Contact-constrained Finite Element Analysis to Evaluate Obstetric Forceps Placement

Omar Valladolid García, Rudy Lapeer
School of Computing Sciences (CMP), University of East Anglia (UEA)
Norwich, UK, r.lapeer@uea.ac.uk

***Abstract*—Obstetric forceps are frequently used when physiologic childbirth fails to progress. It is commonly accepted in obstetrics that the use of the instrument is safe when placed and handled correctly. Conversely, obstetric forceps may cause significant damage to the fetal scalp, skull bones and brain if they are not applied correctly. In this paper, we assess obstetric forceps placement in-silico by creating virtual models of the fetal head and obstetric forceps. We establish mechanical contact between the fetal scalp and forceps blades. We then run implicit quasi-static Finite Element Analyses to assess the deformation of the fetal scalp when in contact with the forceps blades. Progressive steps are described to arrive at a final simulation that compares the symmetric placement of the forceps blades against their asymmetric placement. We show that the deformation of the fetal head is significantly more problematic when the forceps blades are asymmetrically placed relative to the fetal head.**

Keywords—Fetal head moulding; Biomechanics; Contact mechanics; Instrumental delivery; Virtual Reality.

I. Introduction

The human childbirth process comprises three stages: The first stage involves the process from initial to full dilation of the uterine cervix (approx. 10 cm in diameter) to enable the fetal head to leave the uterus; the second stage starts at full cervical dilation and involves the expulsion of the fetus from the birth canal; the final and third stage facilitates the delivery of the placenta. The second stage is the most complex in terms of the contact mechanical interactions between the fetal head and the maternal anatomy comprising the bony pelvis and pelvic floor soft tissues. It is during this stage that the expulsion of the fetus may be ground to a halt; a phenomenon that is called “dystocia” or “obstructed labour” in obstetrics. Dystocia may be caused by a variety of reasons, for example, cephalo-pelvic disproportion, where the fetal head is proportionally large in comparison to the pelvic canal, or abnormal fetal positioning. Depending on the severity of the dystocia, a sequence of interventions may be considered, usually starting with instrumental delivery to extract the baby through the “normal” path, though when this fails, a Caesarean Section may be the only option left to deliver the baby at the abdominal side. Instrumental delivery either involves the use of obstetric forceps or the vacuum extractor (aka ventouse) although they are often used in sequence. In this paper, we will evaluate the correct use of obstetric forceps via an in-silico simulation of the mechanical contact interaction between computer-generated forceps and the fetal head using Finite Element Analysis (FEA).

II. Background

Obstetric forceps “lookalike devices” may be several millennia old and would have been used by various cultures to typically extract stillborn babies with the aim to save the mother. It is commonly accepted in the medical specialties of obstetrics and midwifery that the first prototypes resembling modern obstetric forceps and aimed at extracting live babies, were developed by the Chamberlen family in the 17^{th} century. The currently used Neville-Barnes forceps were created by John Barnes and adapted by Robert Neville with an axis-traction handle in the late 19^{th} century [1]. Figure 1 shows “virtual” Neville-Barnes forceps applied to a fetal head replica model.

Training of obstetric forceps placement is commonly done using dummy models or “mannequins” such as the Prompt birthing simulator [2]. Although such mannequins are useful for training purposes, they are typically one size for all thus not capable to represent specific cases unless manufactured on a patient-specific basis, which would be very costly. Virtual Reality (VR) models have the advantage over mannequins in that they can be adjusted in size and shape with little effort and no additional cost thus allowing them to be easily matched to specific cases. VR based training simulators with haptic feedback, such as BirthSim [3], have been used to train and evaluate practitioners in the correct placement of obstetric forceps.

Other computer-based simulations focus on the use of the Finite Element Method (FEM) to evaluate the effect of obstetric forceps on the fetal scalp. Lapeer et al. [4] analysed symmetric and asymmetric placement of obstetric forceps using a static FE model with imposed contact and traction forces on a virtual model of the fetal skull. They found that the degree of deformation of the scalp bones and the magnitude of the shear stresses in the fontanelles are significantly larger when the forceps blades are asymmetrically applied in relation to the fetal head as compared to symmetric placement.

III. METHODS

A. FE model generation

Virtual models of the fetal head and obstetric forceps need to be created to facilitate the analysis of deformation of the former from being in contact with the latter.

The fetal head and more specifically, the fetal skull, is complex as compared to the adult skull. Fetal cranial bones are single-layered and have in-planar orthotropic material properties whereas adult cranial bones have a three-layered structure with two outer cortical bone layers and a spongy cancellous bone layer called the diploë, the latter having isotropic material properties. Fetal cranial bones are relatively thin with average thicknesses well below 1 mm. Additionally, the fetal cranial bones are not yet fully connected and are separated by the soft tissue-based sutures and fontanelles. These soft tissues share the same material properties as the dura mater that protects the fetal brain. The loosely connected fetal cranial bones allow a significant degree of deformation, better known as fetal head moulding – FHM [5] – that may facilitate fetal expulsion from the womb.

In previous work [4], we used a fetal skull model to assess the effect of obstetrics forceps placement. We did not model the forceps blades but estimated the position and magnitudes of the contact forces on the fetal skull and then ran a static FEA. Here we will perform a quasi-static FEA with actual contact constraints between forceps and fetal head models. Since obstetric forceps fit perfectly around an "average" fetal head we need to use a fetal head model rather than a fetal skull model – see Figure 1. For the reported research, we have omitted the fetal scalp at this stage due to its average thickness (~5 mm) being much larger than the fetal skull bone thickness (< 1 mm) thus requiring a compound FE model that connects shell elements (skull) to volumetric elements (scalp). Figure 2 shows three fetal head models with increasing mesh complexity.

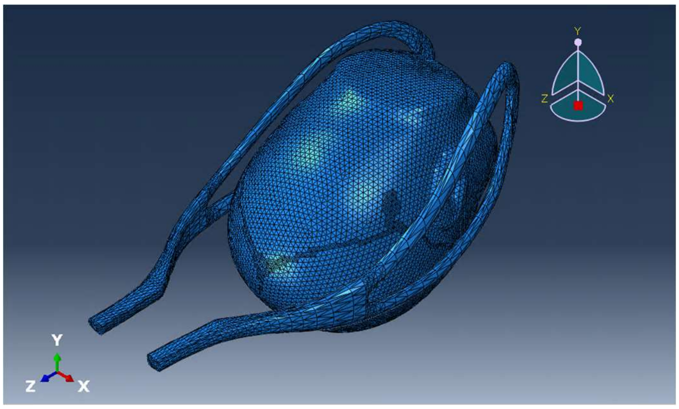

Fig. 1. FE forceps model fitting exactly around virtual fetal head model.

The FE forceps model is shown in Figure 1 and was created in the Blender software [6] from real obstetric forceps. The handles below the blades have been removed to avoid additional contact constraints in the FEA. Since a perfectly fitting forceps will have the left and right handles being in contact with each other, we do measure the distance between the distal ends of the truncated blades to ensure that closure of the "missing" handles guarantees a perfect fit of the blades around the scalp.

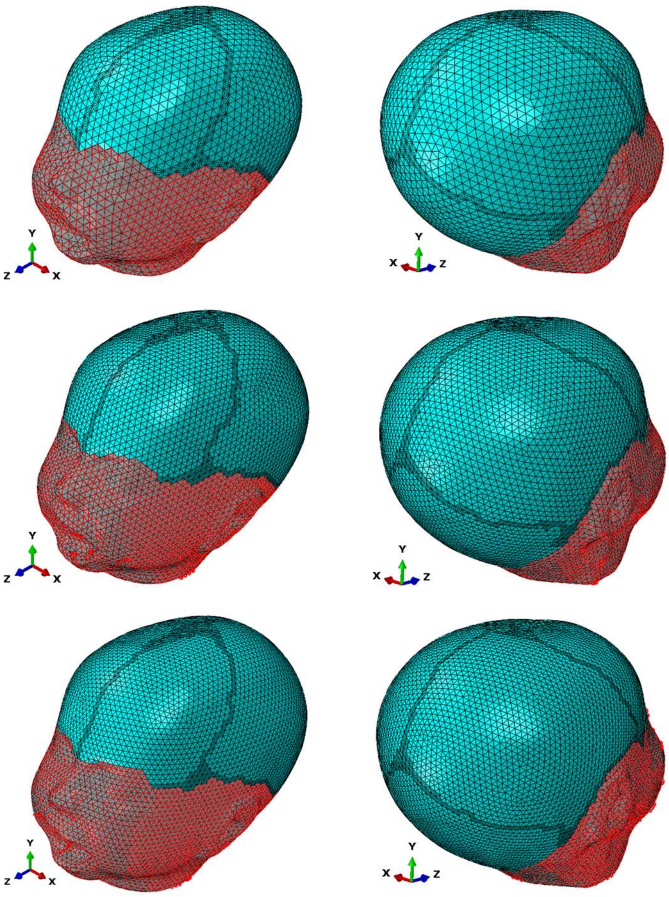

Fig. 2: Fetal head FE meshes: top = 7,908 first-order shell elements; middle = 14,646 elements; bottom = 18,742 elements. Dark green: fontanelles and sutures; light green: cranial bones; brown: skull/head base.

B. Material properties

TABLE I. MATERIAL PROPERTIES

PROPERTY	CRANIAL	FONT./SUT.	BASE
THICKNESS (MM)	0.75	0.75	2.00
MASS DENS (KG/M^3)	1,000	1,000	1,200
MATERIAL TYPE	ORTHO-ELAST.	ISO-HYPEREL.	ISO-ELASTIC
E1 (GPA)	3.86	--	4.46
E2 (GPA)	0.965	--	--
G (GPA)	1.582	--	--
N12 (POISSON'S RATIO)	0.22	--	0.21
N21 (POISSON'S RATIO)	0.055	--	--
C1 (MPA)	--	1.18	--
C2 (MPA)	--	0.295	--

Table I shows the material properties for each of the three material types as shown in Figure 2, i.e. cranial bones, fontanelles and sutures and skull base bones.

C. Experimental plan

In a real scenario, obstetric forceps are applied in the following steps starting with both the left and right blades being disassembled and the fetal head position known [7]:

a) The left blade is gently but firmly introduced from L to R between the maternal pelvis and fetal scalp.

b) The right blade is introduced in a similar fashion in the opposite direction from R to L.

c) The blades are carefully locked resulting in the two blades closing around the fetal head.

d) The forceps are now ready to perform traction.

Our simulation will not model the insertion of the two blades as described in steps a) and b) as they have no direct effect on the deformation of the fetal head. The remaining two steps, i.e. the **closing** (step c) and **traction** (step d) do influence the deformation of the fetal head and will be simulated. In earlier work [4], we modelled these two steps by applying contact and traction forces, described in the literature [8], directly to the fetal head's FE mesh nodes and elements that are in contact with the forceps blades but without modelling the latter. Here we will do a more realistic contact analysis where both forceps blades and head are modelled and brought into contact with one another (closing step) and then traction is applied to the forceps model to move the fetal head model. Preliminary experiments using realistic traction forces as reported by Chachava et al. [8] resulted in unstable simulations, both in the closing and traction steps, due to the lack of resistive forces from the maternal pelvic floor muscles that have been omitted to reduce complexity. Due to the quasi-static nature of the extraction of a fetus using obstetric forceps, we abandoned the use of forces in our simulation and imposed realistic velocity boundary conditions on the forceps' closing (1 mm/s) and traction (5 mm/s) steps. Figure 3 shows all boundary conditions on the fetal head and forceps FE models.

IV. RESULTS

The ABAQUS FE software was used to run a **standard analysis** with **contact pairs** established between each of the forceps blades and both sides of the fetal head. The correct positioning was based on photographic evidence of real forceps interventions described in the literature [7]. As mentioned in the previous section, one analysis comprises a **closing** step at 1mm/s lasting for 2 seconds and a **traction** step at 5mm/s lasting 0.5 seconds of analysis time. We looked at two different scenarios:

- Symmetric placement of the blades relative to the fetal head
- Asymmetric placement of the blades relative to the fetal head due to incomplete internal rotation by 10 degrees [9].

All analyses were run on an Intel(R) Core (TM) i9-14900K, 3.20 GHz CPU with 96 GB RAM

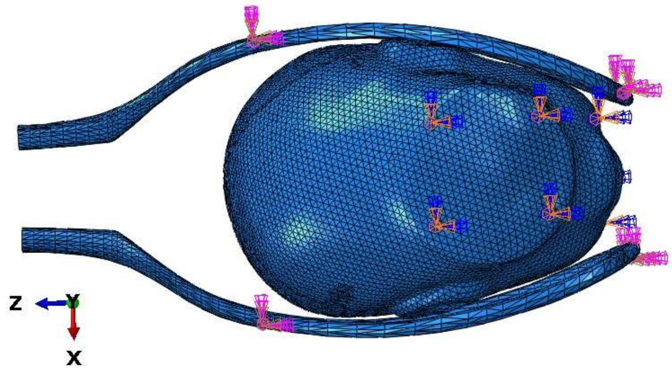

Fig. 3. The boundary conditions on the left and right forceps blades only allow displacements in the x and z directions. The fetal neck is encastred at the four points shown.

Table II shows the maximum overall deformations (Umax), measured at the center of the anterior fontanelle at the top of the fetal head, and Von Mises (VM) stresses (Smax), measured near the jaw where the tip of the forceps blades are in contact, for each of the three meshes as shown in Figure 2. As expected, the deformation magnitude increases as the mesh is refined whereas a slight decrease is observed for the VM stresses. The remainder of the results will be reported on the finest mesh with 18,742 first-order (ABAQUS S3R) shell elements.

TABLE II DEFORMATION AND STRESSES

Mesh complexity	Umax (mm)	Smax (GPa)
Low (~8K els)	1.98 E-03	0.213
Medium (~15K els)	2.02 E-03	0.203
High ((~19K els)	3.29 E-03	0.186

Figure 4 shows the deformations in the x-direction – the direction of **closing** the forceps blades – of the symmetric and asymmetric cases respectively. We observe that the deformation on the left-hand side of the head (blue colour) is substantially higher for the asymmetric case as compared to the symmetric case. This is due to the asymmetrically placed left blade (blue) having less uniform contact with the head than the symmetric equivalent thus causing deformations of almost 3mm in the negative x direction near the jaw and temporal bones. Figure 5 shows the deformations in the z-direction – the direction of the forceps traction – for the symmetric and asymmetric cases respectively. The symmetric case shows higher overall deformation in the direction of traction and y direction, due to better contact (i.e. less slip) with the forceps blades. This causes a degree of FHM that is relatively harmless to the fetal scalp and underlying anatomy due to it being uniformly distributed across the skull. The asymmetric case shows very high localized deformation (bulging) near the bridge of the nose that may be potentially dangerous and cause local damage.

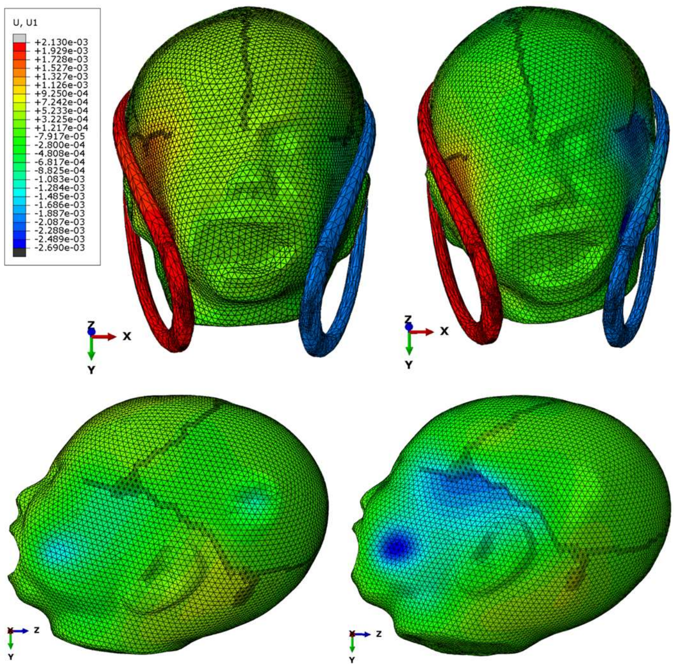

Fig. 4. Top: Front view of fetal head subjected to symmetric (L) and asymmetric (R) forceps placement respectively for deformation in x (U1) in m. Bottom: Lateral view with forceps removed. Deformation magnification factor is 2.0.

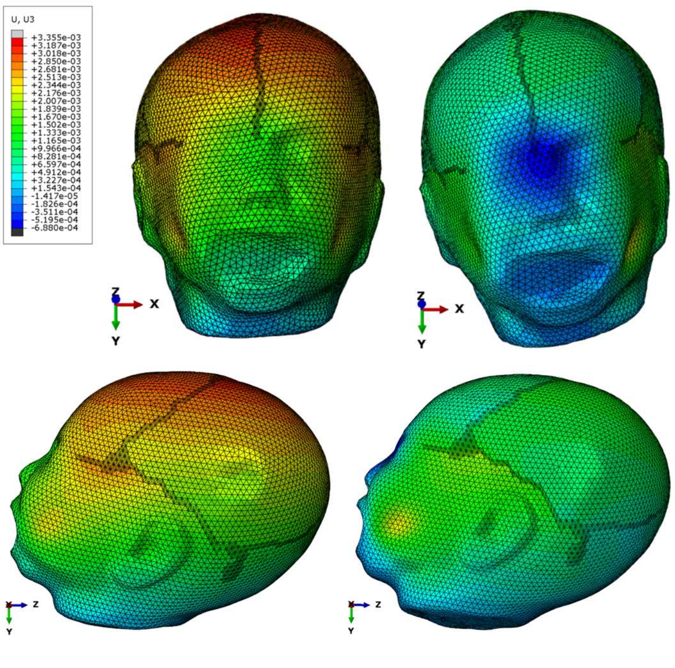

Fig. 5. Top: frontal view; Bottom: lateral view. Left: symmetric forceps placement; Right: asymmetric forceps placement. Deformation in z-direction (U3) in m, shown with magnification factor 2.0.

V. Conclusions

We have presented a realistic in-silico simulation of obstetric forceps placement using detailed FE models of the fetal head and obstetric forceps. A quasi-static implicit analysis was run with general contact between the forceps blades and fetal head whilst imposing a constant velocity of 1 mm/s (2s duration) for closing and 5 mm/s (0.5s duration) for traction. The analyses were run on three meshes of increasing complexity to assess the effect of mesh refinement. As expected, the finest mesh was selected for further analyses that involved the comparison of symmetric placement of obstetric forceps relative to the fetal head with asymmetric placement due to an incomplete internal rotation by 10 degrees. We observed substantially larger local deformations (up to 3mm) near the fetal jaw and temporal bone, and protruding frontal bones near the nasal bridge, for the asymmetric case as compared to the symmetric case. The latter showed higher uniform deformation due to better contact of the fetal head with the forceps blades but this is no different to the FHM that occurs during normal delivery and, unless excessive, not harmful to the baby. Future work will include reducing the processing times (which currently take several hours on the earlier mentioned CPU) by exploiting the use of multiple GPU cores.

From a clinical perspective, we conclude that in order to reduce harm to the baby, asymmetric application of obstetric forceps should be avoided at all cost. Additionally, obstetric forceps fit well to average sized babies but not to bigger (macrosomic) babies or babies with cephalopelvic disproportion so in this case the use of obstetric forceps should be avoided entirely [10].

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