Toward an Interactive, Patient-specific, VR-based Obstetrics Simulator

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***Abstract*—This paper presents a nascent collaborative effort to achieve a Virtual Reality (VR)-based, real-time, haptics-driven patient-specific obstetrics simulator. The high-level architecture and preliminary results are presented here; the latter are based on offline birthing simulation developed by team in conjunction with open-source visualization tools. The cornerstones of this simulator will be high-fidelity generic offline birthing simulation, an anatomy-to-image nonrigid registration pipeline exploiting fetal MRI, the open-source interactive medical simulation toolkit IMSTK augmented by high-throughput deep learning-based soft tissue deformation, open-source musculoskeletal dynamics simulation platform SimTk for representing fetal motion.**

Keywords- birthing simulation; obstetrics; virtual reality; bimanual haptics.

I. INTRODUCTION

There is *high variability in obstetrics performance* within the United States, as well as *an egregious underperformance of the US* against developed countries and *of developing countries* against developed countries, all of which suggest that the current approach to obstetrics training could be improved**.** Specifically, Glance et al found that 13 percent of the four million US women giving birth annually experience one or more major complications [1]; they used multivariable logistic regression to assess the variation in obstetric complication outcomes across US hospitals (based on 750,000+ deliveries) and found an alarming disparity between high and low-performing hospitals. Lower-graded hospitals had *complication rates double those of better hospitals in vaginal deliveries*, at 22.55% and 10.42% respectively, as well as *five times those of better hospitals in cesarian deliveries*: 20.93% vs. 4.37%. In addition, a comparison study *found the US to be the worst-performing in maternal mortality in a group of 11 developed countries* [2]: in 2018, there were 17 maternal deaths for every 100,000 births in the US, a ratio more than double that of most other high-income countries [2]. Furthermore, *obstetric complications in developing countries are also distressing*, with 530,000 women worldwide dying annually and 95% of these deaths occurring in Africa and Asia [3].

An important risk factor in labor is *shoulder dystocia*, depicted in Figure 1, a difficulty in the delivery of the fetal shoulders after delivery of the head. Shoulder dystocia is characterized by approximate incidences of 1% for babies under 4 kg [4][5], 5% for babies between 4 and 4.5 kg, and 10% for babies heavier than 4.5 kg [5] respectively. Neonatal complications include death and cerebral palsy due to loss of oxygen to the baby's brain, from the dystocia itself, and brachial plexus injury complications such as Klumpke’s paralysis and Erb's palsy caused by the action of the obstetrician. Maternal complications include vaginal and cervical lacerations as well as post-partum hemorrhage [6].

The current emphasis in simulation-based obstetrics training is on *mannequins* [7][8], as seen in Figure 2. These trainers are limited by the *paucity of clinically relevant complication*

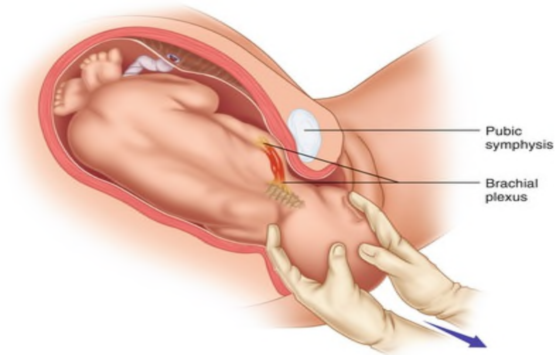


Figure 1. Shoulder dystocia. Mechanism of shoulder dystocia – retention of the anterior shoulder of the neonate above the pubic symphysis. Reproduced with permission from Obgynkey.com [10].

Figure 2. Birthing mannequin simulators. Leardal's SimMom reproduced with permission [7].

models, their *inextensibility to specific patients*, and *prohibitive costs precluding third world applications*. A seasoned obstetrician confronted with shoulder dystocia can draw from a set of appropriate corrective procedure such as the McRoberts maneuver, suprapubic pressure, delivery of the posterior arm, and a corkscrew maneuver, just to name four. Mannequins often enable only one correct procedure that can be invoked, which restricts the instruction. In contrast, VR simulation flexibly accommodates an inventory of solutions, predictive of the expert's approach. <u>*The consideration of competing treatment options is readily supported in a suitable VR setting; it is infeasible on a mannequin*</u>. VR simulation can be *personalized by warping multi-surface anatomies to a fetal medical image*, enabling practice on a patient of particular interest. One can retroactively warp a set of fetal and maternal anatomies to MRI datasets associated with complications [9], accounting for risk factors like maternal obesity and twin or premature pregnancies, *systematically preparing obstetricians for worse-case scenarios*. Fast-forwarding a few years, this project could potentiate midwives worldwide, namely in developing countries, through a suite of complication-embedding patient-specific simulations running on a tablet or cellphone, and personalized simulation of their patient of interest, imaged with a portable ultrasound scanner [11], feasible via *Anatomy Transfer (AT)* [12].

II. MATERIALS AND METHODS

A. Building on Medical Ontologies and on a Descriptive Offline Birthing Simulation

This paper will sketch a high-level picture of the nascent project and preliminary design objectives, while also alluding to resources available either through project members or open-source tools. The starting point for this planned interactive simulation is the work of Parente, Natal Jorge et al., [13], the offline birthing simulation represented in Figure 3, along with the biomechanical finite elements simulation of the maternal pelvic floor, during a simulated birth. The main components of the simulation are intended with practical clinical requirements in mind. In general, we advocate designing a medical simulation based on rigorous constraints founded on medical ontologies [14], which describe the intervention of the physician in terms of a sequence of discrete steps, within an algorithmic workflow. To this end, it is useful to exploit as a starting point a typical workflow that governs the actions of an obstetrician confronted with a shoulder dystocia case. In general, to make the simulator extensible in the future as well as representative of other complications, such as perinatal asphyxia uterine rupture, or excessive bleeding, this ontological workflow has to embed the typical response, such as found in a textbook or paper, to common complications. As shoulder dystocia is concerned, the workflow depicted in Figure 4 is considered typical [15] and can serve as a basis for our clinical requirements. In particular, the clinical response emphasizes the gradual application of maneuvers of increasing severity from the repositioning of the mother and suprapubic pressure, to the Corkscrew Maneuver, to Posterior Arm Delivery, to the Zavelli Maneuver and cesarean delivery, just to mention these few. The decision to transition to the next option, more drastic than the current technique, depends on the response of the fetus, as to whether or not it advances successfully. The implication of such a flexible, responsive approach on the part of the expert obstetrician, as a desirable training outcome, argues in favor of a VR-based interactive simulation, given the relative inflexibility of mannequin-

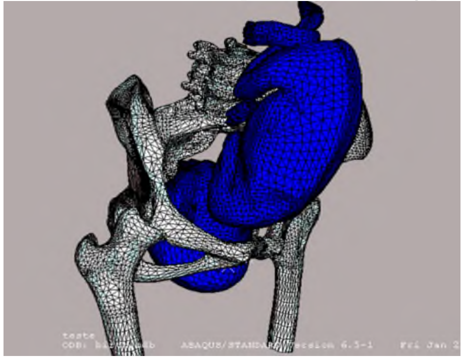


Figure 3. Prior results of Parente, Natal Jorge et al. [13] demonstrating birthing simulation under occipito-anterior neonate position and the biomechanical impact of these scenarios as pelvic floor stresses.

based training, which tends to emphasize a single solution or maneuver. Our expert clinician (AA) argues that the Posterior Arm Delivery and corkscrew maneuvers must be emphasized in particular by the simulation.

B. *Preliminary Work in Predictive Simulation*

In the prior work of Parente, Natal Jorge et al., [13][16], the fetus was considered has having a high stiffness, being controlled trough the usage of four control points. The fetus movements were optimized and defined in order to present the birth canal, the smallest possible fetus head diameter. After this manual optimization process, the final childbirth simulation was obtained, which included the deformation of the pelvic floor muscles. For these muscles a hyperelastic, transversely isotropic, constitutive model was used, which included the muscles fibers. Therefore, although being an advancement in term of childbirth simulation, this initial work contained several limitations and shortcomings, that we intend to improve upon.

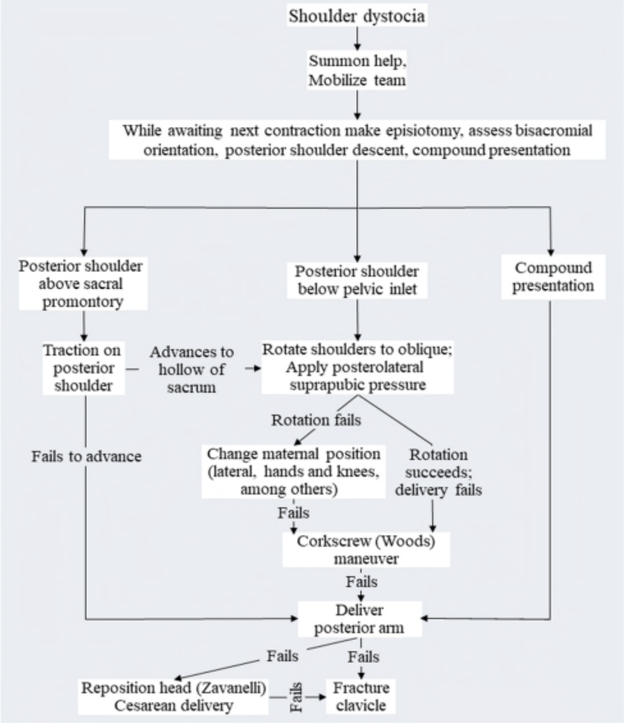


Figure 4. Obstetrics workflow, adapted from Hill [15], which will serve as ontological basis for the simulation.

C. *Overview of Design Approach and High-level Features*

One of the immediate implications of the clinical requirements alluded to above is that the anatomical model of the fetus used in the VR simulation must be as faithful as possible to the biomechanics of the live neonate, in manner consistent with a real-time application, in order to enable some of the maneuvers encoded in this ontological workflow depicted in Figure 4. In particular, while the finite elements-based birthing simulation of Parente [13] corresponds to the state-of-the-art so far, despite a simple four-segment fetal model with folded arms as in Figure 3b, the interactive obstetrics simulator underway must have a fetus with fully animated limbs, especially biomechanically faithful arms, to enable training on the Posterior Arm Delivery. If the ObGyn resident were to reach for the posterior arm and manage to grip it, the arm must be movable and responsive to the intended maneuver. The anatomy of the fetus must also realistically respond to being nudged outward by the arm. As a result, it is apparent that one of the cornerstones of the simulator must consist of a dynamic piecewise-rigid simulation of the skeleton, in the style of Stanford University’s OpenSim [18], with a haptic response provided by a pair of gloves such as Haptx [19].

Moreover, the original simulation of Parente took several hours to run [16], while we must strive to use every efficiency possible in order to achieve a real-time response, i.e. at least several times a second, with interpolative tricks to maintain visual and haptic feedback at suitable rates (30Hz, 200 Hz). This real-time requirement leads to several important design choices, which are made explicit in Figure 5, which describes the high-level architecture and design features. First, this real-time consideration justifies a highly efficient approach to skeletal mechanics of the fetus, based on OpenSim [18]. One of the main challenges to this project will be to integrate OpenSim musculoskeletal simulation with haptics, even simple 6 degree-of-freedom haptics, to which end we will first integrate OpenSim with a real-time biomechanics simulation platform that also supports haptics: the Interactive Medical Simulation Toolkit (IMSTK) [20]. Second, and perhaps more critical given the likely soft-

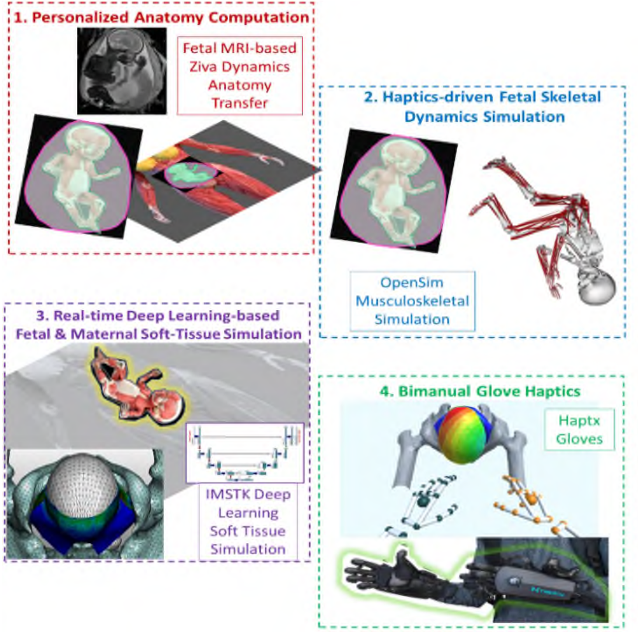


Figure 5. Main design features. From top to bottom: 1) patient-specific anatomical modeling, via Ziva Dynamics Anatomy Transfer, emphasizing a whole-body fetal model and a portion of the maternal anatomy; 2) haptics-driven fetal skeletal dynamics based on OpenSim [17]; 3) Deep Learning-based simulation of soft-tissue biomechanics based on IMSTK; 4) bimanual haptics via Haptx gloves.

tissue bottleneck, real-time constraints presuppose that we adopt the fastest soft-tissue simulation techniques available, in conjunction with IMSTK, without which this project would be an exercise in futility. To this end, we will be exploiting a Deep Learning approach to soft tissue finite elements analysis, in the manner pioneered by Mendizabal, Cotin et al recently [21], which runs on a comparable real-time biomechanics platform SOFA. They were able to demonstrate *two orders of magnitude acceleration over comparable finite elements engines*: a volumetric beam simulation that would typically iterate at 0.5 second on SOFA ran at roughly at 4 ms based on Mendizabal's deep neural network implementation. While the SOFA deep learning FE synthesis is not yet available in open source, there are several DL-based finite elements simulation implementations available on GitHub, which could serve as a template for IMSTK's DL approach to finite elements analysis, whose implementation details are also published, such as Ononenko's MLFEM in 3D [22][23] and Xu's NNFEM in 2D [24][25]. Briefly, the Mendizabal method, termed U-Mesh, and the competing techniques also cited here all apply a U-Net architecture [26] to estimating deformations from a mesh coinciding with the elastic solid of interest, based on training achieved by finite elements simulations. The original U-Mesh is a parameterized function that accepts a {3 x n_x x n_y x n_z} force tensor **f** as input and produces a displacement tensor **u** of the same size as output. Training data for U-Mesh are generated by solving a discretized *boundary value problem* (BVP) with the FE method. U-Mesh computations ran over 100 times faster than comparable FE simulations also designed for interactive processing, typically under 0.01 seconds, with graphical processor unit hardware [21]. The difference with this application, compared to any other DL elastic response simulation that preceded it, is that the fetal soft-tissue "envelope" must track the piecewise-rigid motion of the limbs: the estimation of the elastic tissue response would be intractable without first modeling the skeletal piecewise-rigid transform, which justifies the use of OpenSim. Ideally a detailed representation of muscles of the fetus and their activation should serve as the basis for the DL training. However, it may in fact be computationally onerous to model every muscle in such a detailed manner; an alternate solution may lie in an anatomically terse soft tissue layer, based on thick shell elements, which wraps over the bone scaffold and tracks the motion of the skeleton, in a manner first proposed by Parente.

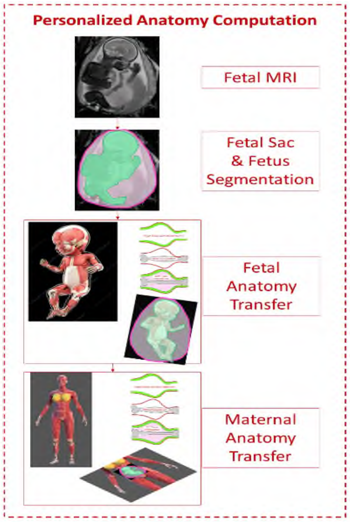


Figure 6. High-level approach to personalized anatomy computation: beginning with a fetal MRI volume, segment the fetal sac and the fetus, using a DL approach, trained with a deformable surface model [27] [28], use Anatomy Transfer to identify the fetus' skin surface, register bones in a piecewise-affine manner, warp soft tissues to the layer between bone and skin, and proceed likewise with maternal anatomy visible in the MRI.

D. *Anatomical modeling and musculoskeletal simulation*

A detailed approach to modeling the musculoskeletal anatomy and its corresponding function could involve the warping of a descriptive model of the human body and associating the activation of each muscle with a tensing or flexing of that muscle, as implemented respectively with Ziva Dynamics' Anatomy Transfer technique, as depicted in Figures 6 and 7, and Muscle Firing simulation [29]. Our plan is to purchase an anatomist-drawn musculoskeletal model of a baby, from a digital content company such as TurboSquid or CGHero [30][31]. The first author has prior contacts with CGHero in particular, such as a ligamentoskeletal model of the spine and torso, which is being warped to target CT images for scoliosis surgery planning [32][33]. A naïve but more quickly computed soft-tissue representation would simply involve a simple soft-tissue layer covering the skeleton, whose thickness would vary anatomically: thin at the hands and feet, slightly thicker in the rest of the limbs and head, thickness around the torso. Such an approach could be computed as a distance map from the MRI-derived bone anatomy of the fetus and modeled with a collection of thick shell elements. IMSTK would produce the initial simulations that would serve to train the DL-based finite elements synthesis.

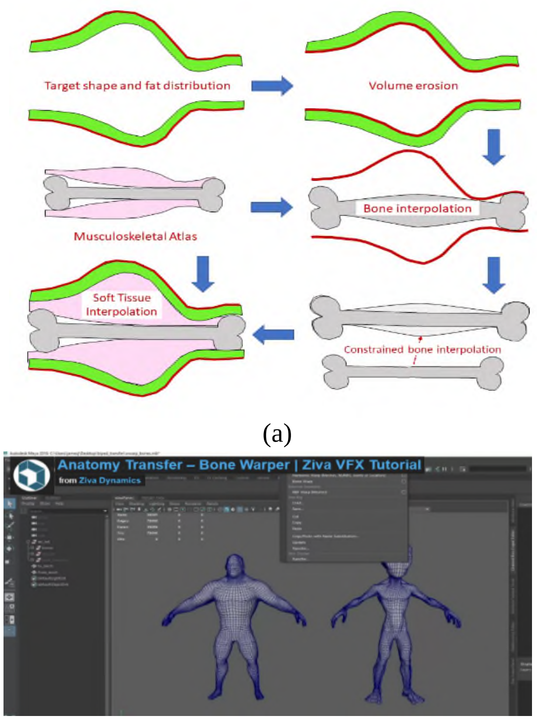
In addition to the above strategy for modeling the dynamics of the bones and soft tissue, the actual personalization of the fetal model will require some form of Anatomy Transfer (AT) technique, based on the original AT pioneered by Dicko et al., [12], and implemented by Ziva Dynamics, as shown in Figure 7.

The AT technique consists of an image analysis pipeline that uses as inputs a multi-surface musculoskeletal atlas and a putative skin surface of the subject, erodes the contained volume to model a fat layer, then applies a piecewise-affine registration followed by a relatively stiff elastic transformation to map a skeletal model within that inner layer, followed by an adjustment of the bone model based on a constrained, shape-preserving constrained registration and a final soft-tissue interpolation to scale and position the soft-tissue (muscle) layer within the fat layer.

This technique will be refined further over time based on two research tangents: i) accuracy improvements based on multi-surface deformable models developed by the author, which will imbed shape and pose statistics derived from fetal MRI and expert correction, and ii) surface mesh-based neural network-mediated automation, founded on a platform such as MeshCNN [35], which will obviate user supervision for the AT approach.

E. *OpenSim-based Musculoskeletal Simulation*

Stanford's OpenSim is the leading open-source dynamic musculoskeletal simulation platform (Figure 8). An OpenSim Model is a codified description of a musculoskeletal system and its dynamics, and represents a topological graph of interconnected components [36]. Each component represents a self-contained module (biological structure, mechatronic device, etc.) comprising the Model, and contributes to building the computational system. The computational system consists of two parts: (1) the system of equations ("System"), which includes constant physical parameters (mass, dimensions, etc.); and (2) the State, which includes all variables in the System that vary over time (e.g. joint angles). The developer designs an OpenSim Model that represents the physical system; OpenSim constructs the computational system of differential and algebraic equations that describe Model dynamics. This infrastructure will enable us to simulate the piecewise-rigid motion of the fetal and maternal skeletons, which will then determine deformations undergone by their respective soft tissues.



(a)

(b)

Figure 7. Anatomy Transfer. (a) High-level representation of the AT image analysis pipeline, adapted by the first author from Dicko [12]. (b) AT software available commercially from Ziva Dynamics [34].

F. *Virtual Reality-based Viewing and Bimanual Kinematics Integration with Leap Motion*

Virtual Reality-based viewing and integration with bimanual kinematics tracking based on Leap Motion were recently proposed in a thesis at University of Porto (M.P). This VR application leverages the generic anatomy of the mother's pelvis and the fetal anatomy developed by Parente, Natal Jorge and their collaborators. It is described next.

III. RESULTS AND DISCUSSION

The current VR application emphasizes surface rendering of the boundaries of the fetal and maternal finite elements model, based on a series of multi-surface snapshots, or static visualization models, obtained from the finite elements volumetric simulation, in conjunction with the Unity engine and a suitable colormap for visualizing biomechanical quantities such as stress magnitude [39]. This group also recently developed a template for our future bimanual simulation, based on Leap Motion tracking of the users hands, as shown in Figure 9 [38][39]. Obviously, the LeapMotion only keys on kinematics but does not imbed force feedback, which will be a requirement that is provided by the Haptx gloves, which will be supported in our final implementation [38]. IMSTK supports Unity-based 3D graphics as well as a variety of haptic devices [20].

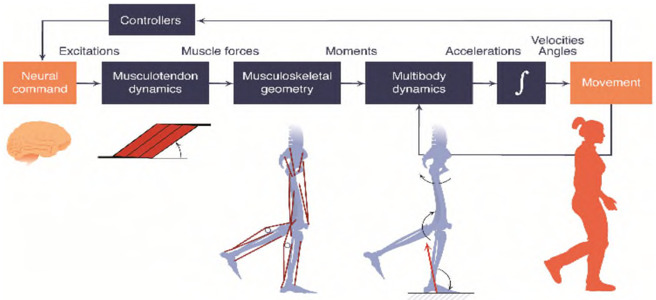


Figure 8. Musculoskeletal (MS) simulation in OpenSim [36]. Movement arises from an orchestration of the neural, muscular, skeletal, and sensory systems [36][37]. (Reproduced from PLOS One, with CCBY License.)

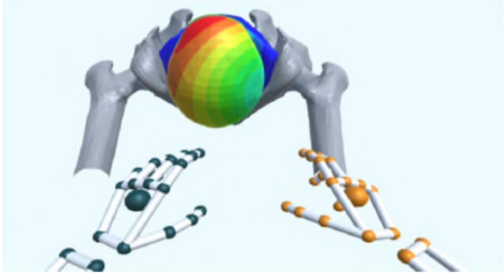


Figure 9. VR and bimanual kinematics implementations of Pinto [4], which will serve as template for the bimanual haptics-driven implementation on IMSTK. Real-time bimanual kinematics in the same 3D workspace as the fetus and mother's anatomy, tracked through Leap Motion's range-sensing analysis [38].

IV. CONCLUSIONS AND FUTURE WORK

This paper centered on the nascent development of an interactive, patient-specific obstetrics simulator, based on substantial clinical justification. The foundation of this effort is the work of the Porto-based senior author's on predictive birthing simulation, featuring generic models of the fetus and of the mother. A second cornerstone that now makes this project feasible is the advent of deep learning-based approaches to simulating biomechanical finite elements, some of which is publicly available on GitHub. In addition, leveraging leading simulation toolkits, namely IMSTK and OpenSim, also is essential to achieving success. The bulk of the future work will center on the challenge of this integration between skeletal motion and soft-tissue layers surrounding this motion. Lastly, the application of a medical image analysis pipeline for personalizing these anatomical models, including the use of Ziva Dynamics' Anatomy Transfer software, as well as tools like SLICER and Insight Toolkit for medical image analysis, is also essential to achieving clinical relevance. The advantage of proceeding this way, while determining the requirements of the simulation based on medical ontologies, is that worst-case scenarios can be effectively synthesized, by artificially worsening cases of shoulder dystocia (increasing the size of the fetus' head for example) or making the umbilical cord take an inopportune path. Downstream of this simulation implementation, it will also be feasible to exploit portable ultrasound scanners, while potentiating the work of midwives in countries with limited access to obstetricians.

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