Modelling the biomechanics of physiological and assisted childbirth

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1. Introduction

The process of human childbirth constitutes a complex interaction between the fetus and maternal pelvic anatomy. In (bio)mechanical terms we can safely label this interaction as a mechanical contact problem between multiple deformable bodies. A contact problem of this kind requires careful thought as to what numerical methods should be applied when the objective is to realistically simulate the childbirth process on a computer. Equally, when using an obstetric forceps or ventouse (vacuum extraction) during assisted delivery, the interaction between the fetal head and the instrument is of a contact mechanics nature. In this paper, we will cover the numerical methods we have developed in the last two decades to simulate both physiological (natural) and assisted (instrumental) childbirths in a virtual environment (VE).

2. Background

Lapeer et al. (2019) recently developed a virtual reality (VR) childbirth simulator software named 'BirthView'. The software provides a way to visualise and simulate interactions between an assembly of fetal and maternal pelvic models. The former more specifically includes the fetal head, skull and neck, and the rest of the fetal body. The latter includes the bony pelvis, the pelvic floor muscles (also known as the levator ani muscle – LAM – complex), sacrospinous ligaments and the uterine cervix. Each of these models exhibit specific material properties that are used in finite element (FE) algorithms to calculate the deformations of, and stresses in, the soft tissues within the assembly. Due to the mechanical contact between the bony pelvis with pelvic soft tissues and the rigid fetal head with neck, the latter exhibits rotations that are commonly known in obstetrics and midwifery as the mechanisms or 'cardinal movements' of childbirth – See Figure 1. Currently, only the pelvic soft tissues do deform in BirthView even though the fetal head also changes shape during labour; a phenomenon better known as fetal head moulding (FHM). Lapeer and Prager (2001) developed a FE model of FHM during the first stage of labour. This model has been widely used in various clinical applications including the investigation of child head trauma, incontinence following childbirth, fetal growth and more. However, it has not been incorporated in BirthView as of yet.

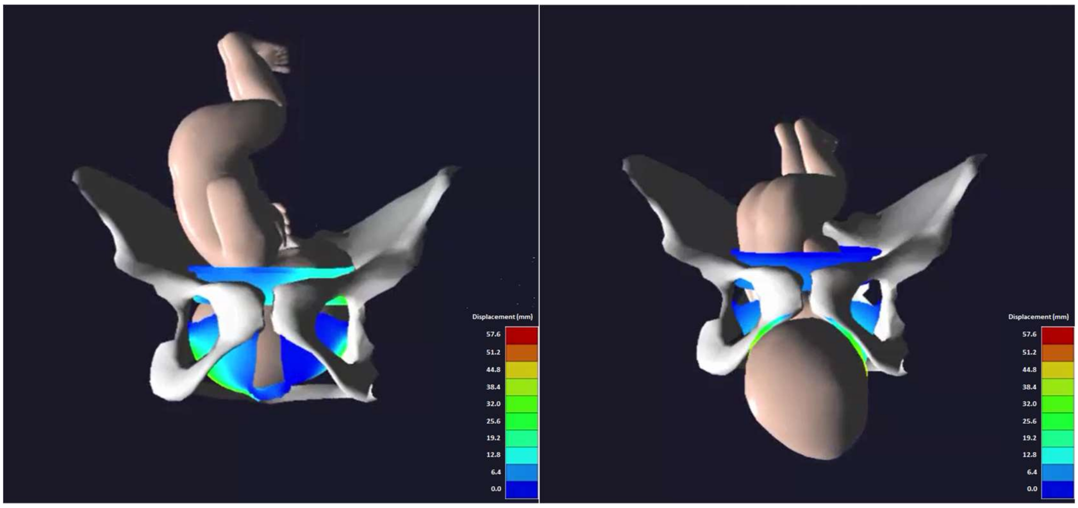

Figure 1 Screenshots from the BirthView childbirth simulator. Left shows the fetus in contact with the uterine cervix and pelvic floor muscles that causes the fetal head to flex. Right shows a further stage in the physiological childbirth process where the fetus, after having internally rotated, has moved past the pelvic floor muscles by extending its head. External rotation of the head will allow the delivery of the shoulders followed by the rest of the body.

Lapeer et al. (2014a,b) also studied the effects of instrumental delivery on the fetal head. The application of an instrument – whether it is an obstetric forceps or a ventouse cup – to the fetal scalp also falls in the category of a mechanical contact interaction. The first study (Lapeer at al. 2014a) confirmed via a numerical experiment the clinical hypothesis stating that the incorrect (asymmetric) placement of the forceps blades will cause significantly higher deformations and stresses within the fetal scalp as compared to the correct (symmetric) placement – See Figure 2.
The second study (Lapeer et al. 2014b) confirmed similar issues with incorrect placement of a ventouse suction cup on the fetal scalp.

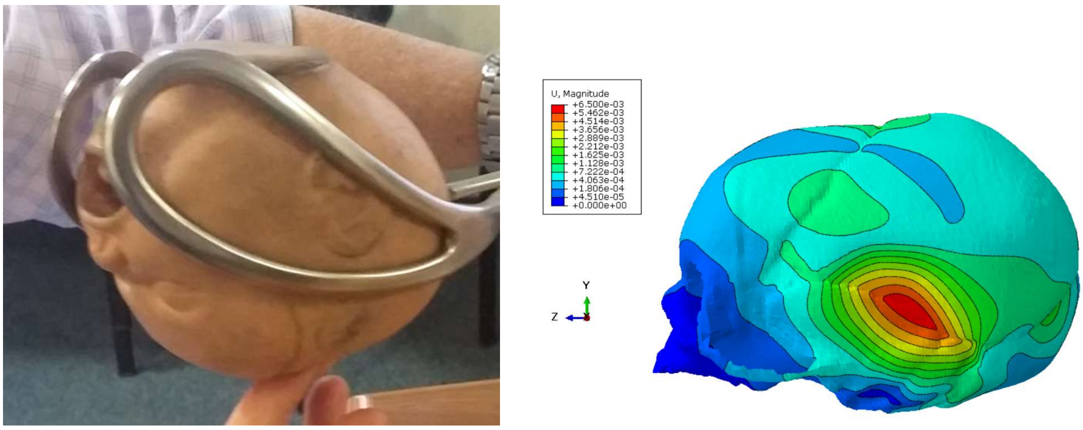

Figure 2 Left shows a plastic dummy model with a real obstetrics forceps placed correctly (symmetric application of both blades). Right shows the result after running a FE analysis of a virtual forceps being incorrectly (asymmetrically) applied to a FE mesh model of a fetal skull. The area coloured red (exhibiting high deformations up to and above 6mm) is where the forceps blades were applied asymmetrically.

3. Numerical methods in childbirth biomechanics

The numerical methods we have developed and implemented on computer over the years include both FE and mechanical contact methods. There are typically two main classifications of FE methods, i.e. implicit and explicit. Both formulations are based on the following FE equation:

$$M\ddot{u} + C\dot{u} + Ku = R \qquad (1)$$

Where u is the displacement vector and its derivatives in time (velocity and acceleration vectors); M, the mass matrix, C, the damping matrix and K, the stiffness matrix and R is the vector of externally applied forces. Since mass and velocity are present in the above equation, it can be applied to dynamical problems. However, since childbirth processes are mostly quasi-static the first two terms in Eq. (1) are often omitted. Modelling FHM in Lapeer and Prager (2001) was accomplished using the simplified version of Eq. (1) in an implicit formulation where the nodal displacements are found from the known external forces and the constructed stiffness matrix K with size proportional to the number of finite elements in the model and the degrees of freedom per element. If the displacement vector u is to be derived from K and R in Eq. (1), then K needs to be inverted. In the FHM example, the fetal skull model has over 60K triangular shell elements which means that inverting K will be costly in processing time and memory usage.

The same approach was used to model the deformations due to (symmetric and asymmetric) applications of forceps and ventouse.

However, since both these studies are pre-occupied with assessing the degree of deformation of the fetal scalp where accurate results are more important than processing speed, the use of an implicit FE formulation is justified.

This is not the case for the more recently developed childbirth simulation where both accuracy and speed are important. Even though the childbirth process is slow (quasi-static), the simulation has to run in real-time. Considering that the second stage of labour may last several hours, an implicit FE approach would take a prohibitively long time. Therefore, we adopted an explicit FE approach ran in parallel on a Graphics Processing Unit (GPU) to further speed up the simulation. The explicit FE formulation we adopted solves Eq. (1) using time integration and is known as the Total Lagrangian Explicit Dynamics (TLED) method by Miller et al. (2007).

We adapted the method to work in conjunction with a projection-based contact method that imposes the contact constraints between the fetal head and maternal pelvic anatomy. This allowed us to set the time step for numerical integration to an upper bound of 16ms that ensured real-time performance of the simulation of the second stage of physiological childbirth (Lapeer et al. 2019).

4. Conclusion

We have presented the background of our research into childbirth biomechanical interactions between the natural agents (fetus, maternal pelvis) during physiological childbirth and between the former and instruments (forceps, ventouse) during assisted childbirth. We briefly discussed the numerical methods we adopted and subsequently adapted to be fit for purpose for our childbirth biomechanics related problems. This started in modesty with the modelling of fetal head moulding about 20 years ago up until the more recent and distinctly more complex simulation of a physiological childbirth process.

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