and late pregnancy. Maternal height was measured in early pregnancy where possible, but at other time points if initially missing. BMI was calculated from concurrent height and weight measures where available, but otherwise using the available height measurement regardless of timing.

Only a subsample ($n = 7703$) participated in the assessment at the time of delivery. This subsample had additional data collected on infant gestational age and anthropometry, the mother's recall of duration of labor, and whether the mother responded positively to the statement that the "baby got stuck" as a marker of obstructed labor. Offspring length, weight and head circumference were recorded within 72 h of delivery for many, but data were also collected up to 42 days postpartum if the birth weight window was missed.

## 2.2 | Data processing

Women's current age and age at marriage were recorded as integer values in "running years," that is, the year they are running in rather than the year of age already completed (y) and were then converted to completed years (running years minus 1) for analysis. Due to small numbers outside this range, we restricted analysis to women aged 14–35 years inclusive, omitting 15 women (0.1%) younger and 183 (0.9%) older than this age range. Maternal age groups were then categorized as follows: 14–16 years, 17–20 years, 21–24 years, 25–28 years, and 29–35 years. Women's marriage age was categorized as a categorical variable: <13 years, 13-15 years (childhood), 16–17 years (adolescence) or 18+ years (above legal age of marriage or older). We excluded mothers of twins ($n = 145$) and triplets ($n = 1$).

Educational attainment, recorded as the number of years in school, was categorized for each parent according to the structure of the education system in Nepal: never went to school, primary/lower secondary, or secondary/higher (Ministry of Education Nepal, 2016). Caste affiliation was categorized as disadvantaged (Dalit, Muslim), middle (Janjati, other Terai), or advantaged (Yadav, Brahmin). The wealth score data were converted into quintiles.

As some women gave birth to more than one infant during the trial, we restricted the analysis to one pregnancy and one offspring per woman to ensure that measures were independent. The number of previous pregnancies was categorized as 0, 1, 2, 3, or 4+. Births were categorized using a questionnaire that permitted one of the following responses: normal vaginal delivery, manual manipulation, vacuum extraction, forceps, episiotomy, or cesarean section. In the case that manual manipulation preceded other intervention the latter intervention was recorded. In the subsample, the duration of labor was categorized as <24 or > 24 h, a convenient marker of lengthy labor used in other studies in Nepal (Rayamajhi et al., 2009). From the data on assistance at delivery, we generated a binary variable, whether a skilled health worker was present or not.

Neonatal anthropometric values were restricted to those measured <8 days after birth. Maternal height was categorized into three groups, using cutoffs for short stature of <145 cm (equivalent to the ~15th centile) and 145–148 cm (equivalent to the ~30th centile). Maternal BMI was categorized into four groups in early (<19.0, 19.0–20.49, 20.5–21.99, 22+ kg/m$^2$) and late (<21, 21–22.49, 22.5–23.99, 24+ kg/m$^2$) pregnancy respectively, to differentiate thinness, normal weight and lower and upper levels of overweight.

## 2.3 | Statistical analysis

The magnitude of bias due to selective data collection following delivery was assessed by comparing maternal characteristics for those with delivery data against those lacking such data. Data summaries (frequencies and percentages) were provided for all exposure and outcome groups, as well as potential confounding variables.

Deliveries by cesarean section or episiotomy were considered the primary outcomes. Secondary outcomes, due to the smaller sample size, were labor lasting >24 h and obstructed labor. Exposures were maternal age groups, using the oldest group as the reference; the number of previous pregnancies, using 4+ as the reference; maternal short stature, using women >148 cm as the reference; and maternal BMI in late pregnancy, using women <21 kg/m$^2$ as the reference. Preliminary analysis indicated that BMI in late pregnancy was more predictive of birth outcomes than BMI in early pregnancy, and was therefore preferred in the multivariable models described below. Preliminary analyses also found paternal education more predictive than maternal education, so paternal education was used in final models.

Chi-squared tests were used to assess differences in the frequency of adverse birth outcomes in association with maternal age groups or the number of previous pregnancies, and with the frequency of sons by maternal anthropometric categories. The same approach was used to assess age differences in the frequency of short stature, or high BMI in early/late pregnancy.

In the subsample with available data, neonatal anthropometry was compared across groups of maternal age and the number of previous pregnancies. Each component of neonatal size was also converted into approximate tertiles, using the following cut-offs: birth length (cm) <47, 47–48.99, 49+; birth weight (kg) <2.6, 2.6–2.99, 3+; birth head circumference (cm) <32.5, 32.5–33.9, 34+. Chi-squared tests were used to assess differences in the frequency of adverse birth outcomes in association with different categories of birth size, however, this analysis was not undertaken for cesarean section as the sample size for anthropometry among those receiving this procedure was very low.

Correlations between maternal traits were tested using Spearman's coefficients. Mean neonatal size was described (mean, SD) across categories of maternal phenotype, and trends were analyzed fitting linear regression models.

Data on neonatal head girth allow calculation of head cross-sectional area and volume, based on two assumptions: that head circumference represents a circle, and that head volume represents a sphere. On this basis, the radius ($r$) of the circle ($C$), its cross-sectional area ($A$), and the volume ($V$) of the associated sphere can be calculated using the formulae $r = \frac{C}{2\pi}$, $A = \pi \times r^2$, and $V = \frac{4}{3}\pi \times r^3$.

Finally, multivariable logistic regression models were fitted to investigate independent associations of the exposures (maternal age, pregnancy number, height, and BMI) with the two primary outcomes, taking into account potential confounders (namely, education, wealth, and offspring sex). Similar models were developed for the secondary outcomes in the subsample. Due to the large amount of missing data on maternal BMI in late pregnancy, we did not implement a multiple imputation procedure, and initial models included only maternal height. Additional models tested the effect of adding in maternal BMI for a complete-case scenario. We also tested whether the trial arm was a significant covariate in these models, adjusting for the cluster as a random effect.

All analyses were undertaken using SPSS 26 (IBM Corp., Armonk, NY).

## 3 | RESULTS

There were differential levels of data capture at the different study time-points, such that respondent numbers differ for given exposures and outcomes. The potential biases resulting have been described in detail (Saville et al., 2020) and are in all cases small in magnitude.

Among women within the eligible age range ($n = 24\,414$), data on the primary outcome, C-section, were available for 19 103 (78.7%). Compared to those with data, those with missing data ($n = 5210$) were slightly younger (−0.8 years), wealthier (+0.19 wealth score), more educated (+0.1 years), had slightly more educated husbands (+0.1 years), and had been slightly older at marriage (+0.3 years). However, while these differences were all statistically significant, the magnitudes of effect were in each case negligible relative to the span in the population, so were not considered likely to affect any of the subsequent analyses. There was no evidence that height or BMI in early pregnancy varied in association with missing data ($p = .4$). There was a trend to higher BMI in late pregnancy in those missing data ($p = .075$), however the magnitude of the effect was small (+0.4 kg/m$^2$).

A description of the 19 103 women (aged 14–35 years inclusive) analyzed is given in Table 1. The majority (~70%) were aged between 17 and 24 years. The median age at first pregnancy was 17 (inter-quartile range 3) years. Almost two thirds had no education at all, with one fifth having attended primary/lower secondary school, and only 15% secondary school or higher. Similarly, almost half of all husbands were uneducated, and only a quarter had either primary/lower secondary school, or secondary school or higher, respectively. In 42% of households (8032), neither parent had any

**TABLE 1** Summary statistics ($n$ = 19 103)

| | *n* | % |
|---|---|---|
| Maternal age (years) | | |
| 14–16 | 1618 | 8.5 |
| 17–20 | 7398 | 38.7 |
| 21–24 | 5837 | 30.6 |
| 25–28 | 2531 | 13.2 |
| 29–35 | 1719 | 9.0 |
| Maternal age at marriage (years)[b] | | |
| <13 | 889 | 4.7 |
| 13–15 | 9062 | 47.4 |
| 16–17 | 4789 | 25.1 |
| 18+ | 1705 | 10.4 |
| >19 | 980 | 5.2 |
| Maternal education | | |
| Never went to school | 12 394 | 64.9 |
| Primary/lower secondary | 3820 | 20.0 |
| Secondary or higher | 2824 | 14.8 |
| Husband's education | | |
| Never went to school | 9239 | 48.5 |
| Primary/lower secondary | 5201 | 27.3 |
| Secondary or higher | 4598 | 24.2 |
| Caste | | |
| Dalit/Muslim disadvantaged | 6763 | 35.4 |
| Janjati/middle class | 8145 | 42.6 |
| Yadav/Brahmin least disadvantaged | 4195 | 22.0 |
| Number of previous pregnancies[a] | | |
| 0 | 6598 | 34.6 |
| 1 | 5039 | 26.5 |
| 2 | 3843 | 20.2 |
| 3 | 2111 | 11.1 |
| 4+ | 1460 | 7.7 |
| Place of delivery | | |
| Home | 11 290 | 59.1 |
| Health institution | 7588 | 39.7 |
| On the way to health institution | 225 | 1.2 |
| Type of delivery | | |
| Normal vaginal delivery | 15 566 | 81.5 |
| Manual manipulation | 458 | 2.4 |
| Ventouse | 29 | 0.2 |
| Forceps | 55 | 0.3 |
| Episiotomy | 1546 | 8.1 |
| Cesarean section | 1449 | 7.6 |
| Labor >24 h (subsample of 6305) | | |
| No | 5143 | 81.6 |
| Yes | 1162 | 18.4 |
| Baby got stuck (subsample of 6305) | | |
| No | 5386 | 85.4 |
| Yes | 919 | 14.6 |

[a]Missing data $n$ = 53.
[b]Missing data $n$ = 2658.

education. Over 40% of households were from the middle caste grouping, with one-third being from the disadvantaged caste and one fifth from the advantaged caste.

Around one-third of the mothers were undergoing their first pregnancy, with the majority of the others in their second or third pregnancy. However, 8% of the sample had >4 previous pregnancies, with the maximum being 10.

Overall, 59% of the women gave birth at home, while 40% delivered at a health institution, and 1% on the way to such an institution. The majority of the women (81%) had a vaginal delivery, with 8.1% having an episiotomy and another 7.6% a cesarean section. The vast majority of surgical operations (cesareans 98.7%; episiotomies 98.1%) were undertaken at a health institution. In the subsample of 6305 women with more detailed data about delivery, 18.4% had experienced labor for more than 24 h, and 14.6% recorded that the "baby got stuck" during delivery. Home births accounted for 34.7% and 36.3% of those involving labor >24 h and obstructed labor, respectively.

The vast majority of episiotomies (94.4%) and cesarean sections (93.0) occurred in births where a Skilled Health Worker was present, however around a quarter of births characterized by lengthy duration of labor (26.9%) and obstructed labor (22.5%) occurred in the absence of a skilled attendant. The proportion of births where a Skilled Health Worker was present increased in association with both maternal and paternal education (Table S1).

A subsample of 7703 women had data on assistance during delivery. Those with such data were slightly taller (0.1 cm) and poorer (−0.1 wealth score) than those missing data, and were less likely to have delivered in a health institution (odds ratio [OR] 0.93, 95%CI 0.91, 0.95), but there was no difference in age. Among these women, there was wide variability in who assisted most at delivery (Table 2). The main source of help differed significantly according to the location of birth, with medical

**TABLE 2** Distribution of main delivery attendants

| | *n* | % |
|---|---|---|
| Doctor | 1004 | 13.0 |
| Staff nurse | 1385 | 18.0 |
| Auxiliary nurse midwife | 509 | 6.6 |
| Health assistant/auxiliary health worker | 455 | 5.9 |
| Maternal and child health workers/ village health worker | 61 | 0.8 |
| Female community health volunteers | 133 | 1.7 |
| Traditional birth attendant/trained or traditional/chameni | 1188 | 15.4 |
| Mother in law | 842 | 10.9 |
| Other relatives | 729 | 9.5 |
| Neighbor/friend (including medical shop owner) | 644 | 8.4 |
| Village practitioner | 386 | 5.0 |
| Shaman | 3 | 0.0 |
| Nobody assisted | 364 | 4.7 |

*Note:* Subsample of 7703 women interviewed between 0 and 42 days after delivery.

personnel (doctor, nurse, ANM) restricted almost entirely to health institutions (>90%). The vast majority of episiotomies (96.9%) and cesareans (99.5%) were undertaken where a doctor, staff nurse, or ANM was the main source of help during delivery.

Women in the subsample for more detailed birth outcomes were poorer (−0.1 wealth score) and shorter (−0.3 cm) but did not differ in age or BMI in early or late pregnancy compared to those missing this assessment. Women in the subsample were less likely to have had an episiotomy (7.0 vs. 8.6%, $p < .0001$) or cesarean delivery (5.4 vs. 8.7%, $p < .0001$) compared to those missing this assessment. In the subsample, labor >24 h was associated with an increased risk of episiotomy (OR 4.20, 95%CI 3.44, 5.13), cesarean section (OR 5.24, 95%CI 4.19, 6.56) and with an increased risk of obstructed labor (OR 3.98, 95%CI 3.42, 4.63).

Table 3 presents correlations between maternal traits. Household wealth, education of both the mother and her husband, and height all correlated negatively with age, BMI positively. Anthropometric outcomes correlated positively with education of both mother and her husband. Height correlated inversely with BMI, though not significantly so in late pregnancy, while there was a strong correlation as expected between BMI in early and late pregnancy.

Overall, mean height in the sample was 150.5 (SD 5.4) cm, while mean BMI was 20.9 (SD 2.4) kg/m$^2$ in early pregnancy and 22.6 (SD 2.5) kg/m$^2$ in late pregnancy. The trends of these variables with age are shown in Figure 2. Those aged 14–15 years were ~0.5 cm shorter than those aged 16–22 years. From the latter age, height showed a small, non-significant decline with increasing age, indicating a secular increase over the last two decades of +0.3 cm (95%CI −0.1, 0.8) per decade. BMI was likewise lower in women aged 14–15 years in early pregnancy (−0.6 kg/m$^2$, 95%CI −1.3, 0), however from 16 years to 28 years there was little variability. Those aged 29+ years tended to be heavier in early pregnancy (0.6 kg/m$^2$, 95%CI 0.2, 0.9) than those aged 16–28 years. In late pregnancy, there was less of an association with age, and differences of those aged 14–15 years (−0.1 kg/m$^2$, 95%CI −0.8, 0.5) and those aged 29+ years (0.3 kg/m$^2$, 95%CI −0.1, 0.6) relative to those aged 16–28 years did not reach significance. Overall, age explained <1% of the variability in each of these physical characteristics.

Table 4 presents neonatal anthropometry stratified by categories of maternal phenotype. All three components of neonatal size broadly increased in association with maternal age, the number of previous pregnancies, height and BMI in both early and late pregnancy. The frequency of delivering sons was significantly greater in association with taller maternal height ($p = .013$) and heavier early pregnancy BMI categories ($p = .04$) but not with heavier late pregnancy BMI categories (Table S2). Birth size showed no significant trend with the frequency of episiotomy, whereas the frequencies of lengthy duration of labor and obstructed labor increased in association with birth length, weight, and head circumference (Table S3).

Delivery outcomes are compared by maternal traits in univariable analyses (Table S4). Among the whole sample, all adverse birth outcomes became significantly less common with increasing maternal age. A similar pattern was evident for parity, with first-time mothers most affected by adverse outcomes. However, when the analysis was restricted to first-time mothers only, the age-associations changed. The rate of episiotomy still declined with age, whereas the rate of cesarean increased, while long labor and obstructed labor now showed no trend. Figure 3 plots the rate of episiotomies, cesarean delivery and other procedure (forceps or ventouse) by age group. Combining these three outcomes as a composite indicator of childbirth complications, 28.8% of the youngest group underwent one of the two operations, in comparison with 9.3% of the oldest group. However, the number of previous pregnancies was very strongly associated with maternal age group, with 92.2% of women aged 14–16 years, but only 5.8% of women aged 29+ years, delivering for the first time (Table S5). This emphasizes the need to disentangle associations of childbirth

**TABLE 3** Correlations between maternal traits

| | Wealth | Education | Husband's education | Height | BMI early pregnancy | BMI late pregnancy |
|---|---|---|---|---|---|---|
| Age | −0.11 | −0.28 | −0.16 | −0.02 | 0.06 | 0.04 |
| Wealth | | 0.40 | 0.42 | 0.13 | 0.09 | 0.10 |
| Education | | | 0.54 | 0.12 | 0.04 | 0.05 |
| Husband's education | | | | 0.11 | 0.05 | 0.07 |
| Height | | | | | −0.10 | −0.02 |
| BMI early pregnancy | | | | | | 0.75 |

*Note:* All correlations significant p < 0.05 except between height and BMI in late pregnancy.

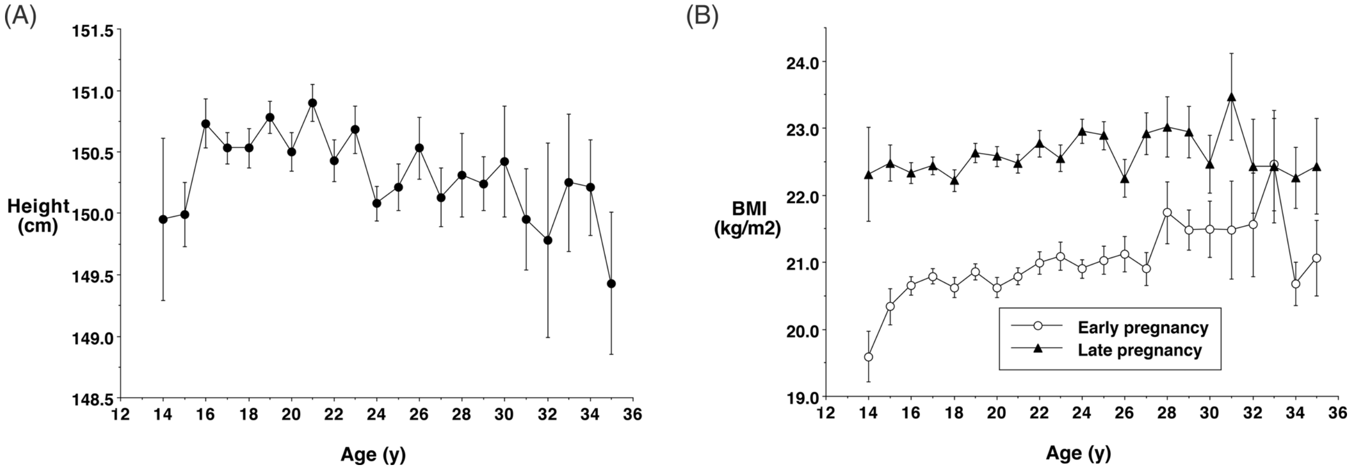


**FIGURE 2** Mean and standard error for (A) maternal height and (B) maternal body mass index (BMI) in early and late pregnancy, by maternal year of age

outcomes with age and parity. Regarding physical traits, short women and those with higher BMI in early pregnancy were more likely to have a cesarean delivery. In late pregnancy, higher BMI was associated not only with greater likelihood of cesarean delivery, but also of obstructed labor, and there was suggestive evidence of a similar association for episiotomy.

Among mothers who reported lengthy or obstructed labor, only a small minority had either an episiotomy or a caesarean, nevertheless they were four to five times more likely to have surgical intervention compared to those who did not report lengthy or obstructed labor (Table S6).

Multivariable logistic regression models for the prediction of episiotomy and cesarean delivery are given in Table 5. Due to the low sample size available for BMI in pregnancy, this variable was initially excluded from the models. When husband's education was included in models, associations for maternal education were non-significant, hence only husband's education was retained. However, maternal education showed broadly similar associations.

Among 14 261 women with complete data, the model showed that the likelihood of undergoing episiotomy was greater in younger mothers (≤20 years), and those experiencing their first or second pregnancy. Conversely, the likelihood was lower among women with uneducated husbands, and in those with lower household wealth than the wealthiest group. For those with height 145–147.99 cm and < 145 cm, episiotomy risk was only slightly and not significantly increased. This model explained 16.6% of the variance in the outcome. When BMI in late pregnancy was added to the model, the sample size was substantially reduced ($n = 2573$), and high BMI was not a significant predictor of episiotomy risk (Table S7), nor was neonatal size predictive (Table S8).

For cesarean delivery, the outcome was significantly more likely to occur in those experiencing their first or second pregnancies, if the infant was a boy, and if the mother was short, with the likelihood greater among those <145 cm and 145–147.99 cm relative to those <148 cm. However it was less likely to occur in younger mothers (<24 years), once these other variables were

**TABLE 4** Neonatal anthropometric traits stratified by maternal age group and parity

| | Birth weight (kg) | Birth length (cm) | Birth head circumference (cm) |
|---|---|---|---|
| **Maternal trait** | **Mean (SD)** | **Mean (SD)** | **Mean (SD)** |
| Age (years) | | | |
| 14–16 | 2.63 (0.40) | 47.9 (2.8) | 33.0 (1.6) |
| 17–20 | 2.76 (0.42) | 47.6 (2.6) | 33.3 (1.4) |
| 21–24 | 2.86 (0.41) | 48.1 (2.6) | 33.5 (1.4) |
| 25–28 | 2.86 (0.43) | 48.0 (2.7) | 33.5 (1.5) |
| 29–35 | 2.84 (0.43) | 48.1 (2.7) | 33.8 (1.4) |
| *p*-value | <.0001 | <.0001 | <.0001 |
| Number of previous pregnancies | | | |
| 0 | 2.69 (0.42) | 47.3 (2.2) | 33.2 (1.5) |
| 1 | 2.84 (0.42) | 47.9 (2.1) | 33.4 (1.4) |
| 2 | 2.87 (0.42) | 48.1 (2.2) | 33.5 (1.4) |
| 3 | 2.89 (0.44) | 48.2 (2.2) | 33.6 (1.4) |
| 4+ | 2.87 (0.43) | 48.2 (2.2) | 33.6 (1.5) |
| *p*-value | <.0001 | <.0001 | <.0001 |
| Stature (cm) | | | |
| <145 | 2.66 (0.42) | 47.1 (2.6) | 33.1 (1.5) |
| 145–147.99 | 2.76 (0.46) | 47.5 (2.6) | 33.3 (1.5) |
| 148+ | 2.85 (0.42) | 48.1 (2.6) | 33.5 (1.4) |
| *p*-value | <.0001 | <.0001 | <.0001 |
| BMI early pregnancy (kg/m$^2$) | | | |
| <19 | 2.75 (0.46) | 47.2 (2.3) | 33.1 (1.5) |
| 19–20.49 | 2.72 (0.42) | 47.2 (2.0) | 33.2 (1.5) |
| 20.2–21.99 | 2.84 (0.45) | 47.9 (2.0) | 33.6 (1.5) |
| 22+ | 2.90 (0.43) | 48.0 (2.0) | 33.5 (1.4) |
| *p*-value | <.0001 | <.0001 | <.0001 |
| BMI late pregnancy (kg/m$^2$) | | | |
| <21 | 2.71 (0.46) | 47.3 (2.0) | 33.0 (1.3) |
| 21–22.49 | 2.77 (0.40) | 47.9 (2.0) | 33.5 (1.4) |
| 22.5–23.99 | 2.85 (0.42) | 47.9 (2.1) | 33.5 (1.3) |
| 24+ | 2.97 (0.54) | 48.3 (2.2) | 33.8 (1.4) |
| *p*-value | <.0001 | <.0001 | <.0001 |

*Note: p*-value for trend by regression analysis. For maternal age and parity, $n = 4135$. For anthropometric correlations, $n = 3292$ for maternal height, $n = 939$ for early pregnancy BMI, and $n = 1201$ for late pregnancy BMI.

controlled for. Cesarean delivery was also less likely among those whose husbands had no education or low education levels, and the lower the wealth quintile, the lower the likelihood of having a cesarean. This model explained 6.2% of the variance in the outcome. When BMI in late pregnancy was added to the model, in the smaller sample of 2573 (Table S7) being in the highest BMI category was associated increased cesarean risk (OR 1.88, 95%CI 1.22, 2.90).

Similar models were constructed for labor >24 h and obstructed labor (Table 6). For obstructed labor ($n = 5185$), the main model showed that the outcome was more likely among those experiencing their first pregnancy and those with height < 145 cm. The risk of obstructed labor was reduced among women whose husbands were uneducated, but there was no association with maternal age or household wealth. This model explained only 3.3% of the variance in the outcome.

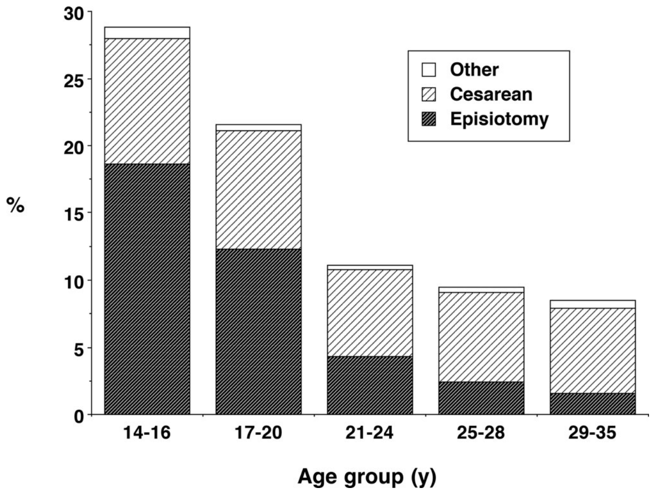


**FIGURE 3** Prevalence of episiotomy, cesarean section, or other procedure (forceps or vacuum extrcation) by maternal age group

When BMI in late pregnancy was included ($n = 1759$; Table S9), all groups higher than the thinnest group demonstrated increased risk compared with those with higher BMI in late pregnancy, and this model explained 6.1% of variance in the outcome. When the three components of neonatal size were added to the model, birth weight was a significant predictor: each additional kilogram increased the odds of obstructed labor nearly 2.5 times (OR = 2.42, 95% CI 1.35, 4.35), however there was little change in the OR for maternal BMI, indicating that the association of maternal BMI was not mediated by neonatal size (Table S8).

For labor >24 h, the main model demonstrated no significant predictors (Table 6), however when maternal BMI was added, the highest BMI category was associated with an increased risk (OR 1.40, 95%CI 1.01, 1.94; Table S9). When neonatal size was additionally added, each additional cm of head girth was associated with an increased risk (OR 1.37, 95%CI 1.06, 1.78; Table S10).

Additional models compared the effects of including maternal BMI (and where relevant, neonatal anthropometry) or not, only in the women who had complete data (Tables S11–14). For episiotomy, cesarean section and lengthy labor, the change in the proportion of variance in the outcome explained was negligible. However, for obstructed labor, the inclusion of maternal and neonatal anthropometry increased the Nagelkerke $r^2$ value from 6.4 to 9.6%. When trial group was included in the models, adjusting for the cluster, it showed no significant associations with our outcomes of interest, while other coefficients changed negligibly. Therefore there was no indication that the intervention had shaped childbirth outcomes.

A schematic diagram summarizing the associations for all four birth outcomes is given in Figure 4. For episiotomy, cesarean section and obstructed labor, the majority of the associations where significant were consistent regarding the direction of risk but differed in their significance, the one exception being maternal age which showed more divergent associations. In contrast, the duration of labor showed much weaker associations.

## 4 | DISCUSSION

In a population where it remains the norm for women to commence reproduction during adolescence, and where chronic under-nutrition is now interacting with the nutrition transition, we identified several risk factors for selected childbirth complications, mainly connected to obstructed labor and related interventions. These risk factors broadly showed consistent patterns of risk for episiotomy, cesarean section and obstructed labor, though there was heterogeneity regarding age-associations. In contrast, associations with labor >24 h were relatively weak and showed limited consistency with the other outcomes except for birth size, suggesting that the underlying pattern of risk is different. We therefore focus the remainder of this discussion on the risks of episiotomy, cesarean section and obstructed labor.

Our analysis draws on an evolutionary framework that focuses on different components of phenotypic plasticity. For decades, the primary evolutionary approach to human childbirth emphasized a generic challenge for all humans, namely, antagonistic selective pressures acting on the dimensions of the maternal pelvis and the fetal head (Washburn, 1960). This approach has been critiqued (Dunsworth et al., 2012; Walrath, 2003; Warrener et al., 2015; Wells et al., 2012), and a fresh evolutionary perspective is focusing on how phenotypic variability among individuals and populations mediates the relationship between adaptation to ecological conditions and childbirth complications (Wells, 2015; Wells et al., 2012). This approach treats the obstetrical dilemma as a "more-or-less scenario," driven by individual-level differences in traits that affect the "coordination" of maternal and neonatal phenotypes. Life history trade-offs related to growth, defense, and reproduction may impact relevant physical dimensions of both mother and fetus (Casanueva et al., 2006; Onagoruwa & Wodon, 2018; Rah et al., 2008; Rosenberg, 1988). For example, a high infectious disease load in early life might elicit increased energy allocation to immune defense, at a cost to growth, decreasing the size of the obstetric pelvis; similarly, early marriage may maximize women's fertility but lead to childbirth typically commencing when the dimensions of

**TABLE 5** Multivariable logistic regression models of the risk of episiotomy or cesarean section

| | Episiotomy ($n$ = 14 261) | | | Cesarean section ($n$ = 14 261) | | |
|---|---|---|---|---|---|---|
| | Nagelkerke $r^2$ = .166 | | | Nagelkerke $r^2$ = .062 | | |
| | OR | 95%CI | $p$-value | OR | 95%CI | $p$-value |
| Maternal age (years) | | | | | | |
| 14–16 | 1.89 | 1.16, 3.08 | .011 | 0.55 | 0.38, 0.78 | .001 |
| 17–20 | 1.68 | 1.05, 2.68 | .030 | 0.57 | 0.42, 0.77 | .0001 |
| 21–24 | 1.27 | 0.79, 2.04 | .3 | 0.64 | 0.48, 0.85 | .002 |
| 27–28 | 0.90 | 0.53, 1.53 | .7 | 0.88 | 0.65, 1.17 | .3 |
| 29+ (ref) | 1.0 | – | – | 1.0 | – | – |
| Previous pregnancies | | | | | | |
| 0 | 10.08 | 5.45, 18.66 | <.0001 | 3.03 | 2.15, 4.27 | <.0001 |
| 1 | 2.68 | 1.44, 5.00 | .002 | 1.89 | 1.34, 2.65 | <.0001 |
| 2 | 1.32 | 0.69, 2.51 | .3 | 1.03 | 0.73, 1.45 | .8 |
| 3 | 0.98 | 0.48, 2.00 | .9 | 1.00 | 0.70, 1.43 | .9 |
| 4+ (ref) | 1.0 | – | – | 1.0 | – | – |
| Husband's education | | | | | | |
| None | 0.72 | 0.61, 0.86 | <.0001 | 0.61 | 0.52, 0.72 | <.0001 |
| Primary/low secondary | 0.87 | 0.73, 1.03 | .1 | 0.74 | 0.63, 0.88 | <.0001 |
| Secondary (ref) | 1.0 | | | 1.0 | – | – |
| Wealth quintile | | | | | | |
| 1 | 0.77 | 0.61, 0.97 | .028 | 0.42 | 0.33, 0.54 | <.0001 |
| 2 | 0.80 | 0.65, 0.99 | .042 | 0.65 | 0.53, 0.80 | <.0001 |
| 3 | 0.74 | 0.60, 0.91 | .004 | 0.67 | 0.55, 0.81 | <.0001 |
| 4 | 0.82 | 0.67, 0.99 | .038 | 0.81 | 0.67, 0.96 | .018 |
| 5 (ref) | 1.0 | – | – | 1.0 | – | – |
| Offspring sex | | | | | | |
| Female (ref) | 1.0 | – | – | 1.0 | – | – |
| Male | 1.07 | 0.94, 1.22 | .2 | 1.23 | 1.08, 1.40 | .001 |
| Maternal stature (cm) | | | | | | |
| <145 | 1.08 | 0.89, 1.30 | .4 | 2.08 | 1.76, 2.44 | <.0001 |
| 145–147.99 | 1.18 | 0.99, 1.41 | .063 | 1.38 | 1.16, 1.64 | .001 |
| 148+ (ref) | 1.0 | – | – | 1.0 | – | – |

the pelvis are still increasing (Sharma et al., 2016). In the current analysis, we investigated both physical and demographic aspects of maternal phenotype, along with several markers of childbirth complications, while also taking into account how poverty may constrain access to healthcare facilities. Our analysis sheds new light on variability in childbirth experience in rural agricultural societies.

The risks of all three childbirth complications were increased among mothers undergoing their first pregnancy, and this also applied to those in their second pregnancy for episiotomy and cesarean section. These associations should therefore be taken into account when considering risk-associations with age. Among first-time mothers only, the crude rate of episiotomy declined with age, whereas that of cesarean section increased. Obstructed labor showed a trend to increased risk in younger mothers that was not significant, probably due to the reduced sample size. In the adjusted models, these patterns persisted. Since they were independent of household wealth and education levels, these associations indicate that difficulty delivering the neonate tends to be addressed with a more minor surgical procedure in younger mothers, whereas a more

**TABLE 6** Multivariable logistic regression models of the risk of lengthy labor or obstructed labor

| | Labor >24 h ($n$ = 5185) | | | Obstructed labor ($n$ = 5185) | | |
|---|---|---|---|---|---|---|
| | Nagelkerke $r^2$ = .016 | | | Nagelkerke $r^2$ = .033 | | |
| | OR | 95%CI | $p$-value | OR | 95%CI | $p$-value |
| Maternal age (years) | | | | | | |
| 14–16 | 1.00 | 0.67, 1.50 | .9 | 1.29 | 0.84, 1.99 | .2 |
| 17–20 | 1.06 | 0.76, 1.47 | .7 | 1.07 | 0.74, 1.55 | .7 |
| 21–24 | 1.02 | 0.75, 1.40 | .8 | 0.95 | 0.67, 1.34 | .7 |
| 27–28 | 0.90 | 0.65, 1.25 | .5 | 0.80 | 0.55, 1.15 | .2 |
| 29+ (ref) | 1.0 | – | – | 1.0 | – | – |
| Previous pregnancies | | | | | | |
| 0 | 1.45 | 0.99, 2.04 | .054 | 1.41 | 0.95, 2.10 | .089 |
| 1 | 1.02 | 0.72, 1.45 | .9 | 0.84 | 0.56, 1.24 | .3 |
| 2 | 0.92 | 0.65, 1.29 | .6 | 0.78 | 0.53, 1.14 | .1 |
| 3 | 0.88 | 0.61, 1.27 | .4 | 0.82 | 0.55, 1.23 | .3 |
| 4+ (ref) | 1.0 | – | – | 1.0 | – | – |
| Husband's education | | | | | | |
| None | 0.91 | 0.75, 1.10 | .3 | 0.79 | 0.64, 0.98 | .031 |
| Primary/low secondary | 1.03 | 0.84, 1.25 | .7 | 0.95 | 0.77, 1.18 | .6 |
| Secondary (ref) | 1.0 | – | – | 1.0 | – | – |
| Wealth quintile | | | | | | |
| 1 | 0.85 | 0.66, 1.09 | .1 | 0.95 | 0.72, 1.25 | .7 |
| 2 | 0.83 | 0.66, 1.06 | .1 | 0.91 | 0.70, 1.18 | .4 |
| 3 | 0.82 | 0.65, 1.03 | .089 | 0.99 | 0.77, 1.27 | .9 |
| 4 | 1.01 | 0.81, 1.26 | .9 | 0.96 | 0.75, 1.22 | .7 |
| 5 (ref) | 1.0 | – | – | 1.0 | – | – |
| Offspring sex | | | | | | |
| Female (ref) | 1.0 | – | – | 1.0 | – | – |
| Male | 1.00 | 0.87, 1.16 | .9 | 1.18 | 1.01, 1.38 | .041 |
| Maternal stature (cm) | | | | | | |
| <145 | 1.06 | 0.87, 1.30 | .5 | 1.31 | 1.07, 1.62 | .011 |
| 145–147.99 | 1.07 | 0.88, 1.29 | .5 | 1.10 | 0.89, 1.36 | .3 |
| 148+ (ref) | 1.0 | – | – | 1.0 | – | – |

invasive option tends to be used in older mothers. However, the use of cesareans may not always relate to obstructed labor, as other complications such as hypertension and ante-partum hemorrhage are also more common in older mothers (Chakraborty et al., 2003; Mehari et al., 2020).

Mothers from poorer households, and those whose husbands were uneducated, had a reduced likelihood of undergoing either episiotomy or cesarean section, suggesting that they may have been less able to access these medical facilities, or pay for these procedures, though they might also have less knowledge about their availability and how to access them. Similarly, mothers who had less education, or whose husbands had less education, were less likely to benefit from the presence of a SBA. Despite national legislation promoting SBAs, the source of assistance varied widely during delivery and this was associated with the availability of medical procedures, as was the case in the early 20th century in high-income countries (Reid, 2011; Reid, 2012). However, the risk of obstructed labor did not itself vary across the wealth quintiles. This suggests that wealth differences did not account for variability in this particular cause of childbirth complications, and instead wealth predicted variability in the treatment provided. It is not clear why the risk of obstructed labor was reduced among women

**FIGURE 4** Schematic diagram summarizing the direction and significance of associations between maternal biological, demographic, and socio-economic traits with the risk of four markers of childbirth complications

| | Episiotomy | Caesarean | Long labour | Obstructed labour |
|---|---|---|---|---|
| Maternal trait | | | | |
| Young age | ↑ | ↓ | - | - |
| First pregnancy | ↑ | ↑ | ↑ | ↑ |
| No education* | ↓ | ↓ | - | ↓ |
| Low wealth | ↓ | ↓ | - | - |
| Son | - | ↑ | - | ↑ |
| Short stature | ↑ | ↑ | - | ↑ |
| High BMI ** | - | ↑ | ↑ | ↑ |

* indexed in models by husband's education status ** reduced sample size

↑ = increased risk, ↓ = decreased risk, - = no association

Grey shaded cells indicate association significant $p<0.05$, unshaded cells indicate association significant $p<0.1$

whose husbands were uneducated. The association disappeared following adjustment for maternal BMI, this may reflect either that these women were thinner, or simply the reduced sample size.

Both cesarean section and obstructed labor were significantly more likely to occur among mothers of sons, compared to daughters, though the association was weaker for episiotomy and did not achieve significance. This pattern of risk may relate to the larger average birth size of sons, and is consistent with other studies (Lieberman et al., 1997; Wells et al., 2018). However, while the associations with sex lost significance when birth size was entered in the model for cesarean delivery, this was not the case for obstructed labor. One possible explanation could be a socio-cultural preference for different surgical interventions depending on the sex of the child, however, we lack evidence to confirm this hypothesis. Although sex determination during pregnancy is illegal in Nepal, many mothers nevertheless do determine the sex of the fetus and sex-selective abortion is becoming more common (Frost et al., 2013). Males are also more prone to fetal distress (Bekedam et al., 2002), hence interventions might be made earlier during labor, even if the sex of the offspring is not yet known. Alternatively, we may lack relevant information on birth size. Shoulder dystocia is a common cause of childbirth complications (Ezegwui et al., 2011; Ju et al., 2009), and it is possible that male neonates have wider shoulders and are more prone to obstructed labor than females, even when weight, length and head circumference are taken into account.

The probability of having a son was significantly greater in mothers who were taller and heavier in early pregnancy, though no such association was apparent for BMI in late pregnancy. The "Trivers-Willard" hypothesis is often invoked to explain a higher frequency of daughters among less well-nourished mothers (i.e., that mothers in poor condition should prioritize investment in daughters; Trivers & Willard, 1973). However, an alternative explanation might be that shorter mothers are poorer and less educated, and thereby less likely to pay for sex-determination and sex-selective abortion of their female fetus prior to term (Frost et al., 2013).

Short mothers had an increased risk of cesarean section and obstructed labor. The pattern was weaker for episiotomy, being significant for the middle group of height but not the shortest group. These findings are broadly consistent with numerous other studies from different geographical regions showing higher rates of childbirth complications among shorter women (Amoa et al., 1997; Desai et al., 1989; Sokal et al., 1991; Wells, 2017), and is supported by recent work showing that reduced tibia length, a marker of growth variability in early life, predicts smaller pelvic dimensions in adult South Asian women (Shirley et al., 2020). Importantly, other analyses on this cohort have shown that both early marriage and early childbearing are associated with shorter height in this population, indicating trade-offs between skeletal growth and early reproduction (Marphatia et al., 2021). The finding that independent of early childbearing, early marriage is also associated with lower adult height suggests either that early marriage is associated with reduced access to food for young women in the marital household (Harris Fry et al., 2018); or that it is associated with psychosocial stress, where activation of the energy-costly stress response might itself reduce the energy available for adolescent growth (Marphatia et al., 2021).

High maternal BMI increased the risk of cesarean section and obstructed labor, however, the effect was weaker for episiotomy and did not reach significance. We detected no increased risk of childbirth complications in the thinnest group of mothers, suggesting that it is heavier women producing larger babies, rather than slimmer women who could be expected to have smaller pelvic dimensions, who are most at risk. We did not have data on gestational diabetes in this cohort, however this condition could amplify any effects of high maternal BMI on birth weight, as was demonstrated in a similar analysis in India (Wells et al., 2018). Associations of maternal BMI with childbirth complications might be mediated by neonatal size. For example, a previous study in Guatemala found that the highest risk of cesarean delivery occurred when infants with large head circumference were born to mothers of short stature (Merchant et al., 2001), while a study in Mexico found that both higher birth weight and short maternal height predicted cephalo-pelvic disproportion (Mendez-Dominguez et al., 2020). In our study, maternal BMI and neonatal weight were identified as independent predictors, but there is some consistency between the studies as estimated neonatal head cross-sectional area of the highest maternal BMI group was 4.8% greater than in the lowest group, which translates into a 7.2% difference in head volume. These associations highlight the heightened trade-off between fetal investment in brain growth and maternal mortality risk from childbirth complications, in women of higher BMI who invest more in their offspring.

One surprising finding was that neither maternal height nor BMI during pregnancy increased substantially after the age of 17 years, though there was a modest trend of increasing BMI with age throughout the adult age range. Mothers aged <16 years were ~ 0.5 cm shorter and ~ 0.6 kg/m$^2$ lighter, but the magnitudes of these effects were modest. This contrasts notably with analysis of recent DHS data from India, where maternal height showed a maximum value at 30 years (Wells et al., 2018). Other studies in India support the notion that linear growth continues well into the third decade (Satyanarayana et al., 1981; Satyanarayana et al., 1989), and it is not clear why the same pattern is not evident in this sample from Nepal.

If childbirth is a coordination problem, then maternal overweight appears the most disruptive challenge, and could potentially be addressed by interventions. Increasing BMI in these women is likely to be strongly associated with elevated adiposity, though we do not have direct evidence for this. However, the levels of BMI associated with increased childbirth complications in this population are very modest compared to published literature (Wells, 2017), where the thresholds for assessing risk are conventionally BMI > 25 or > 30 kg/m$^2$, hence further work would be needed to identify how such interventions might be developed and targeted.

Importantly, however, the "coordination problem" may also be sensitive to social context. There is growing understanding that traditional birthing practices, such as delivering while standing or squatting, may promote uncomplicated births (Stone, 2016; Veile & Kramer, 2018). A recent analysis across three generations of Mayan mothers in Mexico found that declines across generations in the use of traditional practices, associated with the increasing medicalization of childbirth, were accompanied by an increase in childbirth complications, and yet no change in infant mortality rate (Veile & Kramer, 2018). In our population, the likelihood of having a surgical intervention was very strongly determined by whether the birth was at home or in an institution. Whether differences in social support contribute to such differences is an important topic for further research.

More generally, our findings for physical components of maternal phenotype are broadly consistent with a previous analysis of Indian data, where both short stature and maternal high BMI increased the risk of cesarean section, while low parity and male offspring also increased the risk (Wells et al., 2018). Adolescent childbearing is well established to increase the risks of adverse birth outcomes (Ganchimeg et al., 2014) but our analysis adds to growing evidence that this is partly explained by the fact that such mothers tend to be reproducing for the first or second time.

Our findings provide support for our evolutionary framework, demonstrating that the risk of childbirth complications is associated with variability in both maternal and fetal traits that, in turn, can be seen to reflect the consequences of life history trade-offs. Lower energy allocation to growth, and more energy allocation to energy stores, both increase the risk of childbirth complications, and these risks also increase in first-time mothers, who are generally of young age and who may not have completed pelvic growth. Producing male offspring is also more risky, which may in part reflect the larger physical dimensions of male neonates. These associations were all independent of markers of wealth and education, which are likely to be important determinants of access to medical care in this population.

Strengths of the study include the large sample size (though this was substantially attenuated in the multivariable models, especially so in the analysis of labor), and the availability of information on several different markers of childbirth complications. Previous research has relied on cesarean delivery as a marker of obstructed labor, whereas here we were able to analyze this outcome directly, albeit depending on self-report. Another strength is the rare opportunity to analyze data from a vulnerable population, where early childbearing is common, and women suffer from very low levels of empowerment, as well as low wealth and education levels. The study provided detailed data on nutritional status and birth outcomes among women in a society where they are largely confined to the home, and where the majority (59%) also delivered at home.

Limitations include missing data. There was no evidence that this resulted in any substantial bias, but some of those missing might have died in childbirth or soon after, and such women would be unlikely to be randomly distributed across the independent variables we investigated. Also, we lacked information on the prevalence of maternal or neonatal birth injuries, and whether either episiotomy or cesarean section were actually justified by medical need. Similarly, we focused on indications of complicated labor without considering how they might predict later morbidity. Nor did we include neonatal mortality as an outcome, as we propose to analyze mortality patterns in this cohort separately. We therefore recommend that future studies should collect more data both on immediate birth injuries (e.g.: fistula, tears) and their longer-term consequences such as social exclusion. Although difficult in such studies, it would be valuable to improve follow-up of neonatal mortality.

More generally, our study is limited by the difficulty of assessing how well our outcomes indexed physical difficulties during delivery. On the one hand, we relied on maternal self-report, which may be relatively accurate for cesarean and episiotomy, but not necessarily so for lengthy or obstructed labor, and our questionnaire was not validated. Second, even clinical decisions are not necessarily well-informed about the underlying birth process, which is sensitive to social context through the mediating mechanism of the stress response (Rutherford et al., 2019).

## 5 | CONCLUSIONS

In summary, our analysis has shown that adverse childbirth outcomes are concentrated among those experiencing their first or second pregnancy, and those who are short and of high BMI. Overall, younger mothers were at higher risk, but the pattern of risk also depended on the birth outcome. These findings took into account the fact that mothers who were poorer or who had uneducated husbands were less likely to undergo surgical procedures, potentially indicating inadequate information on, knowledge of, or access to the necessary facilities. Our results add to growing evidence that the risk of childbirth complications varies in association with maternal traits that in turn are shaped by both external ecological and socio-ecological conditions (Wells et al., 2012). Our study demonstrates the value of using an evolutionary framework, by showing how the experience of childbirth is shaped by several different components of phenotype, each of which may be considered to represent the outcome of life history trade-offs between fertility, growth and defense (diverting energy to either immune function or the stress response). In turn, this approach helps understand why increasing maternal BMI, in association with nutrition transition, is likely to increase the prevalence of childbirth complications in a population where short stature remains common due to factors constraining skeletal growth.

In South Asia, it is near-universal for marriage to precede childbearing (Marphatia et al., 2017), and early marriage may therefore represent a key marker of risk for childbirth complications. However, we have shown that the adverse risks of giving birth in adolescence are partly mediated by low parity, hence to some extent delaying childbirth to later age might simply push these risks forward in time, though other risks may remain. Age at marriage, and hence at first childbirth, therefore appears to index a balance of competing risks, and further work is needed to understand the full implications of early marriage for childbirth.

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## AUTHOR CONTRIBUTIONS

**Jonathan Wells:** Conceptualization; formal analysis; funding acquisition; investigation; methodology; writing-original draft; writing-review and editing. **Akanksha Marphatia:** Conceptualization; writing-review and editing. **Dharma Manandhar:** Conceptualization; funding acquisition; project administration; writing-review and editing. **Mario Cortina Borja:** Formal analysis; funding acquisition; methodology; writing-original draft; writing-review and editing. **Alice Reid:** Conceptualization; formal analysis; funding acquisition; writing-original draft; writing-review and editing. **Naomi Saville:** Conceptualization; data curation; formal analysis; funding acquisition; investigation; project administration; writing-original draft; writing-review and editing.

## CONFLICT OF INTEREST

All authors declare no conflict of interest.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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