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Subject-specific foetal modeling workflow towards complex cardinal movement simulation based on medical imaging

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1. Introduction

Despite recent progress in the medical care of childbirth, perineal complications still affect a significant proportion of women after a vaginal delivery (Oliveira et al, 2017). To better understand and evaluate childbirth's associated risks, computational models are under investigation. A recent literature review (Chen et al, 2020) points out that present models lack of realism, partly due to an oversimplification of foetal models. In fact, most often, only the head is modelled, and joints are not included. This prevents from modelling the foetal cardinal movements, which play a crucial role during labor. Neuromusculoskeletal (NMS) modelling offers the possibility to increase the biofidelity of foetal models dedicated to childbirth simulations by allowing joint motion. The aim of the present work is to propose a workflow to simulate the foetal cardinal movements using a generic full-body foetal NMS model for OpenSim, scaled using patient-specific data retrieved from medical imaging.

2. Methods

2.1 Modelling workflow

The proposed workflow contains three main processing steps, summarized in Figure 1. Medical images of the foetus, saved in DICOM format, constitute the input data. Those images are imported within the software 3D Slicer, and automatic segmentation based on pixel intensity thresholding is performed to extract the subject's skeleton. The foetal skeleton is then automatically part-segmented into 23 separate bony parts using a deep-learning algorithm proposed in Ferrandini et al. (2024a), based on the PointNet++ neural network (Qi et al, 2017).

During the second processing step, the segmented geometries are rigidly transformed to set the subject in anatomical posture. This operation is performed using a custom-made Python Script that articulates the foetal skeleton. The definition of the joints coordinate systems is based on ISB recommendations and the work of Ferrandini et al. (2023). To perform this operation, the Python Script uses as input the coordinates of 58 anatomical landmarks, manually positioned over the foetal skeleton. It outputs a set of STL geometries set to anatomical posture. This allows to easily measure the subject's global height and segment lengths, and serves as a preliminary step towards future development of a foetal statistical shape model (SSM). The foetal weight can be retrieved from the metadata associated to the DICOM images.

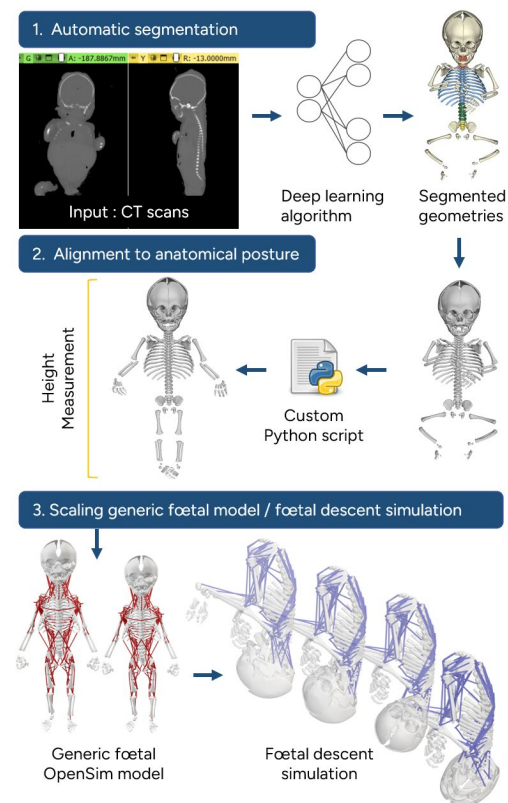


Figure 1: Modelling workflow

Finally, the subject's anthropometric data are used as input to scale the full-body foetus specific NMS model for OpenSim proposed in Ferrandini et al, (2024b). This model contains 22 joints and 65 muscles. Specific attention was given to the cervical spine, which is fully articulated, as this model was designed to simulate the cardinal movements at childbirth. Once scaled to subject's proportions, this generic model is used to replicate the kinematics of the theoretical foetal descent trajectory, described by the curve of Carus (Lapeer et al, 2015).

2.2 Application to existing foetal data

Data from 52 subjects from the New Mexico Decedent Image Database (Edgar et al, 2020) was processed using the workflow described in the previous section. The DICOM images provided correspond to post-mortem computed tomography (CT) scans. The data used to illustrate the workflow in Figure 1 correspond to subject 102717 (height = 45cm, mass = 2.95kg).

3. Results and discussion

The presented workflow uses available work from the literature to simulate the theoretical foetal descent trajectory based on subject-specific data. The automatic part segmentation algorithm used in step one provides a highly accurate segmentation of the foetal skeleton into 23 segments within a few seconds, compared to manual part segmentation (mean accuracy = $95.7\% \pm 4.7\%$). Then, as the linear scaling tool proposed within OpenSim only alters the bone length while their morphology remain unchanged, the use of a generic foetal model enables to reduce the scaling approximations compared to the use of a scaled adult model. As only the foetal head theoretical trajectory during the delivery was available in the literature, motion at the other joints could not be simulated yet. Nevertheless, future physics-driven simulations will involve motion modelling at all available joints.

This research constitutes a preliminary work towards realistic childbirth simulations. Future investigation will focus on creating a full-body foetal SSM, to improve the biofidelity of the scaled foetal model compared to the patient's anatomy, by allowing alteration of the bone shapes. The development such model requires to align data from a large number of subjects. This justifies the need for processing steps 1 and 2. Indeed, if the subject's global height can be directly retrieved from metadata, one could proceed directly to step 3 and scale the generic foetal model to patient's size. Additionally, future work will be dedicated to combine the foetal NMS model with a deformable model to accurately simulate childbirth and associated complication scenarios (Ballit et al, 2023).

4. Conclusions

The presented work constitutes a first step towards the creation of a standardised process to simulate childbirth based on patient-specific data retrieved from medical imaging.

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Conflict of Interest Statement

The authors declare that there are no conflicts of interest related to the present work.

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