A computer-based simulation of vacuum extraction during childbirth

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Abstract: Vacuum extraction is an instrumental method used in obstetrics when childbirth labour fails to progress. The instrument used during vacuum extraction is the ventouse. It comprises of a suction cup attached to the fetal scalp through a vacuum, and a chord or chain to apply a traction force to expedite the delivery of the baby. It is claimed in the obstetric literature that incorrect placement of the cup, in particular across the anterior fontanelle, may cause serious injury to the fetal scalp. Here we put this theory to the test using a computerised simulation with finite element analysis. The results show substantially larger soft tissue deformations near the anterior fontanelle which may constitute quantitative evidence of qualitative assessments reported in the obstetric literature.

1. Introduction

The natural delivery of the newborn baby may fail to progress for a variety of reasons. Depending on the situation, the midwife or obstetrician may apply an assistive or instrumental method to deliver the baby as quickly as possible. Two instruments are typically used, i.e. the ventouse (vacuum extraction) and the obstetric forceps. The ventouse is often applied first as the traction force applied to the fetal scalp tends to be substantially lower than for obstetric forceps (Govaert, 1993). The latter is most commonly used when no progress is made when using the ventouse. The ventouse is merely a suction cup attached to a chain or flexible chord or plastic tube. The suction cup of older versions (e.g. the Malmström ventouse) has a diameter ranging from 40-60mm and is made of stainless steel (Ali, 2009). Modern versions are disposable and entirely in plastic; including a rigid or soft plastic suction cup of ~50mm in diameter and a plastic tube or cord and double handle. The handle enables manual adjustment of the vacuum inside the cup by a pumping action with the fingers (see Figures 1 and 2). Typical (negative) pressures are 500-600 mmHg to ensure that the cup remains firmly attached to the fetal scalp when a traction force of the order of 100N is applied. The drawback of the ventouse as compared to the obstetric forceps is that there is a lack of manoeuvrability due to the flexible cord which does not allow rotations around its axis (twist).

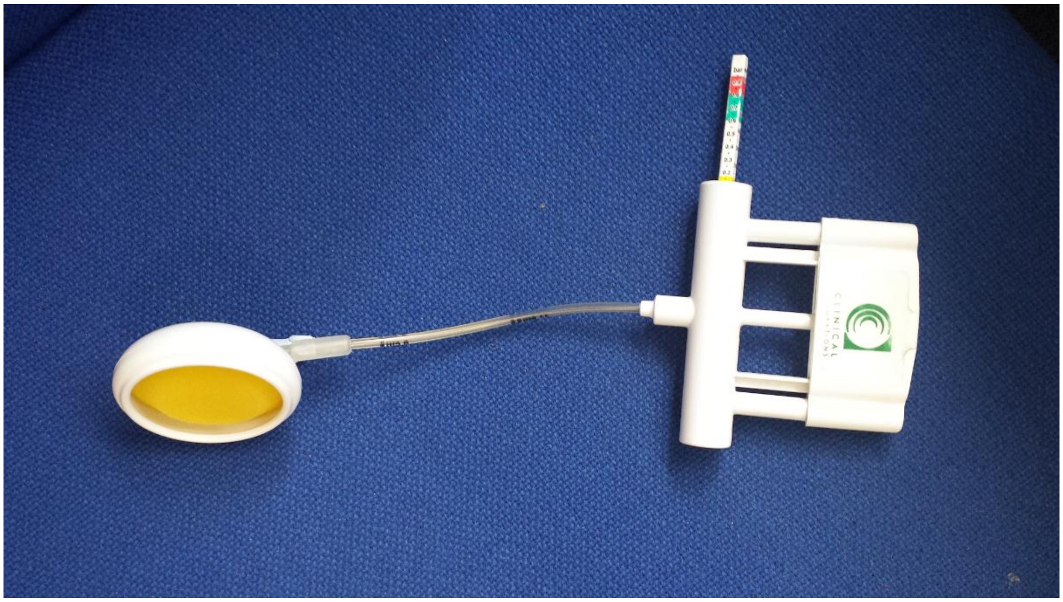

Figure 1. The 'Clinical Innovations Kiwi' hard plastic cup ventouse.

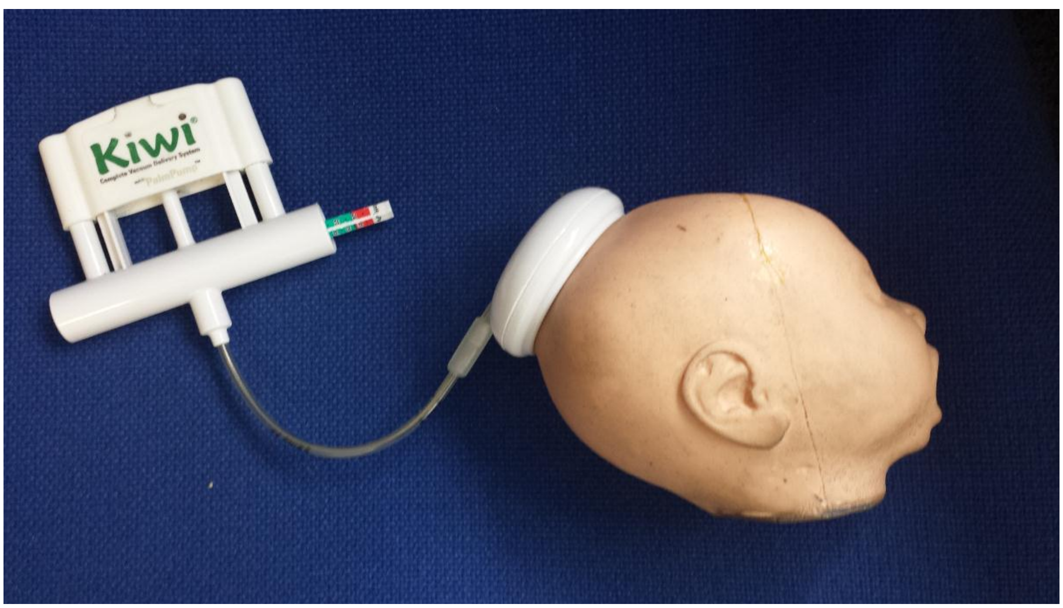

Figure 2. The same ventouse as in Figure 1 as applied to a baby head model (ESP ZKK-240K). The latter experimental setup was used prior to FEA to assess the various forces acting on the fetal scalp as illustrated in Figure 4.

The correct placement of the ventouse on the fetal scalp is absolutely crucial to avoid a range of potential injuries including haemorrhage at various layers of the fetal scalp. Ali et al. (Ali, 2009) point out that the correct placement should be in between the anterior and posterior fontanelle (see Figure 3). They also point out that extreme care should be taken not to place the vacuum cup across the large anterior fontanelle to minimize injury to the fetus and possibly to the soft tissues of the birth canal.

In this paper, we will investigate the effect of the placement of the suction cup on the deformation of the fetal scalp and more importantly, the anterior fontanelle, by computer-based simulation and finite element analysis (FEA) using the Abaqus software.

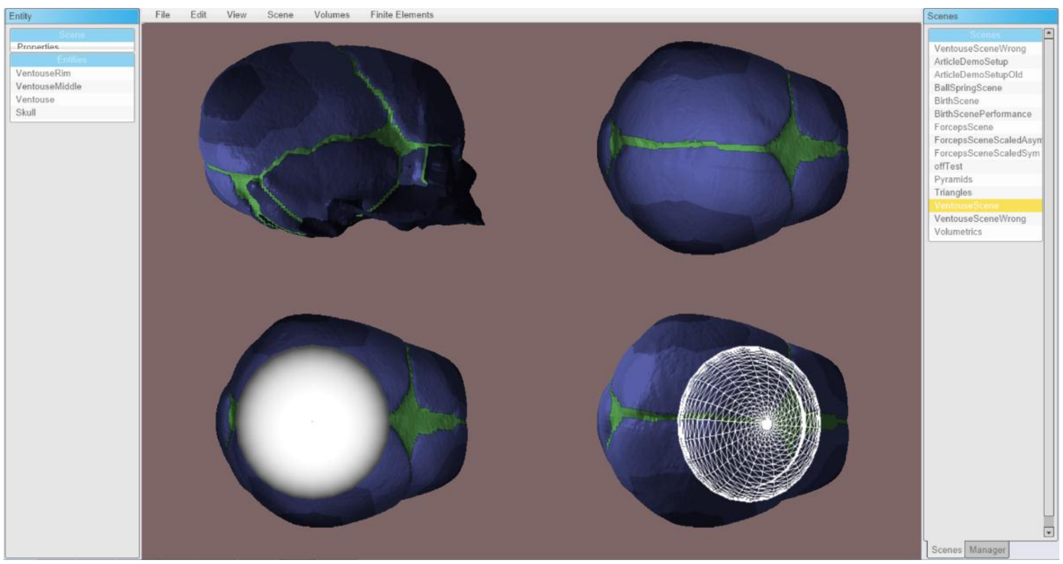

Figure 3. The BirthEngine software showing in the top row the fetal skull model with cranial bones in blue colour (darker areas signify thicker bone) and fontanelles and sutures in green colour. The bottom row shows the correct placement (left) and incorrect placement (right) of the suction cup.

2. Methodology

2.1 Mesh models for FEA

We will employ implicit Finite Element Analysis (FEA) with non-linear geometry to assess the deformation of fetal skull bones and fontanelles when subjected to vacuum extraction using the ventouse. The first step to enable such an analysis is the creation of mesh models of the fetal cranial bones, the fontanelles and the suction cup. It should be noted that the skin, fascia, fat and

muscle layers which lay atop the cranial bones, fontanelles and sutures, are currently omitted to reduce the complexity of the model. We will elaborate on this in Section 5.
Figure 3 at the top shows the major bones (blue) and fontanelles and sutures (green) of the fetal skull. Unlike adult cranial bone, which is isotropic and consists of three layers, i.e. two thin compact bone layers on the outside and a larger spongy layer (called diploë) in the middle, fetal cranial bones are single layer shells with radially orthotropic properties. The thickness of the fetal cranial bones tend to be less than 1mm on average (McPherson, 1978) hence shell elements can be used in the FE model. The cranial bones are not ossified yet (meaning they are disjoint) and are kept together by thin sutures and fontanelles, both exhibiting hyperelastic properties similar to the dura mater (Bylski, 1986). They are also thin hence shell elements can be used. The surface geometry of the model was captured from laser scanning a replica model (ESP ZKK-268-R). Triangle dimensions are of the order of 1mm resulting in 63,917 first order shell elements. The suction cup was modelled in Blender (http://www.blender.org/) using pictures of the Clinical Innovations Kiwi ventouse (Figure 1) and consists of 2,736 triangles.

2.2 Material properties

- Fetal cranial bone: from McPherson (McPherson, 1978) – radially orthotropic with elastic moduli E_t = 3.86GPa (tangential to the fibres) and E_r = 0.965GPa (radial/orthogonal to the fibres). The thickness varies continuously from the centre of each bone towards the periphery and is discretised in three consecutive sections of 0.89, 0.74 and 0.61 mm, respectively. Poisson's ratios are obtained from McElhaney et al. (McElhaney, 1970), i.e. ν_{tr} = 0.22 and Lapeer et al. (Lapeer, 2001), i.e. ν_{rt} = 0.055.
- Fontanelles and sutures: currently, these are approximated by linear elastic properties of adult dura mater as reported by McElhaney (McElhaney, 1970): E = 31.5MPa and ν = 0.45.
- Maxilla and skull base: exhibit similar material properties to adult cranial bone, i.e. E = 4.46GPa and ν = 0.21 (McElhaney, 1970).

2.3 Ventouse to head collision

The collision between the suction cup edge and the skull model is determined in our custom-built BirthEngine software (Figure 3). A multi-stage collision detection algorithm uses axis aligned bounding boxes (AABB's) to create an initial bounding box octree subdivision. The AABB's are then converted to oriented bounding boxes (OBB's) when collision detection is checked between the suction cup and skull models. When colliding OBB's of both models have reached a level in the octree where the number of triangles they contain is equal to a predefined threshold (typically low) then collision detection is further refined to triangle-to-triangle checks between each of the two models. The collision detection algorithm outputs the skull triangles colliding with the suction cup edge. An additional algorithm finds the skull triangles comprising the inner area of the suction cup which are required in the load model discussed next.

2.4 Model loading and boundary conditions

A two step process is needed to model the interaction of the ventouse with the head:

1. Static process: The pressure inside the suction cup is decreased to create a vacuum. This results in a (negative) pressure, p, on the area inside the cup and a positive contact pressure at the edge of the cup. Figure 4 shows the latter as distributed forces around the edge, F_p, which are aligned opposite to the normals of the skull triangles in contact with the cup edge. It should be noted that the edge area is given by $\pi/4\ (d_o^2 - d_i^2) = 4.12\text{cm}^2$ with $d_o = 55\text{mm}$ and $d_i = 50\text{mm}$. The negative pressure, p, is operative on the triangles comprising the inner area of the cup with diameter d_i. These two are in equilibrium however, the edge pressure will depress the underlying triangles, whereas the negative pressure inside the cup will lift the underlying triangles. The vacuum pressure was set to 500 mmHg as reported by Ali et al. (Ali, 2009) which corresponds to $p = 66.7\text{kPa}$.
2. Quasi-static process: Here the operator pulls the fetal head through the handle and chord attached to the suction cup. Since this process progresses very slowly (low velocity) it can be considered as static. The maximum allowable traction force is 131N (considering the vacuum pressure is 66.7 kPa and the area is 19.6 cm^2). A force exceeding this would pull the suction cup from the scalp. Typical forces applied to a ventouse are around 100N which is what we adopted in the model for F_T and is well below the maximum allowable force.

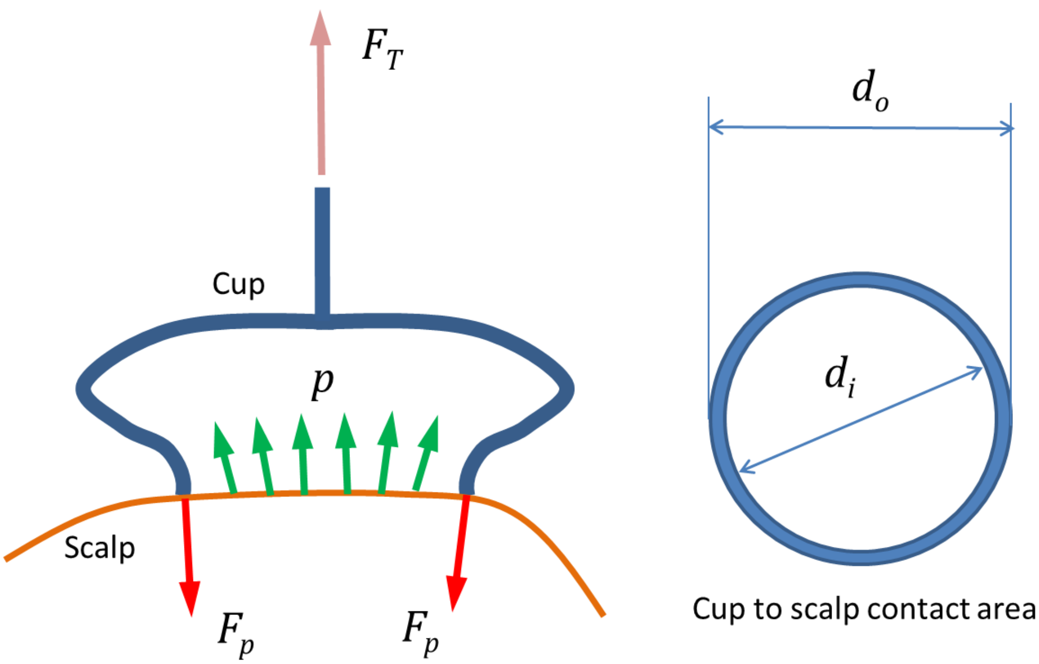

Figure 4. Left: Stage 1: The edge of the suction cup is pressed against the fetal scalp due to the vacuum pressure *p*. Stage 2: A traction force F_T is applied to the fetal scalp. Right: The suction cup with the inner diameter, d_i, designating the area where the vacuum pressure is active, and the outer diameter, d_o.

Finally, the boundary conditions are set by three encastred nodes on the skull base to prohibit rigid body translation and rotation in the coronal and transverse planes. Since we assume that the head does not rotate around the fulcrum, three additional nodes in the facial area are encastred as well to prohibit rotation in the sagittal plane.

3. Experiments and Results

The previous sections outlined all the necessary steps to run a FEA.
Next, we ran a two-step static analysis using the Abaqus Standard finite element software with the non-linear geometry option to assess the deformations of the fetal skull bones, sutures and fontanelles near the position of the suction cup. Two scenarios were assessed: correct placement and incorrect placement i.e. on top of the anterior fontanelle. A second experiment takes the phenomenon of moulding into account. The baby's head is deformed during the first stage of labour due to the contact pressure of the uterine cervix (Lapeer01, 2001), (Pu, 2011). Since the vacuum extraction process starts at the end of the second stage, the head will be already moulded prior to the application of the ventouse. In summary, four analyses were run: correct cup placement on an unmoulded skull, incorrect placement on an unmoulded skull, correct placement on a moulded skull and incorrect placement on a moulded skull. Figures 5-12 show the results. Table 1 shows the deformations and rotations for each analysis.

Table 1. Columns 2-5: values of absolute maximum deformations in x (U1), y (U2) and z (U3) respectively and the overall maximum deformation magnitude U in mm. Columns 6-9: values of absolute maximum rotations about x (UR1), y (UR2) and z (UR3) and the overall maximum rotation magnitude UR in radians.

	U1	U2	U3	U	UR1	UR2	UR3	UR
Correct placement Unmoulded	1.74	3.00	1.30	3.15	0.29	0.25	0.25	0.35
Incorrect placement Unmoulded	2.86	6.73	2.03	7.01	0.49	0.38	0.58	0.69
Correct placement Moulded	2.79	4.46	1.83	4.50	0.43	0.45	0.45	0.58
Incorrect placement Moulded	4.87	8.77	2.72	9.13	0.58	0.57	0.71	0.84

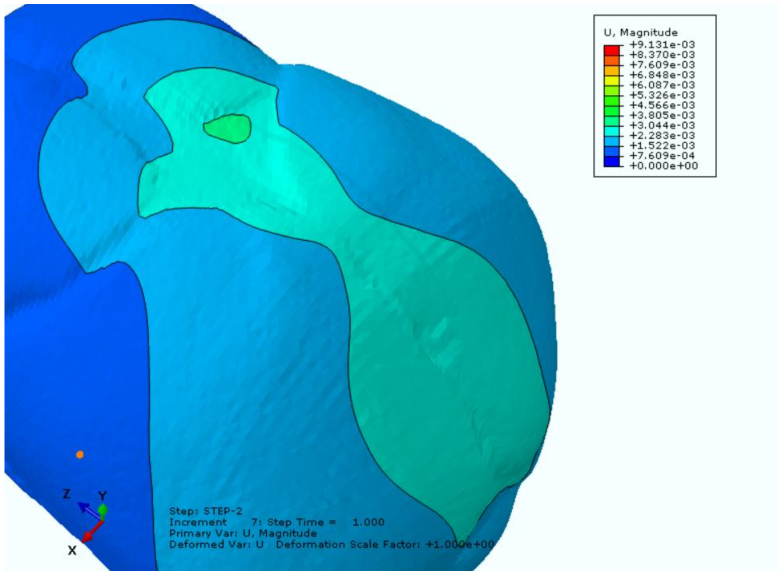

Figure 5. Deformation magnitude (m) for unmoulded skull - correct cup placement.

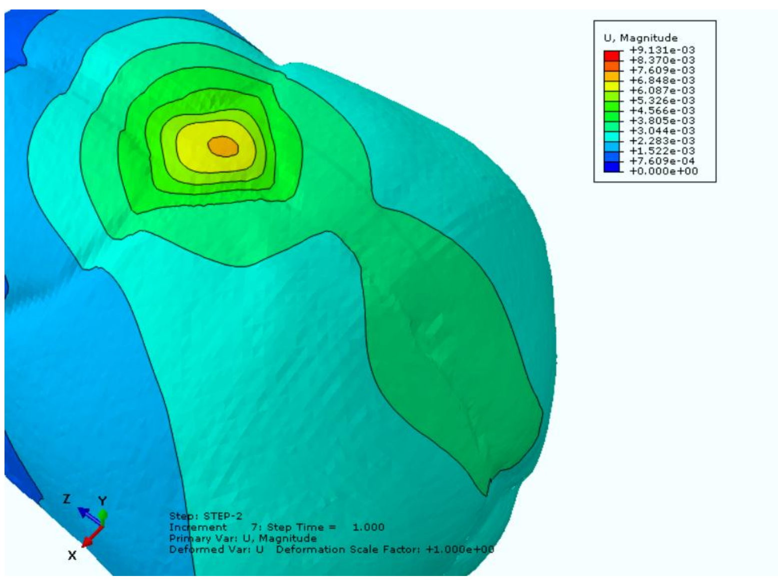

Figure 6. Deformation magnitude (m) for unmoulded skull - incorrect cup placement.

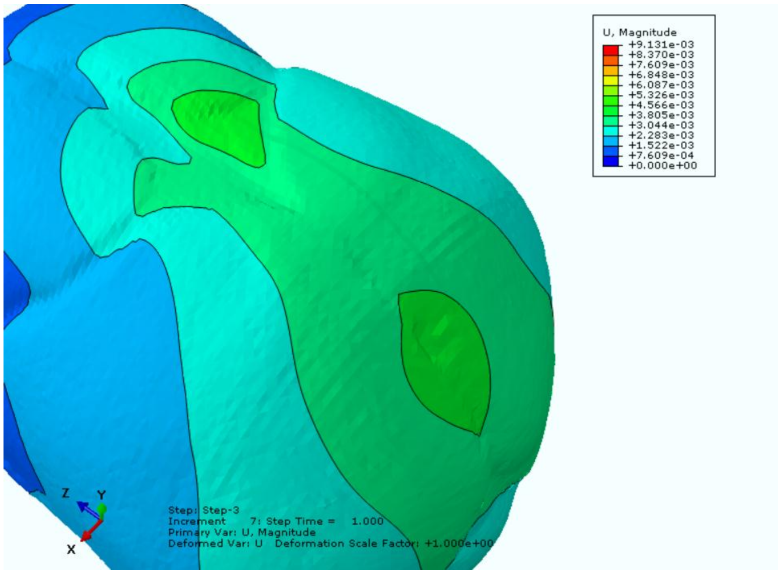

Figure 7. Deformation magnitude (m) for moulded skull - correct cup placement.

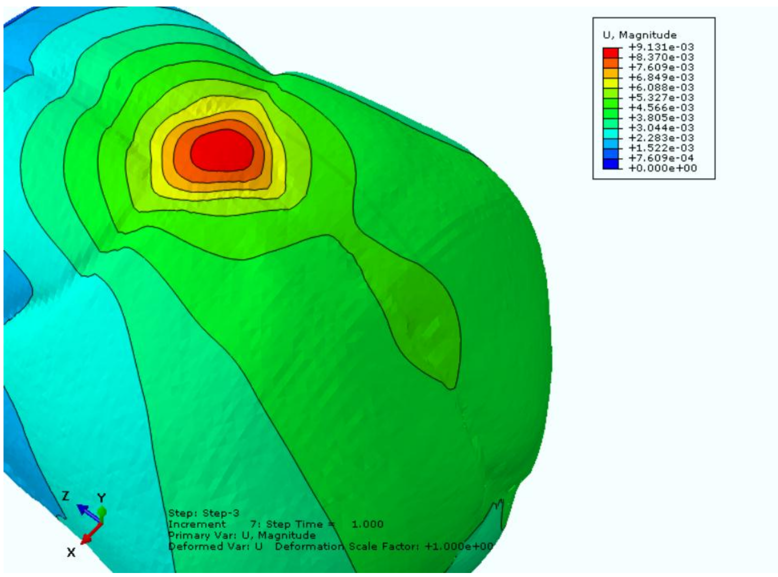

Figure 8. Deformation magnitude (m) for moulded skull - incorrect cup placement.

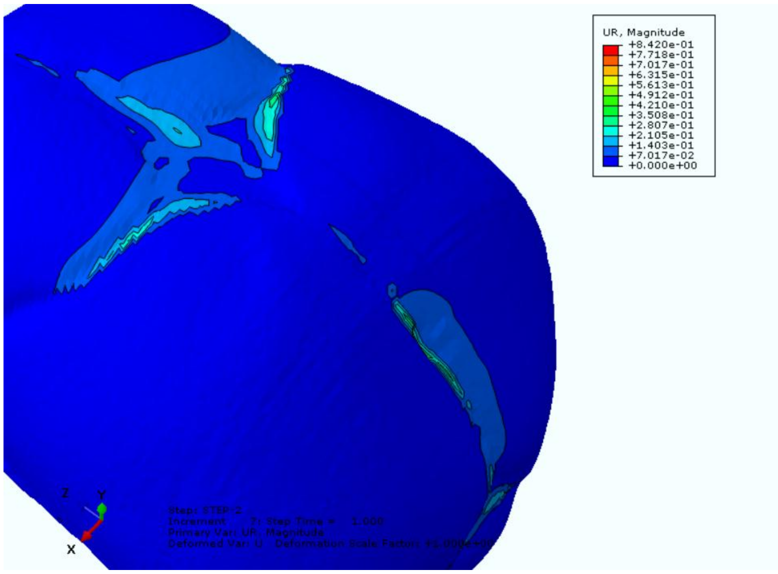

Figure 9. Rotational magnitude (rad) for unmoulded skull - correct cup placement.

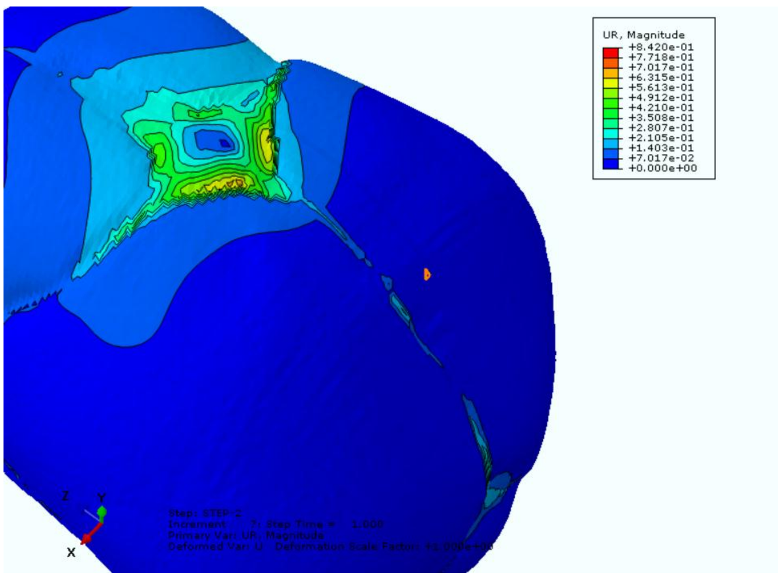

Figure 10. Rotational magnitude (rad) for unmoulded skull - incorrect cup placement.

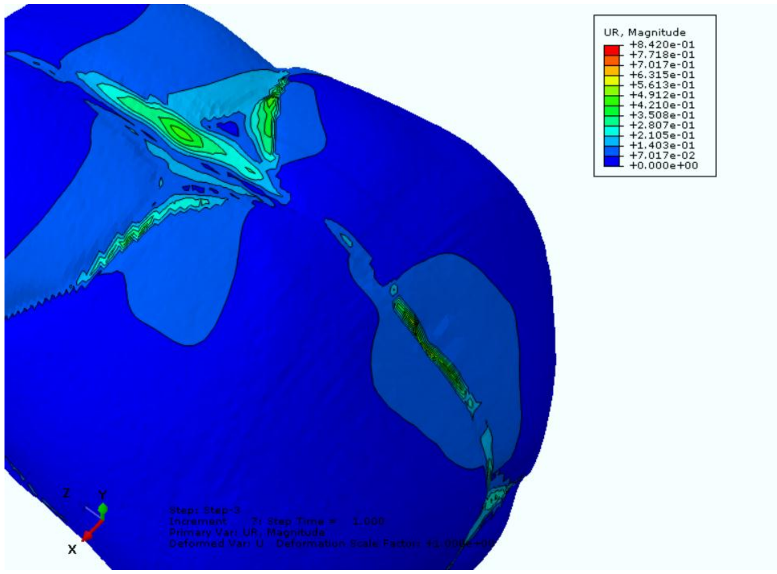

Figure 11. Rotational magnitude (rad) for moulded skull - correct cup placement.

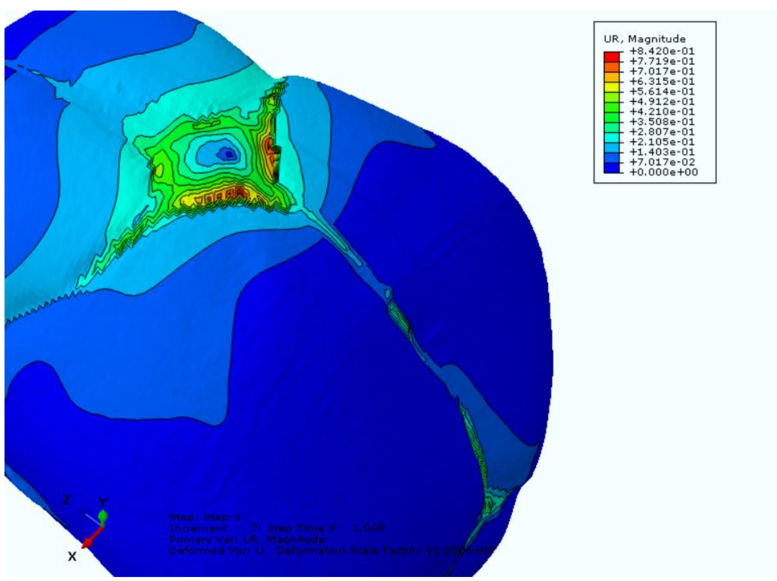

Figure 12. Rotational magnitude (rad) for moulded skull - incorrect cup placement.

4. Discussion

It should be noted that the y-axis is up or normal to the transverse plane; the x-axis is normal to the sagittal plane and the z-axis is normal to the coronal plane. The maximum values for both deformations and rotations are reported for each of the axes and the overall maximum magnitude. Note that values do not necessarily correspond to the same node in the model. It is clear that both deformation and rotation values are higher for the cases of incorrect suction cup placements (Figures 6,8,10 and 12); an effect that is further aggravated by the skull being (pre-)moulded (Figures 10 and 12). Higher deformations are observed in the y-direction (U2) since this is the direction of the traction force, F_T. It comes to no surprise that direct placement across the soft tissue anterior fontanelle is bound to have significantly higher deformations in that area. A clear progression is illustrated in Figures 5-12 with incorrect placements showing higher deformations/rotations than correct placements and pre-moulded skulls showing higher deformations/rotations than unmoulded skulls. The same results are confirmed by the values in Table 1.

5. Conclusion and Future Work

We have presented a first series of experiments to assess the placement of the suction cup of a ventouse. Following guidelines from the obstetric literature (Ali, 2009) we placed the suction cup correctly (between anterior and posterior fontanelles) and incorrectly (on top of the anterior fontanelle) respectively. Additionally, we assessed the effect of the fetal head being moulded due to the first stage of labour (Lapeer01, 2001), (Pu, 2011). Results showed significantly higher deformations near the anterior fontanelle when the cup is placed in that area. The effect of moulding aggravates this observation. Large deformations in this area may cause injury to the underlying anatomy, including blood vessels and may as such result into haemorrhage at different layers (depths) of the fetal scalp. This supports qualitative observations from the obstetric literature (Govaert, 1993), (Ali, 2009).

Currently, a simple model has been used which has omitted the soft tissues covering the scalp. Indeed, these tissues are important when a ventouse is used as the suction cup sucks the skin up and may create the well-known 'caput succedaneum' (scalp edema). Although modelling skin is relatively straightforward, the main challenge is the modelling of the underlying muscles which connect the skin through connective tissue to the skull bones. It is not straightforward to derive data on the adhesive forces of scalp muscle to bone which will be required to assess the effect of the suction cup on the scalp bones and fontanelles if skin, fat and muscle (and connective tissues) act as an interface between the cup and the scalp. Time-dependent visco-elastic effects due to soft tissues (including fontanelles) have been omitted so far as well. Indeed, scalp deformations do not suddenly appear and disappear (it may take days before the fetal scalp returns to its normal shape in particular after instrumental delivery).

However, there is a risk that by increasing the complexity of the model, various parameters will be poorly estimated and will ultimately render the more realistic model less accurate than the currently used simple model. Either way, we will further investigate the potential of making the model more realistic keeping in mind the above mentioned risk.

The current model has used average values for all parameters, i.e. an average Caucasian skull and average material properties. Since the same settings have been used for all experiments, the presented results are comparatively correct. In future work, we will assess the variation of the reported effects under varying parameter settings.

6. References

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