TOWARDS A PATIENT-SPECIFIC OBSTETRIC SIMULATOR THROUGH OPENSIM MUSCULOSKELETAL MODELING

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ABSTRACT

The use of mathematical and computational models to study biological systems is a rapidly expanding field in medicine. It allows the synthesis of complex systems such as the human birth process, and can be used to optimize and personalize medical treatments for patients. The current research builds upon a mature computationally onerous finite elements study to develop an interactive obstetrics simulator. The first stage exploits OpenSim and musculoskeletal models to achieve detailed skeletal fetal and maternal dynamics simulation. The second stage, currently underway, will demonstrate enhanced skin visualization of the fetal and maternal models through Biomechanical Animated Skinned Human (BASH). The latter can provide a more realistic and accurate representation of the birthing process, which can improve the training of obstetricians and advance their techniques in the delivery process, ultimately leading to a safer and more successful outcomes for babies and mothers.

Keywords: Fetal musculoskeletal, OpenSim, shoulder dystocia, BASH visualization, obstetrics simulation.

1 INTRODUCTION

Modeling and simulation in medicine represent a rapidly growing field that uses mathematical and computational models to study biological and physiological systems as well as reproduce medical treatments and interventions (Motta and Pappalardo 2013). These models can take various forms, such as finite element analysis, musculoskeletal dynamics, and soft tissue models.

The use of modeling and simulation in medicine has become increasingly important for a number of reasons. First, it allows for the study of complex biomechanical systems such as in human birth processes, which sometimes are difficult or impossible to study in living human subjects non-invasively (Pinto et al. 2017). This is particularly important for understanding the underlying processes involved in these systems.

Second, modeling and simulation can be used to optimize and personalize medical treatments for individual patients and can be used for educational purposes. For example, personalized digital anatomies can be used to develop patient-specific simulator platforms, allowing for the development of personalized treatment plans or expert rehearsals. Alternately, they can be used to train medical students, residents and practitioners in procedures that are difficult to perform safely in live patients (Audette et al. 2021), especially for important scenarios of relatively low incidence.

Lastly, it can be used to improve the efficiency and cost-effectiveness of medical intervention techniques where the traditional apprentice-based training is inefficient, by using the virtual reality VR and augmented reality AR technology for training sessions to reduce training discrepancies, unnecessary repetitions and enhance practitioners techniques (Scalese, Obeso, and Issenberg 2008).

The purpose of this research is to build on a mature, computationally onerous finite elements birthing simulation to develop a real-time, virtual reality obstetrics simulator that will later use haptic feedback to facilitate better training for obstetricians during delivery processes confronted with challenges such as shoulder dystocia (Audette et al. 2021). The foundation for this interactive simulation project is the work of Parente, Natal Jorge, et al. (Parente et al. 2009), which involved an offline finite elements study of the maternal pelvic floor during a simulated birth. One central element of this research was the development of a fetus that emphasized a surface mesh-based skin, devoid of bones or soft tissues, as shown in Figure 1. This fetus comprised of 4 rigid body points in its head, collar, abdominal and hip positioned in their respective body center mass, which controlled its movement using a pre-defined set of coordinates in 3D space. This offline birthing simulation originally required several hours for completion, as shown in Figure 2.

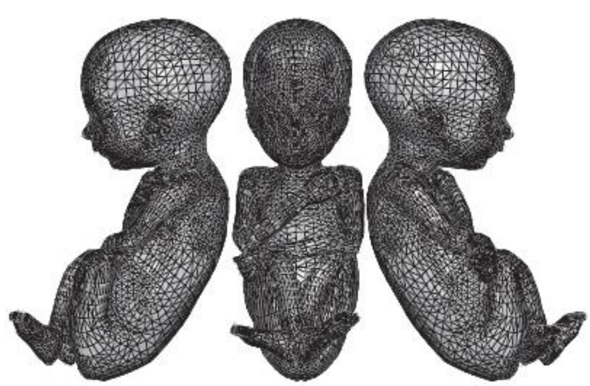

Figure 1: Original figure of Fetal mesh used in the work of (Parente 2008).

A previous research paper by the senior author outlined the architecture and foundation of the emerging interactive simulator, where the core components of the simulator include real-world birthing simulation, a pipeline that processes fetal MRI for voxel-based segmentation and skin surface extraction, and the open-source musculoskeletal dynamics simulation platform OpenSim (Delp et al. 2007) for representing fetal movement (Audette et al. 2021). This paper describes the steps taken to build upon this template by developing a detailed fetal and maternal musculoskeletal models coupled with OpenSim to replicate the offline birthing simulation in real-time.

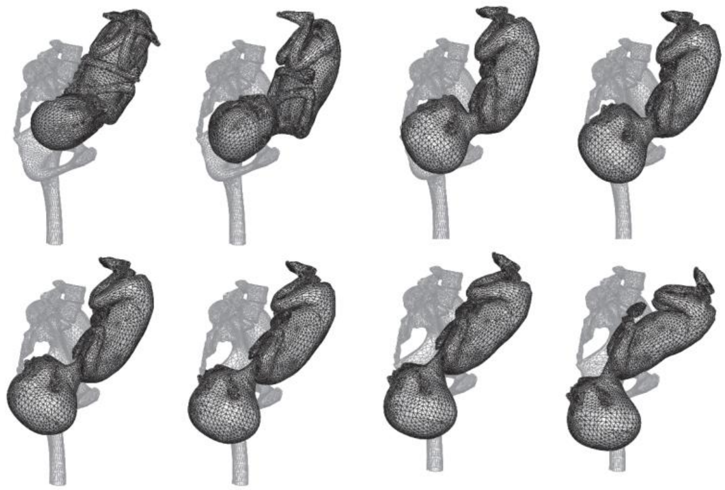

Figure 2: Original figure of Fetal decent during the delivery work of (Parente 2008).

The ultimate goal of this research is to transition from computationally onerous finite elements birthing simulation to real-time, patient-specific bimanual haptics-driven simulation that includes the full maternal anatomy as well as the fetal anatomical model, which can improve the training of obstetricians by manipulating both models, overcoming the current limitations of mannequins, devoid of relevant pathological cases such as shoulder dystocia (Haerling 2018). This approach will ultimately lead to a safer and more successful outcomes for mothers and babies through practice of mitigation techniques such as posterior arm delivery. This research project aims to accelerate and personalize the existing components, taking into account practical clinical considerations throughout the development process.

2 MATERIALS AND METHODS - MUSCULOSKELETAL MODELING

2.1 An overview of OpenSim

OpenSim is an open-source software designed for simulating and analyzing the musculoskeletal models (Delp et al. 2007). An OpenSim model is a representation of a musculoskeletal system and its dynamics, expressed in a structured form. It is made up of interconnected components, each of which represents a separate module, such as a biological structure or device (Seth et al. 2018). The computational system of the model is comprised of two elements: a system of equations that contains fixed physical parameters and a state that holds variables that change over time, such as joint angles. The OpenSim model is created by the developer to replicate the physical system, OpenSim then generates the equations that describe the model's dynamics as shown in figure 3.

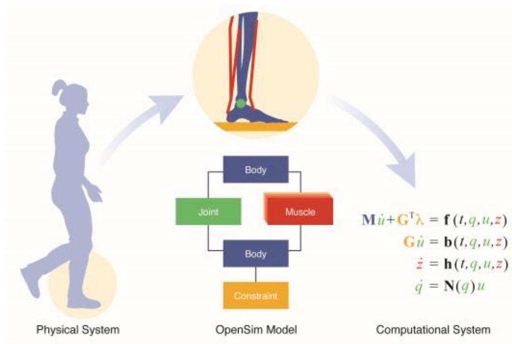

Figure 3: OpenSim framework (SimTK.org).

Its user interface enables access to its tools, such as scale model for resizing, inverse kinematic for calculating the joint movements and inverse dynamic solution for calculating forces and torques. To use OpenSim, first a musculoskeletal system with its environmental interactions (e.g. fetal interaction with maternal structure) should be constructed. The next step is to scale the model based on the specific subject under study using scaling tool. Moreover, to produce the desired simulation the joint movements and muscle activation patterns should be calculated using inverse kinematic and inverse dynamic solutions or to input such data in case prior studies have provided such inputs. Figure 4 shows the user interface of the OpenSim software and its environment.

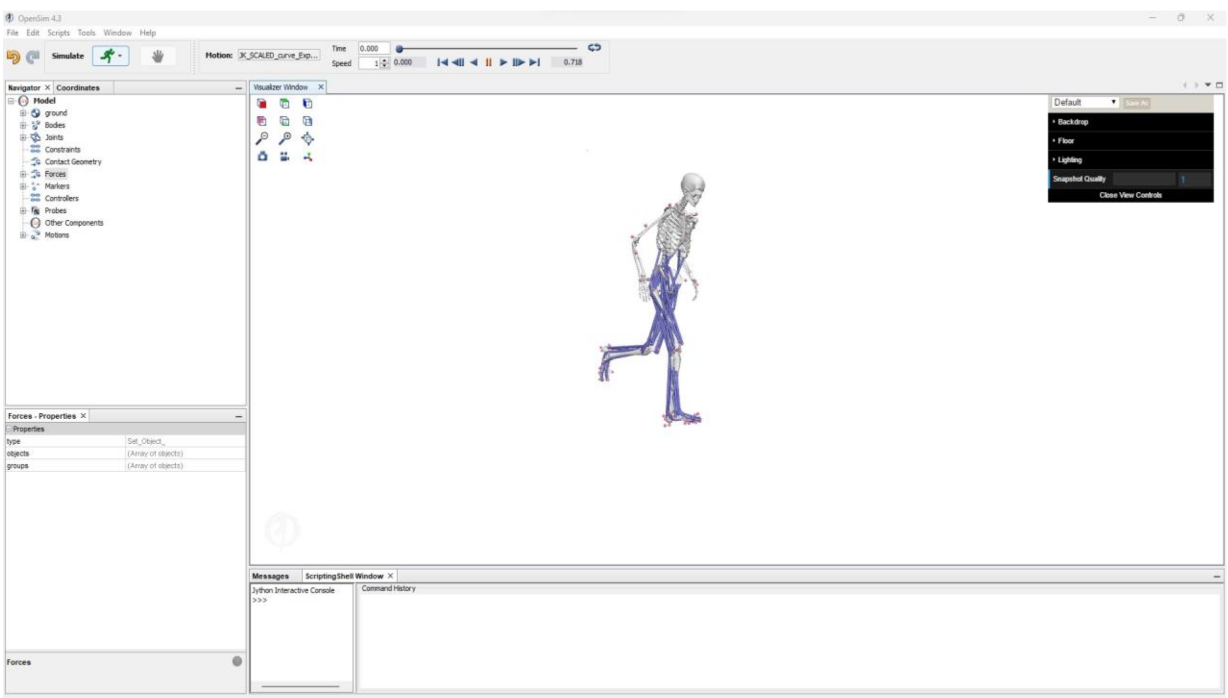

Figure 4: OpenSim user interface and a loaded musculoskeletal model with lower extremities muscle depiction.

2.2 Fetal and maternal musculoskeletal model

This research used a published female adult model developed by Burkhart (Burkhart et al. 2020) as shown in figure 5 as the foundation for developing the fetal musculoskeletal model. This digital adult female served as the maternal anatomy without any significant modification. Moreover, it was resized using the rescale tool of the OpenSim software to create a more accurate representation of the fetal musculoskeletal anatomy. The four rigid body points of the finite element fetal mesh then translated into four markers on the fetal anatomy in the same position. This aggregate anatomy enabled an investigation of the mechanics of the birthing process, while replicating and accelerating the offline birthing simulation in terms of musculoskeletal movement of fetal structure through birth canal. This technique will serve as prelude to the development of a more realistic and patient-specific obstetric simulator, based on fetal MRI in planned future work. The utilization of the rescaling tools in OpenSim was crucial to creating an accurate representation of the fetal musculoskeletal system, which is essential for understanding the birth dynamics in terms of musculoskeletal system.

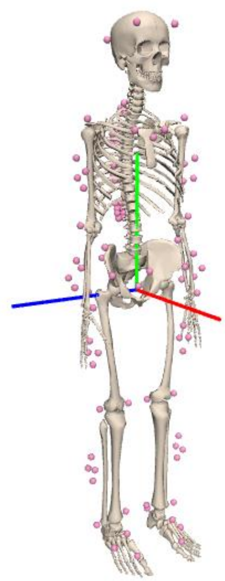

Figure 5: Female full body model, work of (Burkhart et al. 2020).

Table 1 provides the dimensions used in the rescaling tool of OpenSim to create the fetal musculoskeletal model by modifying the pre-existing maternal model. The measurements employed for the rescaling were reproduced from the work of Parente (Parente et al. 2009).

Table 1: Fetal measurements used for re-scaling.

Body-Part	**Measurements (cm)**
Mento-Vertical	13.0
Neck	3.15
Humerus	7.91
Radius	6.42
Femur	7.84
Tibia	8.66
Torso	15.9

The measurements acquired are consistent with literature for average length of newborns (JUDD 1985). Resulting fetal structure produced acceptable measurements in overall height compared to table 1. Using this method, instead of creating the fetal model from scratch, made the process of obtaining the fetal musculoskeletal model much easier. By rescaling the maternal model, it ensured that the model used for the fetus is accurate as possible compared to a complete adult model, including all bones and joints. Figure 6 shows the result of rescaling.

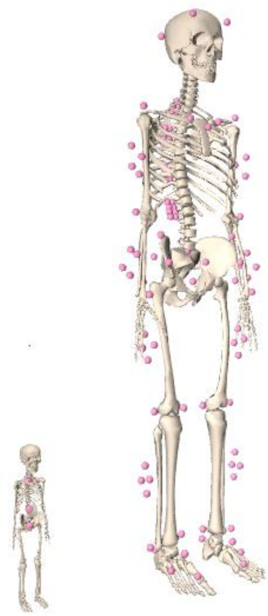

Figure 6: The rescaled fetal model was placed alongside the maternal model for comparison.

2.3 OpenSim implementation

After acquiring the rescaled model of the fetus, the displacement coordinates of four rigid body points in 3D space were extracted from the finite element simulation, tracking 1112 frames of fetus motion during the offline delivery. These coordinates were then put into the Inverse Kinematics IK tool of the OpenSim software. The IK tool used the coordinates to calculate the joint angles and movements of the fetus, providing rotational data of four markers in space that is now governing the OpenSim fetal skeletal movements. This generated a motion file that visually matched the movements captured in the offline simulation.

2.4 Adding Maternal Model

OpenSim allows the incorporation of multiple models in its environment. The maternal model was separately loaded and adjusted respective to fetal position in the scene. Having a complete maternal model as well as the fetal structure, instead of only the pelvis bone opens up many opportunities in terms of simulating the online birthing process in various maternal positions. This allows obstetricians to practice in more relevant scenarios, such as simulating birthing in different positions and with different birthing complications. This provides a more comprehensive and realistic training experience, which can ultimately lead to better outcomes for mothers and babies during the birthing process.

3 RESULTS

In this research, we used a pre-existing female adult model as the foundation for creating a more accurate representation of the fetal musculoskeletal system. By utilizing the rescaling tools available in OpenSim, we were able to develop the fetal model. We captured the displacement coordination of four rigid body points from the offline birthing simulation, which tracked the movement of the fetus during delivery. These coordinates were then input into the inverse kinematic solution of OpenSim, which calculated the angular data of the four markers introduced to the fetal musculoskeletal model, simulating the offline birthing movements. This process also generated a motion file that captured rotational data of the offline simulation. The resulting simulation was visually consistent with the offline birthing movements, which is illustrated in Figure 7.

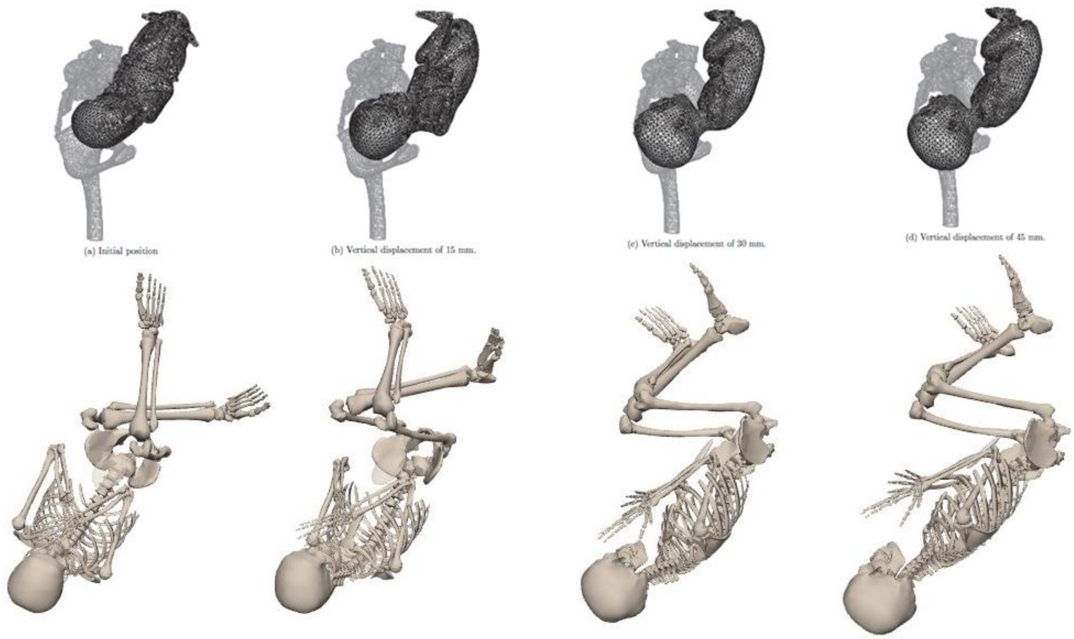

Figure 7: Fetal model movement based on IK result compared to offline birthing simulation.

Although figure 7 depicts snapshots of the IK simulation compared to the finite element birthing process, visually matching the movements, additional analyses between the two models deemed necessary to validate the results. Using OpenSim plotting tool, the movements of pelvis was selected and compared to the initial finite element displacement data extracted from the same rigid hip point. The resulting figure 8 shows matching pattern between the two. Moreover, the correlation analysis between respective axes validated the IK result with more than 97% and 99% correlation coefficient in Y and Z axes respectively.

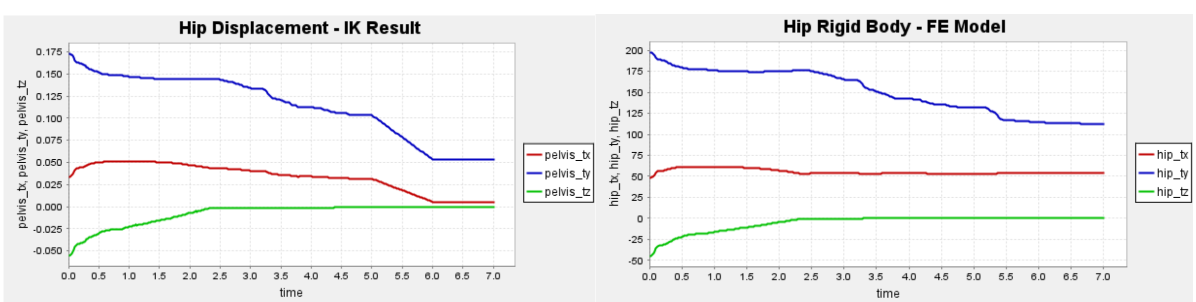

Figure 8: Result validation through pelvis displacement comparison between OpenSim and FE models.

Additionally, by adding the maternal model in the standing position and running the IK result for simulating the fetal movement, the aggregate bodies produced more meaningful results in terms of fetal motion through birth canal. This approach allowed for the investigation of the mechanics of birth and a deeper understanding of the biomechanics of each model. Figure 9 captures both models in the birth process.

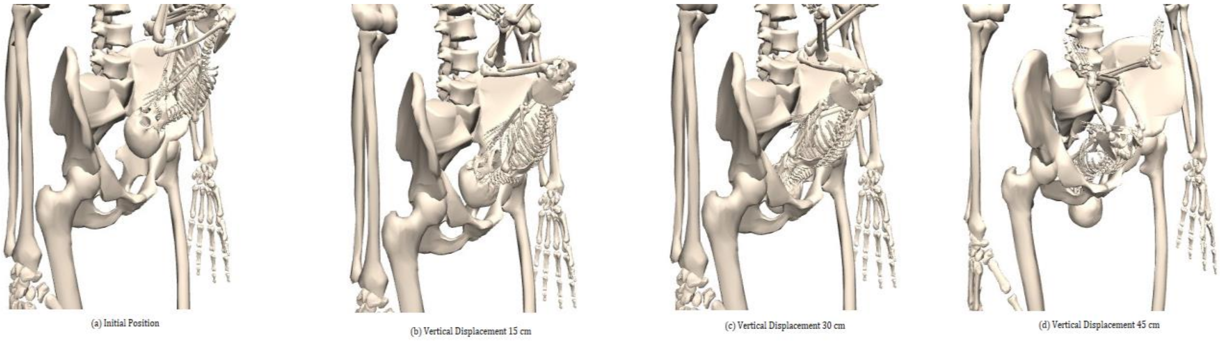

Figure 9: Both models participating in the birth process with maternal model fixed. The snapshots differ in viewing angle.

4 ONGOING AND FUTURE WORK

Currently efforts are underway to increase visualization of both fetal and maternal systems. Authenticity in any training platform is key to getting accepted by its intended users (Chiao, Chen, and Huang 2018). Thus, creating a simulator that enables obstetricians train with fetal models need more realistic presentation of fetal skeletal system. Hence, by adding digital skin surfaces using Biomechanical Animated Skinned Human BASH shown in Figure 10 (Schleicher et al. 2021) this goal can be achieved. These efforts aim to reconstruct animated skin surfaces for representation of biomechanical system such as fetal and maternal structures. The BASH model offers a more realistic representation of a musculoskeletal system defined in the OpenSim format.

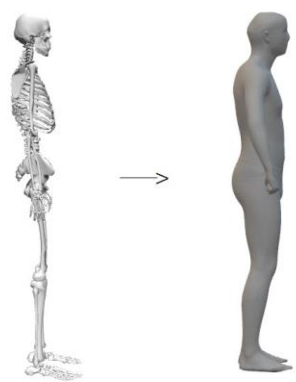

Figure 10: Enhanced visualization of skeletal model using BASH.

After accomplishing the realistic representation of these models, the next step for the patient-specific simulator will be to put the fetal and maternal musculoskeletal models into a VR, haptic feedback friendly environment followed by coupling of suitable VR and haptic devices shown in figure 11 to the hardware. The suggested environment for this goal is the Unity engine which is capable of building real time simulations that can utilize the use of VR and haptic tools (Zhang et al. 2018). The best way to put OpenSim models through the Unity engine is with OpenSim Unity plug-in developed by Abella, J. and Demircan, E. (Abella and Demircan 2019). This plug-in enables the incorporation of OpenSim model into the Unity engine environment.

(a) (b)

Figure 11: Competing options for haptics: (a) Magos haptic feedback device coupled with VR goggles; (b) Hatpx G1 glove, with wireless Air Controller shown in inset.

5 CONCLUSION

In conclusion, this research has demonstrated the importance of using computational models in synthesizing the complex process of human birth. The use of a pre-existing maternal model and the rescaling tools in OpenSim allowed for the development of a more accurate and realistic fetal musculoskeletal simulation, which is crucial for understanding delivery dynamics. The inverse kinematic solution of OpenSim allowed for a deeper understanding of the biomechanics of delivery by generating a motion file that matched the movements captured in the finite elements simulation. Furthermore, the use of a complete maternal model, including all bones and markers, facilitates many opportunities for simulating the interactive obstetrics simulation in various maternal positions. Once bimanual haptics are integrated, this approach will enable a clinically relevant and realistic training for obstetricians, ultimately leading to better outcomes for mothers and babies. This research emphasizes the importance of providing a platform for training and education in obstetrics and the potential of interactive obstetrics simulation in achieving that goal.

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