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Finite element analysis of fetal descent incorporating active uterine contraction.

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1. Introduction

Replicating vaginal delivery presents significant challenges due to its inherent complexity, compounded by ethical constraints and the scarcity of in vivo data. Finite element models, utilizing hyperelastic materials such as Neo-Hookean and Mooney-Rivlin constitutive laws, are commonly employed. However, integrating active uterine contractions is crucial for accurately understanding fetal descent. Despite exploring various constitutive models, issues of uncertainty and validation persist. This study aims to simulate fetal descent under active uterine contractions using a transversely isotropic Mooney-Rivlin model and to analyze the uncertainty of input parameters related to material properties.

2. Methods

2.1 Maternal Pelvis Modeling and Vaginal Delivery Simulation

A model of the maternal pelvis was constructed, encompassing the pelvic bone, sacrum, pelvic floor muscles, female reproductive organs (cervix, uterus), and a fetus at 32 weeks gestation (Bibin et al., 2010). Finite element modeling was conducted using FEBio software. Meshes for all components of the maternal pelvis and the fetal model were generated with linear tetrahedral elements. Mechanical interactions were governed by a sliding-elastic contact algorithm with a friction parameter of 0.05 (Vila Pouca et al., 2019). To simulate vaginal delivery, the smooth muscle tissue of the uterus was modeled using a transversely isotropic Mooney-Rivlin material, incorporating active contractions inspired by cardiac muscle behavior into FEBio.

Additionally, the boundary conditions, the edges of the pelvic bone and the lower part of the sacrum were constrained in all directions to ensure model stability.

In contrast, the section representing the female reproductive organs was left unconstrained, allowing vertical movements induced by the active uterine contractions. When it comes to active contractions of the uterus, the pregnant uterus was segmented into an active portion and a passive portion (Beckmann et al., 2013). The active portion is responsible for contractions that drive the baby downward, while the passive portion remains relaxed and stretches to create more space for the baby's passage. To simulate the spread of electrical stimuli, we hypothesized the existence of a pacemaker located in the uterine fundus, following the findings of (Vila Pouca et al., 2019). Their research showed that electrical signals increase intracellular calcium levels, leading to muscle contractions. This contraction-induced tension in the tissues generates electrical activity in nearby tissues, causing a chain reaction of contractions. According to this model, uterine contractions start in the fundus and propagate downward through the active segment of the uterus. Moreover, the fiber orientation was set in the longitudinal direction, aligning with the smooth muscle fasciculi (Sharifimajd et al., 2016).

2.2 Simulation outcomes evaluation and parameter uncertainty analysis

To evaluate results, we compared the trajectory of the fetal head among finite element simulation findings, MRI childbirth data (Güttler et al., 2012). Moreover, material property uncertainties ($C_1 = 0.01 \pm 1$ MPa, $C_2 = 0 \pm 0.45$ MPa, $C_3 = 0.1 \pm 2.9$ MPa, $C_4 = 1.7 \pm 10.8$ MPa, $C_5 = 0.8 \pm 1.5$ MPa, $\lambda = 1 \pm 1.1$, $Ca_0 = 1 \pm 10$ μ M) of smooth uterus muscle tissue were considered based on (Nguyen et al., 2024). For uncertainty analysis, a non-intrusive Polynomial Chaos Expansions (PCE) method was employed using the UncertainSCI tool to address uncertainty propagation. Uncertain inputs, specifically material properties, were modeled with a uniform distribution for all input parameters. The primary quantity of interest was the displacement magnitude of uterus during the vaginal delivery simulation. Additionally, a global sensitivity analysis was conducted to evaluate the sensitivity of the model output to variations in these input parameters. Furthermore, when selecting the order of the PCE, only the second-orders were considered because the first-order terms represent linear relationships between the input variables and the output, while the second-order terms include both linear and quadratic components, capturing a mix of linear and some nonlinear interactions.

3. Results and discussion

In the simulation of vaginal delivery, uterine contractions cause a decrease in uterine volume through the magnitude of displacement (refer to Fig. 1). This displacement generally reflects the expected movement and deformation of the uterus during these contractions, while the fetus concurrently descends.

This capability arises from the use of tetrahedral mesh elements and hyperelastic materials, which effectively capture the significant deformations of uterine tissue. The agreement between simulated fetal displacement outcomes and in vivo MRI data strengthens the validity of the developed models. Furthermore, the simulation accurately reproduces the fetal movements observed during vaginal birth, including the noticeable flexion of the fetal head, resulting in contact between the chest and chin of the fetus. This correspondence indicates that the models faithfully replicate physiological process, establishing them as crucial valuable reference for clinical and research purposes. Moreover, it underscores the importance of integrating active uterine contractions into simulations of vaginal delivery to ensure realistic and reliable results.

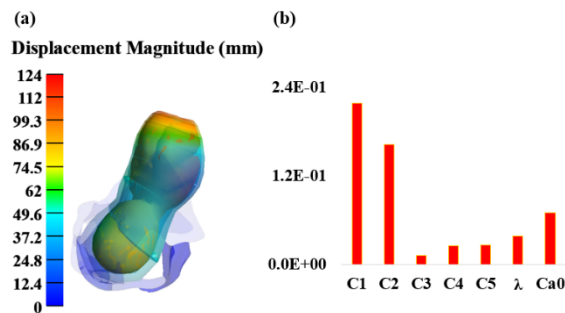


Figure 1. Evolution of displacement (mm) during uterine contraction in vaginal delivery simulation (a) and Global sensitivity analysis of individual variables (b).

Additionally, four parameters (C_1 , C_2 , λ , Ca_0) were identified as having the highest sensitivity (Fig. 1b). This is primarily attributed to the nature of the transversely isotropic Mooney-Rivlin material model, where stiffness properties are controlled by the material constants C_1 and C_2 . These constants dictate how the tissue responds to deformation, with higher values indicating increased stiffness and greater resistance to deformation. Additionally, these parameters such as fiber stretch λ create sarcomere length and Ca_0 represents the maximum peak intracellular calcium concentration, leading to uterus contractions, which is important for regulating muscle contraction. The study emphasizes the critical need to thoroughly assess global parameter sensitivity, parameter uncertainty, and simulation outcomes. Careful consideration of these factors is essential for guaranteeing the reliability and relevance of simulation models in clinical settings.

4. Conclusions

Our findings underscore the necessity of active uterine contraction in simulating vaginal delivery. However, thorough assessment of global parameter sensitivity, parameter uncertainty, and outcome evaluation is

important. In the future, this approach could be extended to patient-specific modeling and simulations of delivery complications, offering insights into risks and potential therapeutic interventions.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest related to the present work.

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