Simulating Cardinal Movements of Human Labour Using Finite Elements

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background

Computer based simulations find numerous applications in medicine. Such applications include training of medical personell, diagnosing patients based on digital data and scientific research to gain better understanding of physiological phenomena. Bio-mechanical simuations are one of the most challenging uses of computer based simulation in medicine. The underlying principles are very complex and thus require sophisticated theoretical formulations and considerable software development efforts.

One of the areas where bio-mechanical simulations are very important is obstetrics related medical simulations.

The main focus of this project is creating a realistic real-time computer based simuation of human childbirth. Simulations of this kind require modeling biomechanical interactions of high complexity. As mentioned, this implyies highly sophisticated. This report will therefore attempt to cover the important aspects of human childbirth.

1.2 Human labour

1.2.1 Cardinal movements

Investigating the mechanisms of labour is an important preliminary step before designing childbirth simulation software. The process of childbirth is complex and involves a multitude of different mechanical processes. **?** describes the cardinal movements as the main mechanisms of labour and lists seven distinct movements: engagement, descent, flexion, internal rotation, extension, external rotation (restitution) and expulsion. **?** gives the following definitions to the movements and provides figures:

1. Engagement — this step is identified by the passage of the widest diameter of the fetal skull through the pelvic inlet (Fig 1.1).

2. Descent – the stage when the fetal head passes further downwards through the cervix towards the birth canal (Fig 1.4).

Figure 1.1: Engagement

Figure 1.2: Descent and flexion

Figure 1.3: Internal rotation

Figure 1.4: Extension

Figure 1.5: External rotation

Figure 1.6: Expulsion

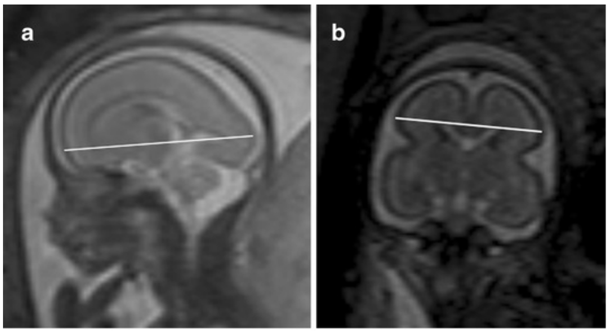

Figure 1.7: Fetal head diameters: a – Fronto-occipital diameter, b – Cerebral biparietal diameter (?).

3. Flexion — is the process when the fetal head flexes with its chin approaching its chest. The shape of the pelvis and the pelvic floor are said to cause flexion. Flexion allows the fetus to pass through the birth canal with a smaller diameter (e.g. the bi-parietal diameter (Fig 1.7) (Fig 1.2).

4. Internal rotation – is also thought to be caused by the shape of the pelvic canal and soft tissues. It is represented by rotation of the fetal head from facing sideways to facing backwards relative to the mother's body. This can be explained by the fact that the pelvic inlet has the widest diameter in the sideways direction, whereas the pelvic outlet is widest in the sagittal axis (Fig 1.3).

5. Extension — happens while the neck of the baby is under the pubic symphysis. During extension the head deflexes and in this stage, chin and head are born facing outwards (Fig 1.4).

6. External rotation (restitution) is represented by external rotation of the head to face sideways as compared to the rest of the body (Fig 1.5).

7. Expulsion -– when external rotation is complete and the shoulder has moved under the pubic symphysis the fetus is born (Fig 1.6).

1.2.2 Problematic labour

1.2.3 Childbirth simulators

There are a number of mechanical childbirth simulators that exist already. Such simualtors are designed to allow tranee obstetricians and midwifes to interact with a maniquin of a birthing woman. The maniquin is normally made of plastic and/or metal. The section

The motivation behind using a computer based simulation in childbirth modeling is dictated by a number of reasons. While having certain advantages the mechanical childbirth simulators often lack very important features. Primarily, mechanical maniquin will typically be very poorly customizable. Such simulator is typically used for training juniour personnel and in many of training cases the simulation scenario is required to be changed based on the type of the case that is being practiced. Using mechanical simulator means that only a specific scenario is available for training with only slight variations. Additional maniquins of a different type will have to be acquired to perform training for alternative scenarios. Contrary to this, computer based simulations allow unrestricted customizability. It is also worth mentioning, that there exsits a hybrid type of simulators, that combine a computer based underlying bio-mechanical model with an external mechanical maniquin to provide the interface between the trainee and the simulator. Such, simualtors combine the advantages of both types of simulators, but also carry the drawbacks of at least one of them.

Computer simulations provide a good tool for representing real world phenomena, but they are only capable of representing the simulated objects to a certain degree of approximation. Better approximations are predominantly much more expensive in terms of computational power. With the increased processing power of modern computers, it is possible to perform simuations with a higher degree of fidelity. However, even the most performant machines can struggle with certain types of high-cost simulations. In such cases, we have to utilize the underlying hardware to the highest degree possible. This can be achieved by a number optimization techniques. One of the most effective techniques is using parallel processing in order to speed up the computation.

1.3 Reverse vs Forward engineered approaches

There is a number mong the existing mechanical and computer based simulators of human childbirth. It is crucially important to contrast the approach chosen for this research project from the existing reverse-engineered simulations.

1.4 Finite element method in surgical simulations

Finite element method (FEM) is

It is desired to achieve the highest fidelity of the simulaitons with as little latency as possible. To this end, performance optimizations and GPU utilization for Finite Element Analysis is one of the main focuses of this thesis. Several available application programming interfaces (API's) will be overviewed as the candidate tools for implementation. It is then shown how the chosen API is used to achieve highly efficient implementation of FEA for soft-tissue simulation.

Another important aspect of creating a computer based simulation of childbirth is acquiring realistic 3D models of the underlying physiological structures. Namely, the fetal body and maternal lower body geometries are required. The possible ways of constructing the required meshes will be covered in this thesis. The approach is not yet decided on.

1.5 Report overview

The organization of the remainder of this report is presented here.

In chapter 2 a literature review is conducted presenting the body of already existing relevant research. The review is split based on relevance to a particular aspect of this research project.

Chapter 3 describes the work that has already been undertaken as of the date of this report.

Three publications have been successfully made in the duration of this PhD course, each of which covered an important topic related to the area of interest of this research. All three papers will be covered in this report. The papers are include in the **??**.

There is a considerable amount of work still left to complete. The 4 chapter focuses on describing the required steps aimed at achieving the objectives of this research project. An approximate work plan is also presented in this chapter featuring a Gannt chart.

Finally chapter 5 presents a proposed thesis structure for the final write-up.

Chapter 2

Literature Review

2.1 Introduction to Literature Review

The literature review in this report contains an overview of the key literature related to work conducted so far in the area of childbirth simulation.

Literature was primarily found through searches of related keywords in Google scholar and DBLP, along with forwards and backwards citation analysis in addition to targeting specific conference proceedings. It is foreseen that the literature review for the PhD thesis will be significantly more detailed within the sections included in this report as well as containing a number of additional topics.

2.2 Existing childbirth simulation systems

Chapter 3

Methodology

3.1 Overview

This chapter covers the work that has been completed to date. The description of the undertaken tasks will be included along the justification for the particular choise of the approach.

It will start by describing the initial developments on creating a forwards-engineered childbirth simulation. Further steps that have been taken on improving the software system are then described.

As one of the most important

3.2 Forwards-engineered Childbirth Simulation

3.2.1 Physics based simulation

Simplified physics models

There are different ways of complexity at which a physics model can be formulated. The same physical concept can be represented with a higher or lower degree of simplified approximation.

Physics based simulations find a great number of applications in various areas. Not all such areas require highest fidelity models. Games and entertainment industry is an exmaple of areas where a simplified model yeilds sufficiently accurate results with a relatively cheap cost of the computation required.

Simplifying assumptions

The intial attempts on creating a forwards-engineered simulation of human childbirth were focused on using simplied physics model. Due to the requirement on having a childbirth simulation working as soon as possible, a list of simplifying assumtions was adopted.

The list included the following assumtions:

1. The soft tissues of the maternal reproductive system do not need to be considered to observe cardinal movements
2. The trunk of the fetal body does not need to be considered to observe cardinal movements.
3. The labour forces can be replaced by a simple periodical force acting on the atlanto-occipital point (Figure **??**) of the fetal skull to observe cardinal movements.

The assumtions allowed for a simpler set of requirements for the software implementation aspect of the project and arriving at a working prototype soon.

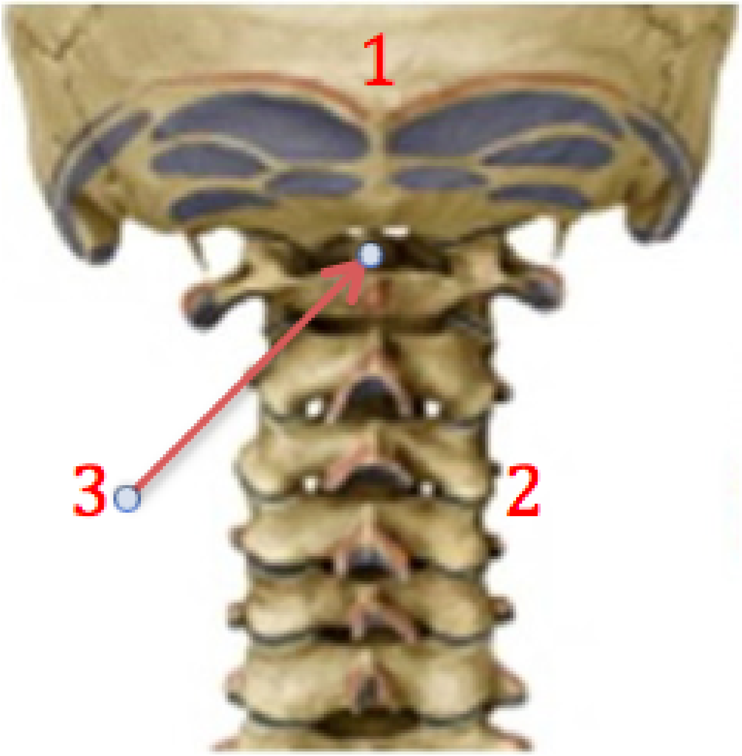

Figure 3.1: The atlanto-occipital point.

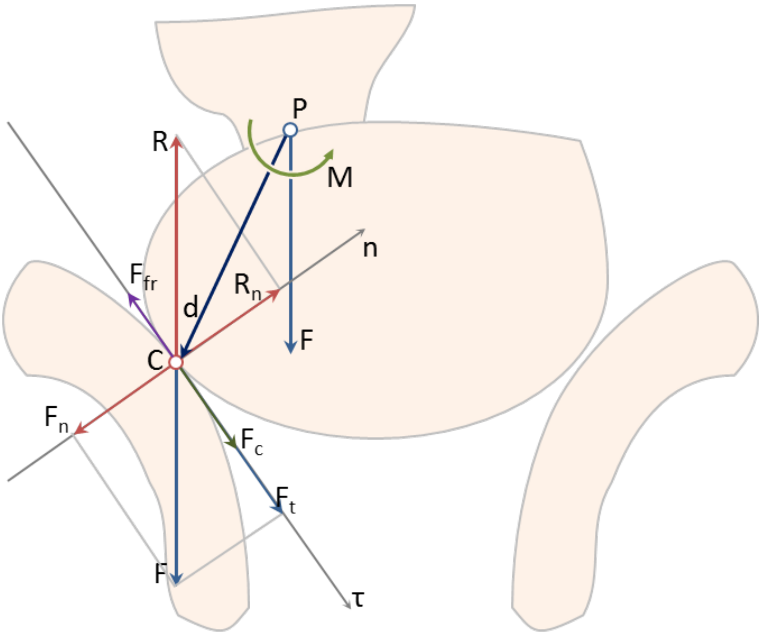

Figure 3.2: A contact between two objects: P – pivot point, C – contact point, F — external (uterine) force, R — reaction (contact) force, F_τ — tangential component, F_n — normal component, n -– contact normal, τ -– tangent plane, d - radius vector, F_{fr} – friction force, F_c – contact force, M – the resulting rotation moment.

3.2.2 Basic contact model

The contact model used in our childbirth simulation system is described in terms of calculating the crucial physical entities. The entities are: friction between the fetal head and the pevlis, forces and rotational moments arising from the contact. The Figure 3.2 describes the model in more detail.

Friction

One of the most often used models for calculating friction between two rigid bodies in contact is Coulomb's law of friction (?). As illustrated on the Figure 3.3, the law states that the friction force is defined by the normal contact force N times the coefficient of friction (μ). In case of a sliding contact, the friction force is exactly equal to μN by magnitude. The direction is defined to be opposite to

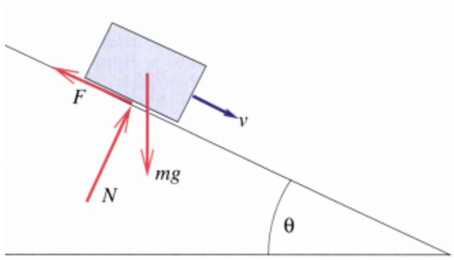

Figure 3.3: Simple rigid body friction problem: F – friction force, N – normal contact force, mg - gravitational force, v - velocity, θ - angle between the surface and horizontal plane (**?**)

the tangential component of the acting force.

The physical model to be used in the childbirth simulation will replace the gravitational force with the uterine contraction force. However, there is a need to specify a suitable friction coefficient for the head-pelvis contact. During the literature review no resources were found where the exact coefficients for this particular case are specified. The work by **?** performed series of experiments and identified friction coefficients between a muscle and a bone. These values vary under different loads between 0.29 and 0.36. Considering that it is not the bare bones interacting, the friction coefficients of lubricated skin were examined. The works by **?** and **?** provide the coefficients, but the values vary widely according to the normal loads and the used lubricants. As it is difficult to choose a single value an average of 0.35 was chosen as the starting option. The value can be changed during further experiments.

Rotational moments

In order to calculate rotational moments caused by collisions it is necessary first to identify a rotational pivot. For the rotational pivot of the fetal head the atlanto-occipital point (Fig **??**) will be chosen. The rotational moment M is found by calculating the cross product of the contact force F_c vector and vector (d), being the position vector from the rotational point to the point of contact. Equation 3.1 shows the relation:

$$\vec{M} = \vec{F_c} \times \vec{d} \tag{3.1}$$

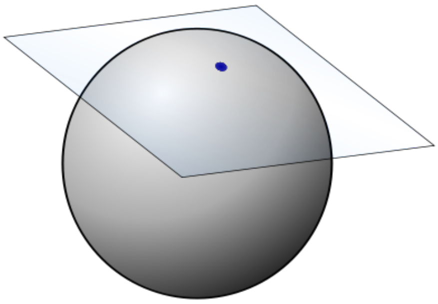

Figure 3.4: Tangent plane of a contact (**?**)

However, the contact force F_c needs to be calculated first. The force is the resulting force acting on the fetal head during contact. It comprises of the normal, tangential and frictional components.

The normal component is trivial to find by projecting the inverted external force onto the contact normal as in equation 3.2.

$$\vec{F_n} = (\vec{F} \cdot \vec{n})\widehat{n} \tag{3.2}$$

The tangential component F_τ of the reaction force is more ambiguous to find. It is known that the normal component is collinear with the normal and the tangential component will be inside the tangent plane as in Figure 3.4, but the plane contains potentially an infinite number of such vectors. However, considering the intersection of the tangent plane with the plane formed by the normal and the force F it is possible to find the tangent vector. Thus, the direction of the tangential component is calculated from the contact normal and the external force F using equations 3.2, 3.3 and 3.4.

$$\vec{R} = -\vec{F} \quad \wedge \quad \vec{F_\tau} = \vec{F} - \vec{F_n} \tag{3.3}$$

$$\vec{F_\tau} = \vec{F} - (\vec{F} \cdot \vec{n})\vec{n} \tag{3.4}$$

Thus, after identifying all the necessary forces for the contact the resulting contact force F_c is defined as in equation 3.5. Equation 3.1 can be worked out now. The rotation of the object is then calculated based on the combined rotational moments as seen in equation 3.6. It should be noted that each of the moments are calculated for each contact point separately.

$$F_c = F_\tau - F_{fr} \tag{3.5}$$

$$M_{comb} = \sum_i^n M_i \tag{3.6}$$

3.2.3 IveTrainer childbirth simulation software

Overview

The IveTrainer software was the first attempt on implementing a forward-engineered childbirth simulation. It was limited to the simplified physics model described above.

The resulting software is a simulation tool capable of performing several different simulations. The set of simulations can be extended easily because of the software design pattern utilisation. The simulations can be run in the fully forward engineered mode or using imposed trajectories and fetal postures in a reverse engineered way. It provides several input modalities, namely: keyboard, mouse and haptic device.

The use of reverse engineering was justified as the chosen forward engineering approach failed to give sufficiently accurate results. However, as mentioned in the Literature Review 2.2, many of contemporary simulation systems use reverse engineering. Additionally, the two forward and reverse engineered approaches were combined, resulting in a hybrid simulation partially dictated by a predefined trajectory and partially by the underlying physics simulation. Figure 3.5 shows the difference between the fully reverse-engineered and the hybrid approach.

Currently, each simulation consists of three objects and a simulation procedure that defines what interactions between the objects are to be simulated. The three objects are: a fetus, a pelvis and a user controlled hand. In the first simulation, the fetus is represented by its head alone, whereas in the second the full articulated fetal body is used. The pelvis is represented by a complex customizable model. The hand is controlled by the user using spatial 3D input from a connected haptic

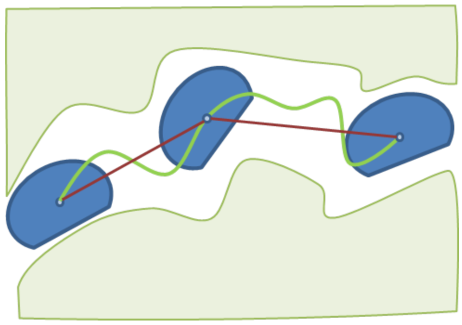

Figure 3.5: The reverse-engineered trajectory in red and the hybrid trajectory in green. It can be seen that the head passes through the specified way-points, but also interacts with passage walls.

device.

Features

The set of features is currently comprised of means for child delivery simulation for predicting potential outcomes and delivery process visualisation for training purposes. The main features of the system in more detail are provided below.

Object Manipulation Object manipulation is a basic, but crucial feature of the system. Considering that the system is meant to be used by medical personal, a user-friendly interface for object manipulation was provided. Thus, the system is incorporated with the means of easy control over the objects' position and orientation using a mouse. This is achieved by implementing an *arcball* input system and a set of keyboard shortcuts.

Cardinal Movements of Fetal Head The first simulation is dedicated to the simulation of cardinal movements of the fetal head only. Provided additional improvement of the underlying physical model and refinement of the set of considered influences, this mode can be used to analyse and investigate the childbirth process and eventually predict the most-likely outcome of a given vaginal delivery.

Customisable Models One of the most important features here is that the system provides a customizable environment. Namely, the main pelvimetric diameters and the diameters of the fetal head can be specified with sub-millimetric accuracy. This may have limited use in predicting real case outcomes, however, it can be used for the purposes of investigation of different child delivery processes.

The coronal, transverse and sagittal extents of the fetal head can be specified, to simulate and analyse how the given diameters affect the outcome of a given delivery. The set of customizable extents for the pelvis consists of the main obstetric diameters, namely: inlet transverse, inlet oblique, inlet anteroposterior, outlet transverse, outlet oblique, outlet anteroposterior and middle anteroposterior diameters. The illustration of all the described diameters will be given in the following sections.

Periodically changing expulsion force The control over expulsion force magnitudes and their temporal change is inspired by the work by **?**. The authors of this work indicated that the periodical nature of the forces cause the head to progress backwards through the birth canal as well forwards as it generally does. They suggested the potential importance of this phenomenon as an additional factor contributing to a successful delivery.

This idea was addressed while developing the software, by incorporating a sinusoidal signal generator. Given minimum and maximum magnitudes and a direction for the expulsion force, the generator can be used to interpolate between the minimum and maximum force magnitudes. The minimum force magnitude can be set to be negative, which allows the backwards propagation of the fetus.

Control over physical quantities The system allows the user to specify the essential physical quantities involved in the physics simulation. The most important ones include: minimal and maximal expulsion magnitudes, expulsion force change period and the friction coefficient. Each of the listed quantities can be set as required.

Imposed trajectory management The system is capable of forward-engineered simulation that extrapolates from the initial position based on the physical model and avoids any imposed characteristics. Along with this mode, the system can utilize predefined trajectories of the fetus, which specify the position, as well as the orientation, of the fetus for an arbitrary number of delivery stages.

The trajectory of the fetus consists of a set of stages. Each stage is a momentary snapshot of the fetal position and orientation at any given stage of the delivery. The snapshots are called *way points* and are arranged into a list that forms a *trajectory*.

The system allows convenient management of the trajectories by providing means to create, delete, edit, save and load them. Given a *trajectory* consisting of several *way points*, the user is able to create new and remove, edit or rearrange existing ones.

Hybrid Simulation A compromise solution for the forward-backward engineered simulation was achieved. This implies that the simulation will proceed in the forward engineered mode, unless the simulated fetus deviates from the specified trajectory in terms of position and orientation. This allows current position and orientation to be optimized. Thus, using this approach the system can avoid cases when simulation leads to unrealistic outcomes.

Shoulder Dystocia Visualisation The second simulation is purely demonstrative visualisation of a shoulder dystocia case discussed in section **??**. It shows how the case occurs starting from the initial stages of labour till the state when the shoulder is pressed against the *symphysis pubis*. The limitation of it is that the body of the baby is completely rigid.

Face Presentation One of the predefined trajectories demonstrates face presentation delivery. As expected the head will pass through the pelvis fully extended, but will be arrested near the outlet.

Manipulating Articulated Fetus The third simulation is a result of further development of the shoulder dystocia visualisation described above. The main improvement here is that the simulation has become more interactive rather than purely demonstrative. This is due to the development of an articulated fetus that the user can interact by using a haptic device. This feature required implementing haptic input management and inverse kinematics. The user is able to use a haptic device to select the head, a hand or a foot of the fetus and move it as required. A set of constraints can be enabled to modulate the IK result. The set can be customised for each joint.

3.2.4 Simulation pipeline

The simulation system adopts a typical update loop architecture. The diagram in Figure 3.6. shows the simplest representation of the simulation.

1. The first step includes all the required initialization and pre-processing. This step is only performed once. It should be mentioned that during this stage the spring object is instantiated and is assigned with two attachments. The attachments are represented by the attached dynamic objects' references.

2. Step two involves complex processing of the geometries and collision detection. This step consists of a loop going through all the simulation objects and pairwise collision detection. The calculated contact information is used to compute the resulting contact force for each contact.

3. Steps 3 and 5 represent the same process of force and moment accumulation. For the linear component the application is a simple addition. It should be noted that the same process is used for contact and spring force application, which contributes towards a more generic physics engine and conforms with the Don't Repeat Yourself (DRY) principle.

$$F_{all} = \sum_{i=0}^{n} F_n \tag{3.7}$$

$$M_{all} = \sum_{i=0}^{n} F_n \times r_n \tag{3.8}$$

4. The fourth step involves calculating the spring force acting on the attached objects. The force is calculated according to the Hooke's law.

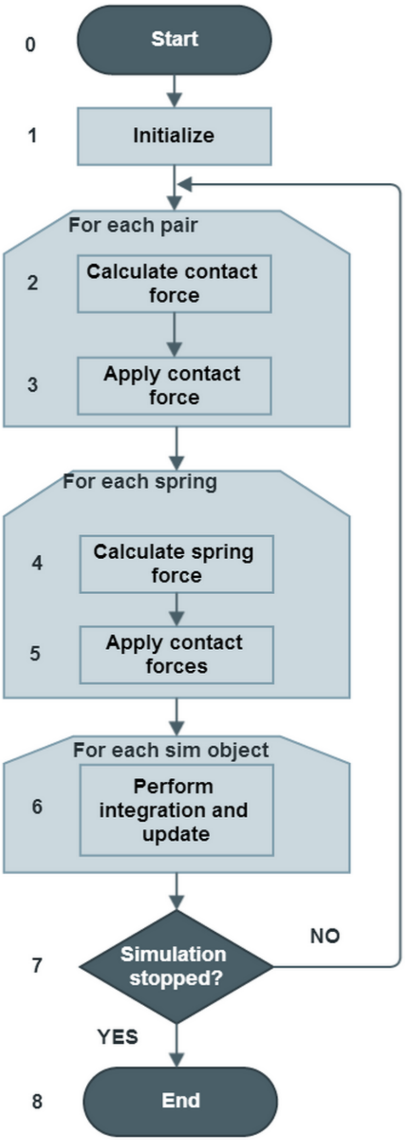
0
Start
1
Initialize
For each pair
2
Calculate contact force
3
Apply contact force
For each spring
4
Calculate spring force
5
Apply contact forces
For each sim object
6
Perform integration and update
7
Simulation stopped?
NO
YES
8
End

Figure 3.6

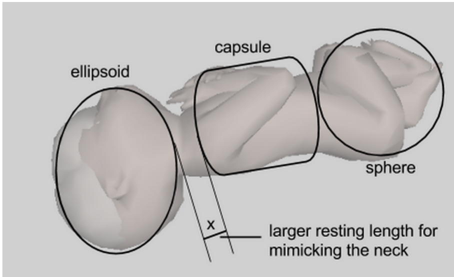

Figure 3.7

5. The resulting spring force is applied to the object in the exact same way as described in item 3. Additionally, according to Newton's third law of motion, the inverted force is applied to the second object.

Full Fetal Body Simulation

The next step in developing a childbirth simulation system was including the full articulated fetal body. Following the simplified physics modeling approach described before, we developed a spring mass model capable of representing the fetal body to some degree accuracy. The spring mass model consists of the primitives comprising the main sections of the fetal body and a number of springs that connect them. Figure 3.7 demonstrates the sample assembly of the fetal body components.

The mass-spring model is implemented using simple Hookean springs. The forces exerted by the spring onto the bodies that it is connected to is calculated according to Hook's law 3.9.

$$F = -k * x \tag{3.9}$$

Figure 3.8 demonstrates in detail how the forces are calculated. Two bodies A and B are connected by a spring with resting (relaxed) length L_r. The attachment points A'_1 and A'_2 are specified in the local coordinates of the objects that the attachment is on. The world vectors A_1 and A_2 are calculated by transforming the local attachment vectors by the respective transformation matrices of the attached objects. The current length of the spring L_s is defined as the length of the vector S, which connects the attachment points in the world space and is

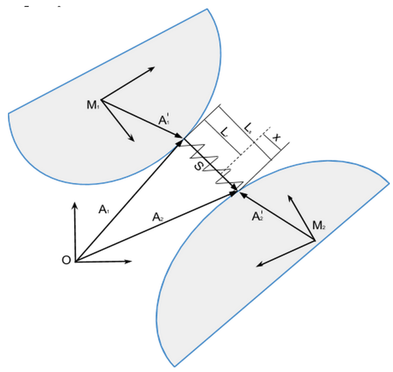

Figure 3.8

equal to $A_2 - A_1$.Thus elongation (compression) x is defined by $L_s - L_r$.

Results and Conclusions

The results of the expermients performed using the described simulation system are described in the published paper Gerikhanov et al. (2013), which is also included in the appendix **??**.

The simulation system was successful on displaying the first three cardinal movemenets. The Engagement, Descent and Flexion were observed in all experiments. As reported by the paper, the Internal Rotation was observed occasionally in cases when the flexion was manually imposed onto the fetal head. When using the hybrid approach, the simulation demonstrated all of the cardinal movements in cases when the number of way-points was sufficient to impose the required trajectory.

Using the simplified full fetal body model did not improve the simulation results. No additional cardinal movements were observed when using the simplified model, but the originally displayed movements were slightly emphasized.

The table **??** summarizes the described experimental resuts.

This simplified forwards-engineered childbirth simulation system is incomplete and requires further development and refinement. This was indeed anticipated as developing a medical simulation software with full functionality can take several years. The resulting system can be seen as an initial step towards a fully functional system for childbirth simulation and obstetrician training. The following sections describe the steps taken in order to improve upon the described simulation system.

3.3 Simulation System Engineering

3.3.1 Requirements

Based on the results and findings of the experiments presented in section 3.2, we have come with a set of requirements for the next iteration of our simulation system.

It was decided to drop the older IveTrainer software in favour of developing a new system from ground up. IveTrainer was aimed to be a well scalable and extendable simulation system, but during the development many of the features were constructed in a poorly extendable way.

The new version of the system is required to be much more scalable and portable. The system is also required to include support for more sophisticated physical models.

The updated software has adopted industry standard software design techniques. The software developed during this project also adheres to the 'good' programming practices. Improved modularity and high coherence leads to unconstrained testing and functionality extension.

3.3.2 BirthEngine with .NET/Mono

Crossplatform runtime

The

3.4 Finite Element Method soft Tissue Simulation

3.4.1 FEA concepts

3.4.2 Total lagrangian explicit dynamic FE

3.4.3 CPU based implementation

Traditional FEA simulation

Traditionally FE analyses are performed on a particular setup with fixed parameters. Time frame is one the most important aspects of the simulation. To perform an analysis a starting time and a finishing time are normally chosen and the simulation is commenced. The natural and essential external loads are varied throughout the timeframe according to well defined laws and functions.

The developed BrithView TLED simulation system is capable of performing this type of a simulation. The dedicated component class called *FixedTimeSimulationComponent* can be used to perform a fixed-time simulation.

The advantage of such type of simulations is apparent when a highly controlled analysis environment is required. When testing the stability and strength of mechanical structures such simulations allow greater control and repeatability of the analyses.

However, there are cases when the analysis is required to flow continuously throughout the simulation. For such cases we have developed an alternative simulation framework described in section 3.4.3.

Interactive real-time simulation

In contrast to the previously described type of FE simulation, an interactive simulation is not limited to a fixed timeframe.

3.5 Parallel FEA Simulations Using GPU

3.5.1 General purpose computation with GPU's

3.5.2 C++AMP, OpenCL and CUDA

3.5.3 TLED using OpenCL

Changes to the algorithm

Efficient memory utilization

Data-race problem

Chapter 4

Future Work

This chapter outlines future work to be performed as part of the project, split into different areas of focus.

4.1 Experiments

The main target of this research is establishing all seven cardinal movements of human labour in a simulated environment without imposed trajectories. Purely physics based simulation is to be used to accomplish this, as opposed to the hybrid method described in the previous section.

Unfortunately we do not possess any quantitative data on the trajectory of fetal descent that can be used to meaningfully compare with the observed trajectory during our simulation.

4.1.1 Bony structures with a basic pelvic floor model

A scenario where the fetal skull is descending through the maternal pelvis with a simple pelvic floor model attached. This scenario is a potential starting point for simulation experiments. This experiment will be directed at validating the simulation system. The work presented in **?** !!! represents a very simillar scenario, although more simplified. We beleive that having a realistic skull model will improve fidelity of the observed experimental values.

4.2 Volumetric mesh generation

Mesh generation is designated as one of the higher priorty tasks to accomplish. Having acquired or generated high quality tetrahedral or hexahedral meshes is a crucial requirement in being able to perform the research experiments.

4.3 Improved contact model

Mesh generation is designated as one of the higher priorty tasks to accomplish. Having acquired or generated high quality tetrahedral or hexahedral meshes is a crucial requirement in being able to perform the research experiments.

Chapter 5

Proposed Thesis Structure

1. Introduction
2. Literature Review
    (a) Introduction
    (b) Reverse-engineered Simulators
    (c) Physics Based Simulators
    (d) Finite Element Analysis
    (e) Mechanical Contact Modeling
3. Methodology
    (a) Forward-engineered simulation of childbirth
    (b) Finite Element Method based simulation of childbirth
        i. Theoretical principles
        ii. Explicit Dynamic approaches
        iii. Total Lagrangian Dynamic Explicit FEM
    (c) Parallel implementation of FEM on GPU
        i. General Purpose Graphics Processing Units
    (d) Mechanical contact
4. Experiments and Results
    (a) Validation
        i. Comparison with other FEM packages
            A. Abaqus CAE
            B. NiftySim
    (b) Experiments
        i.
5. Conclusion

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Gerikhanov, Z., Audinis, V., and Lapeer, R. (2013). Towards a forward engineered simulation of the cardinal movements of human childbirth. In *E-Health and Bioengineering Conference (EHB), 2013*, pages 1–4. 25

Chapter 6

Appendices

6.1 BirthView application screenshots