A Computer-Based Simulation of Obstetric Forceps Placement

Rudy Lapeer[1], Vilius Audinis[1], Zelimkhan Gerikhanov[1], and Olivier Dupuis[2]

[1] School of Computing Sciences, University of East Anglia, UK
[2] Université de Lyon, Maternité CHU Lyon Sud, France

Abstract. Obstetric forceps are commonly used when the expulsion of the baby during childbirth fails to progress. When the two forceps blades are applied correctly, i.e. symmetrically, the inner surface of each blade maximises the area in contact with the fetal head. On the contrary, when the blades are applied asymmetrically, the contact areas between the inner surface of the blades and the fetal head are minimal and at distinct locations at the left and right sides of the fetal head. It is therefore assumed in the field of obstetrics that asymmetric application is bound to cause intra-cranial damage due to significantly higher shear forces and significant deformation of the fetal cranial bones as compared to symmetric application. In this paper we present the first of a series of studies to analyse the mechanical contact between head and forceps under different conditions using finite element analysis. We used high fidelity mesh models of a fetal skull and obstetric forceps. The fetal cranial material properties are known from previous studies. We observed significantly higher deformations and stresses for the asymmetric application of the blades as compared to symmetric placement.

1 Introduction

Obstetric forceps are used when the childbirth delivery process fails to progress, a situation which may lead to death or life-long disabilities of the fetus [1]. An alternative or complementary method used during assisted (instrumental) vaginal delivery is vacuum extraction using an instrument usually described as the ventouse. The latter is most frequently used prior to obstetric forceps. A ventouse is merely a suction cup attached to a chain[1] where the cup can be firmly attached to the fetal scalp after removing air from the head to cup space. Since there is no rigid connection between cup and handle, only a traction force can be applied to the fetal head. Therefore, its lack of manoeuvrability may result in an unresolved failure to progress scenario. This is where the obstetric forceps proves to be useful as it enables a large degree of rotation (scoop motion) around the normal of the sagittal plane. However, the application of the forceps blades

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[1] Modern versions are disposable and entirely in plastic, i.e. a plastic suction cup and plastic tube and double handle, the latter enabling manual adjustment of the vacuum inside the cup.

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to the fetal scalp is a difficult task in particular to the untrained professional [1]. The baby's head is barely visible when the forceps blades are inserted[2] which implies that placement of the first blade is based on knowledge of the fetal head station and position. The effortless locking of the second blade to the first blade should be an indicator of correct symmetric placement of the blades around the head. A clinical study conducted by Dupuis et al. [2] shows that from a cohort of 68 neonates, of which 50 were delivered by forceps, 15 of the latter group had intracranial lesions versus none in the group of spontaneous deliveries (with 18 neonates). Dupuis et al. [2] believe that the damage caused by obstetric forceps is due to the incorrect or asymmetric placement of the blades and that this causes a higher degree of deformation of the fetal scalp and introduces levels of high (shear) stress at distinct locations near the placement of the forceps which may ultimately lead to intracranial lesions. In this paper, we aim to put this 'qualitative' theory to the test by simulating the interaction of the forceps with the fetal head in a virtual environment using finite element analysis with the aim to derive quantitative evidence to either support or dismiss this theory.

2 Methodology

2.1 Mesh Models of the Head and Forceps

The first components required in the simulation are models of the fetal head and obstetric forceps. A model of the entire head (ignoring the brain) would require the skull and further layers of skin, fascia, fat and muscle. However, since the mechanical effect of the forceps on the head will only affect the fetal cranial bones and the fontanelles, we have omitted the soft tissue at this stage of development. A fetal skull comprises four distinct components, i.e. the skull base, the maxilla, the fetal cranial bones and the fontanelles. The latter are the gaps in between the cranial bones and have similar material properties to the fetal dura mater [3]. We created a fetal skull model from laser scanning a dry skull model. The model consists of around 63K triangular shell elements. The elements of each of the four components of the skull, which display different material properties (see next section), were encoded in our custom-built visualisation software BirthEngine (see Figure 1). The same figure shows the model of the obstetric forceps (Neville-Barnes) which was created in Blender [4] using images of a real forceps. Each blade consists of $\sim$12K triangles.

2.2 Material Properties

Fetal cranial bone exhibits distinctly different material properties as compared to adult cranial bone. The former consists of a single layer of fibres with radially orthotropic properties whereas the latter consists of three layers with

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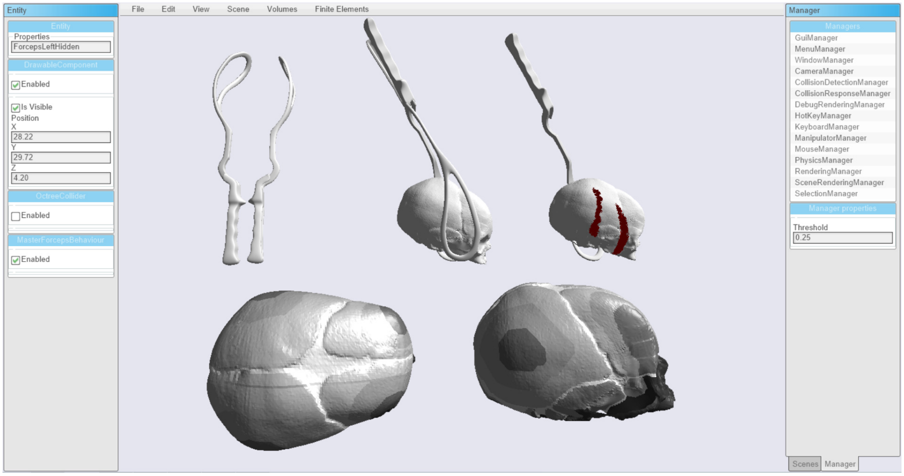
[2] The most commonly used forceps are Neville-Barnes. In the majority of presentations, the left blade is first inserted around the baby's head followed by the right blade after which the shafts of the two blades can be locked together.



Entity
Properties: ForcepsLeftHidden

DrawableComponent
☑ Enabled
☑ Is Visible
Position
X: 28.22
Y: 29.72
Z: 4.20

OctreeCollider
☐ Enabled

MasterForcepsBehaviour
☑ Enabled

Threshold: 0.25

Fig. 1. The BirthEngine software showing a variety of models displayed in the viewport. The top left shows a disassembled obstetric forceps. Note that the blades are assembled similar to scissors. This means that the handles are on the opposite side of the blades. Top middle shows the forceps in contact with the fetal skull. Top right shows the area comprised of triangles in contact with the forceps. In the bottom part, we see the skull with shaded sections corresponding to different thicknesses of the fetal cranial bone. The fontanelles and sutures are coloured white. Darker colours correspond to thicker and/or more rigid materials.

isotropic properties. The orthotropic properties of fetal cranial bone were derived by McPherson [5] and consist of two elastic moduli, i.e. the modulus for the tangential direction to the fibres, $E_t = 3.86$ GPa, and the modulus for the radial direction (perpendicular to the fibres), $E_r = 0.965$ GPa. Furthermore, the thickness of the fetal cranial bones varies from the centre to the periphery. McPherson divided each bone in three different concentric sections with average thicknesses, starting from the centre section to the outer section, of 0.89, 0.74 and 0.61 mm, respectively. McPherson did not report any values on Poisson's ratio. Therefore, we adopted the value of $\nu_{tr} = 0.22$ from McElhaney et al. [6] for tangential compression of adult cranial bone. The value of $\nu_{rt} = 0.055$ was obtained from Lapeer and Prager [7] based on the assumption that in-plane shear stress components on perpendicular faces must be equal in magnitude [8]. The fontanelles exhibit similar material properties as the dura matter with values of $E = 31.5$ MPa and $\nu = 0.45$ as reported by McElhaney et al. [6], Finally, the maxilla and skull base have similar properties to adult cranial bone [6], i.e. $E = 4.46$ GPa and $\nu = 0.21$. The forceps are considered to be of solid steel. Figure 1 shows the fetal skull model in the bottom of the viewport and the forceps in the top left.

2.3 Forceps to Head Interaction

First we need to detect the collision between each of the forceps blades and the fetal skull. We use a hierarchical collision detection (CD) method. The first stage consists of an octree subdivision of axis aligned bounding boxes for each model. These boxes are converted to oriented bounding boxes when collision detection is performed between forceps and skull models. The next stage of CD is when the boxes have reached a level in the octree where their number of triangles is equal to a predefined number (typically low). The remaining forceps and skull triangles are then compared for intersection using the Separating Axis Theorem (SAT) [9]. However, since the skin is missing few of the fetal scalp triangles are in direct contact with the forceps. Therefore, we allowed a clearance of 5mm (approx. order of magnitude of skin thickness at full gestation [10]) between the fetal skull triangles and forceps triangles to flag forceps and head triangles as colliding. Figure 1 shows the application of the forceps to the fetal skull in the top middle and right of the viewport. Next we consider the loading model. Typical traction forces applied to obstetric forceps may vary. Average reported values [11] may range from 30-45 pounds which corresponds to forces of 133-200N. However, the traction force is not the only force transmitted to the fetal scalp. There is also a compression force of the forceps blades against the scalp. This force would be typically low when the blades are applied symmetrically due to the near exact fit of the curved blades with the fetal scalp and high for asymmetric application. We use the clearance value, varying between -2.5mm to +2.5mm, to calculate the compression force per triangle. The maximum compression force corresponding to maximum negative clearance (interpenetration of forceps into skull) was set to 120N as reported in [12]. We defined the following empirical equation[3] to calculate the magnitude of the clearance force $\mathbf{F}_{Cl}$ from the clearance Cl:

$$||\mathbf{F}_{Cl}|| = \frac{120 \times (2.5 - Cl)^2}{5^2} \tag{1}$$

Figure 2 shows the force diagram for a single triangle. Finally, three nodes of the skull base and three nodes of the maxilla were encastred to avoid rigid body rotation and translation.

3 Experiments and Results

Once the forces to each of the contact triangles were calculated as outlined in Section 2.3, we ran the ABAQUS Standard finite element software with the non-linear geometry option to assess the deformation and stresses in the fetal skull after applying the forceps symmetrically and asymmetrically around the fetal head[4]. The total traction force was set to 200N corresponding to the maximum

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[3] The quadratic term gives more weight to negative clearances which correspond to proportionally higher compression forces as compared to positive values.

[4] A realistic scenario of asymmetric placement was adopted in the FE model after tests on an in-silico baby head model (ESP ZKK-240K) and a real forceps.

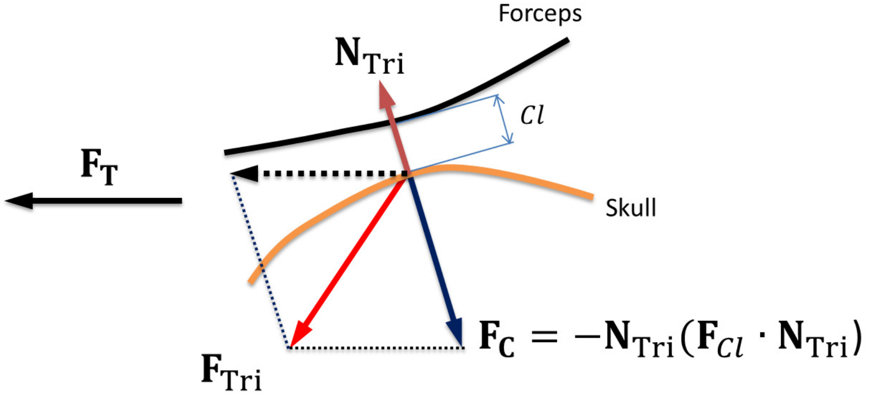

Fig. 2. Forces acting on a single triangle. $\mathbf{F}_{\mathbf{T}}$ is the traction force (total traction force divided by number of contact triangles) acting on the triangle; $\mathbf{N}_{Tri}$ is the unit normal of the triangle; $\mathbf{F}_{Cl}$ is the clearance force (Equation 1); $\mathbf{F}_{\mathbf{C}}$ is the compression force pointing in the opposite direction of the triangle's normal; $\mathbf{F}_{Tri}$ is the resultant force on the triangle.

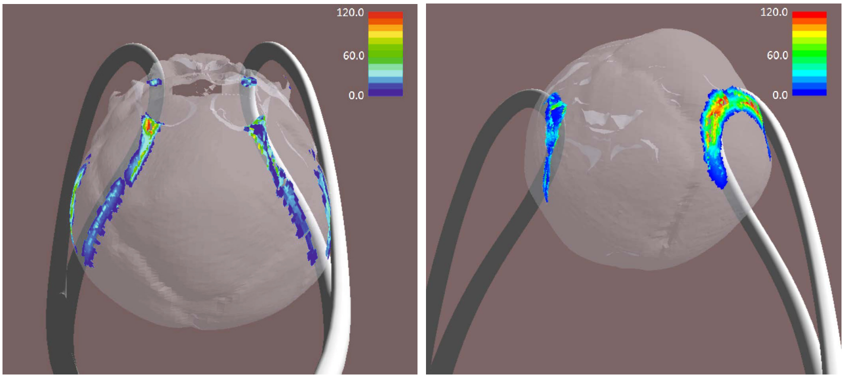

Fig. 3. Forceps blades with exerted compression forces (in N) for symmetric placement (left) and asymmetric placement (right)

Table 1. Values of U (deformation magnitude in mm), S (Von Mises stress in N/mm^2) and S12 (Shear stress in N/mm^2) for Experiments 1 and 2 (forceps applied to unmoulded and (pre-)moulded skull respectively) each with symmetric and asymmetric placement of the forceps.

	U average	U max	S	S12 min	S12 max
Experiment 1 Symmetric	0.136	0.732	10.9	-5.43	+4.14
Experiment 1 Asymmetric	0.449	3.78	45.6	-18.7	+23.5
Experiment 2 Symmetric	0.208	1.33	42.2	-19.5	+13.7
Experiment 2 Asymmetric	0.452	6.45	73.5	-33.3	+38.7

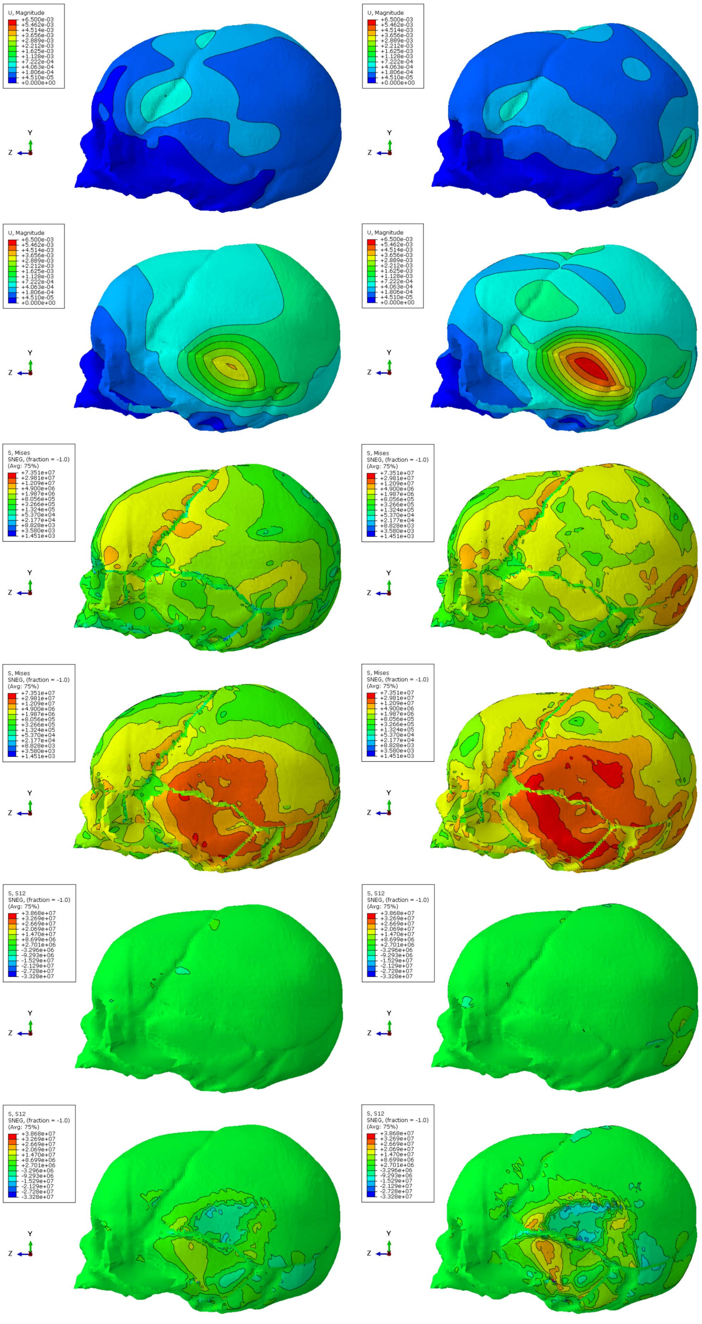

Fig. 4. Columns 1 and 2 show the results for Experiment 1 and 2 respectively. Odd rows (1,3,5) show results for symmetric placement and even rows (2,4,6) for asymmetric placement. Rows 1,2 give the deformation magnitude U in m; Rows 3,4 the Von Mises stress in N/m^2 (Pa); Rows 5,6 the in plane shear stress in N/m^2 (Pa).

force mentioned in the previous section. The compression force was calculated using Equation 1 and Figure 2. Figure 3 shows the compression forces exerted by the forceps blades for symmetric and asymmetric application, respectively. A second experiment took the phenomenon of moulding into account. Indeed, the baby's head will be deformed by the time it reaches the station when the obstetric forceps is applied. Lapeer and Prager [7] analysed fetal head moulding using a computer-based model and found levels of deformation that were in agreement with clinical findings. More recently, Pu et al. [13] created a new computer-based model of fetal head moulding and came to similar results as reported by Lapeer and Prager. We used the latter's model to create a moulded version of the fetal skull which was then subsequently subjected to symmetric and asymmetric forceps applications, respectively. The results of both experiments are shown in Figure 4 for symmetric and asymmetric loading respectively.

4 Discussion

Comparing results shown in Figure 4 and Table 1 we observe the following: Experiment 1 (skull unmoulded): Asymmetric placement of obstetric forceps shows deformation magnitudes which are substantially higher than for symmetric placement. The stress values are also substantially higher for asymmetric placement. Experiment 2 (skull is (pre-)moulded [7]): The same observation, i.e. deformation magnitudes higher for asymmetric placement and also higher stresses are observed. Experiment 1 vs 2: although the maximum deformation magnitude is higher for both symmetric and asymmetric placement when the skull is already moulded , the factor by which the average deformation magnitude and stresses increase (around 2-3), as compared to the unmoulded version (around 4-5), is lower. This 'flattening' trend is likely due to these variables asymptotically reaching their maximum levels beyond which fracture may occur.

5 Conclusion

We have conducted a first series of experiments to evaluate a theory proposed by obstetricians claiming that asymmetric placement of obstetric forceps blades may be at the cause of severe damage to fetal cranial bones and may cause intracranial lesions. Our results showed that for the same model of a fetal skull, asymmetric placements exhibit higher degrees of deformation magnitude and (shear) stresses, as well for average values as for peak values. The effect of moulding prior to application of the forceps showed even higher deformations and stresses for asymmetric forceps placement. Since the geometric model and material properties of the skull are the same for all scenarios, this difference is meaningful and is therefore in line with the proposed theory. However, within the context of translating these findings into potential damage of underlying anatomy (e.g. blood vessels), further refinement of the experimental components is required. First of all, variation in skull geometry and skull material properties, should be considered. Secondly, the soft tissues should be added to the skull. Even though they have no mechanical resistive properties they will affect the transmission of traction and compression forces exerted by the forceps to the underlying skull bones and fontanelles. So far a single-directional traction force was used whereas the application of a Neville-Barnes obstetric forceps follows a scooping motion around the axis in the direction of the normal of the sagittal plane. This more realistic analysis would require a sliding contact model which includes the specification of various friction models.

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