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Scooping Simulation Framework for Artificial Cervical Disc Replacement Surgery

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Abstract— **In the last two decades virtual reality (VR) simulations have had revolutionary effects on many fields such as medicine, architecture, science, financial, and military applications. On the contrary, in medicine, the applications of VR are not as extensive as in other fields. However, realistic VR surgery simulations are in high demand as a result of offering risk-free training environments for physicians. The necessity of realism compels researchers to adopt physics-based models and haptic renderings that place extra computation burdens on real-time rendering pipelines. In this study, we investigate the usability of already built-in physics-based models in physics/or game engine PhysX library, for scooping operations in artificial cervical disc replacement (ACDR) surgery. The motivation behind our work is twofold. First, intricacies involved in ACDR surgery are introduced and the fundamental components towards the development of a surgical simulator are addressed. Second, an on-going framework development is introduced for the scooping action based on the PhysX library which provides optimized and physics-based methods for a plausible simulation. Our simulator framework integrates a haptic device into the PhysX environment for force feedback in order to increase plausibility.**

Keywords*—artificial cervical disc replacement surgery, surgery simulation, vertebrae C4 and C5, physx, virtual reality, curette.*

I. INTRODUCTION

Deficiencies of current traditional education methods yield the virtual reality simulators as subtle instruments in medical training. Impact of medical training is well understood when the report of National Library of Medicine (NLM) is taken into consideration that as many as 98 thousand people in hospitals each year die due to medical errors some of which are a result of surgical procedures or tests [1]. This report reveals that insufficiency of medical training could cost human lives. For that reason, national priority in healthcare delivery is to reduce patient errors and deaths. According to Merril [2][3], physicians have higher error rates when they are newly performing surgical procedures. This effect is called learning curve effect. In order to reduce this effect and let physicians gain necessary skills, there is no current approach more efficient than hands-on experiences with a surgical simulator. Hence, surgical proficiency is a must and the success of surgical training for proficiency can be provided or obtained by hands-on experiences with surgical simulations.

More than 200,000 US citizens suffer from degenerative disc disease in cervical region (neck). Cervical disc replacement is one of the most challenging surgical processes in the medical area due to the deficiencies in available diagnostic tools and insufficient number of verified surgical practices. Therefore, spinal disorder problems in the US have been operated with the fusion of the cervical vertebrae for many years rather than replacing the cervical disc with an artificial disc. The first Federal Drug Agency (FDA) approved artificial disc replacement surgery for lumbar in the US was made in June 2004. Quite recently (July 17th, 2007) FDA approved first artificial cervical disc implant in the US, the Prestige ST Cervical Disc System [8]. For physicians and surgical instrument developers, it is critical to understand how successfully deploy the new artificial disc replacement systems. Without proper understanding of the deployment process it is possible to injure the vertebral body. During the surgical procedure, activities such as compressions and decompressions caused on the vertebrae by new instrumentations that are specifically designed for the disc replacement operations need to be cautiously investigated. Also, stress and strain concentrations on the life-critical contact locations of the vertebrae must be well comprehended.

The Artificial Cervical Disc Replacement (ACDR) surgery mainly consists of three phases; the removal of the disc material called scooping procedure, adequately decompressing the nerve called rasping procedure, and deployment of artificial disc device into the prepared disc space respectively. Our focus in this study will be on the first phase; the scooping procedure. More specifically, the goal of this study is the creation of accurate virtual reality simulation of the scooping procedure with integrated haptic force feedback device for plausible simulation of the physical behavior of both soft tissue and the cervical vertebrae (C4-C5) under the various curette surgical instrument loadings during the procedure.

There are some possible risks associated with the ACDR treatment such as surgical instruments' bending or breaking;

♣First three authors – S. Kockara, E. Ermisoglu, and F. Sen - have made equal contributions to this study

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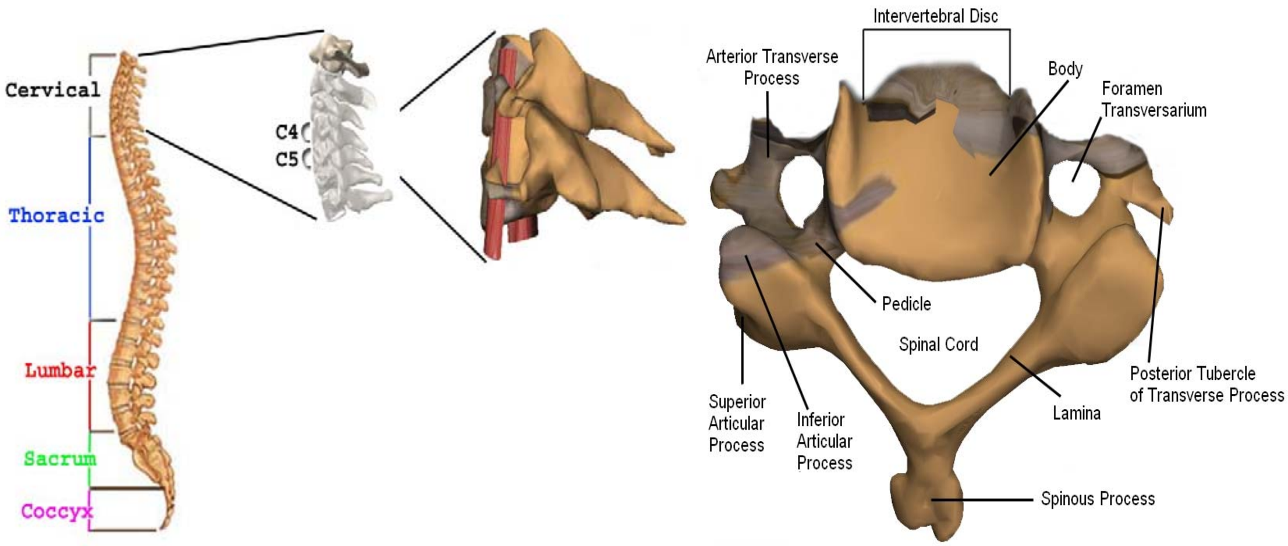

Figure 1. Spine anatomy, cervical discs, real patient's C4-C5 vertebrae's models, and C4 vertebra (left to right)

and causing wound by applying extreme force to critical regions. Alleviation of all these possible risks by the means of surgical simulation training of residences is main purpose of our framework. As a result of this study, it is expected to train surgeons for the scooping procedure with the haptic device (corresponds to curette instrument in virtual scene) to give the surgeon the sensation of directly manipulating the soft tissue in between cervical vertebrae C4 and C5. This would in turn enlighten surgeons about intricacies involved in the procedure; so that human error factors will be reduced.

II. BACKGROUND: ACDR SURGERY

The section under the brain to the neck or to the thoracic spine is called Cervical Spine. The section contains seven bones each abbreviated C1 to C7 vertebrae from top to bottom as given in Figure 1 [1]. The artificial disc replacement (ACDR) surgery deals with the cervical vertebra C3 through C7 that they lay to the neck [3]-[7]. Any risk of harm during the surgical processes may lead to permanent injuries.

On the left and right side of the each vertebra, there are small tunnels called Foramen Transversarium (see Figure 1). Through these holes (Foramina) two nerves leave the spine. The Intervertebral Disc resides directly in front of the Foramina. The center of intervertebral disc has spongy material, called nucleus, provides shock absorption mechanism. The nucleus on top of the Intervertebral Disc is held by annulus which is like serration rings. Degenerate disc (bulged or herniated) narrows the Foramina and puts pressure on the nerve. This is called degenerative disc disease which caused by aging or stress and strain on the neck. By time degenerate disc wears out and this causes the vertebra above degenerated region to lose its original height towards the vertebra below. Because of the abnormal pressure on the joint, articular cartilage, the slippery surface that covers every joint in the body, tears out. This is called arthiritis. The absence of articular cartilage results in generation of bone spurs. These spurs may fill up the Foramina that further narrows nerves' openings. This situation causes pain and other symptoms in the arms and neck. Further pain, weakness, and tingling in the arm can disable the patient. In some situations without surgery permanent damage may result.

The ACDR surgery restores the normal distance between the two vertebrae so that relieves pressure on the nerves and removes the symptoms. Unlike traditional anterior cervical discectomy and fusion methods for treating degenerative disc disease, ACDR preserves natural motions of a healthy disc e.g. rotating and bending. Although the ACDR surgery is extensively performed in Europe, quite recently (on July 17th, 2007), FDA approved the first artificial implant in the US, the Prestige ST Cervical Disc System [9]. ACDR surgery is still a new procedure in the US.

There are some possible risks associated with the ACDR treatment such as surgical instruments' bending or breaking and causing wound by applying extreme force to critical regions. Alleviating all these possible risks in the scooping procedure under dynamic curette loadings is main goal of our training framework.

A. Mesh Generation from 3D CT Scan Data

In order to correctly represent the geometry of the highly irregular C4-C5 vertebrae, the CT scan image of each vertebra and the curette instrument are exported directly into the finite element modeling tool (see Figure 2). The purpose of doing that is to verify numerical accuracy of the generated mesh by performing convergence test in FEM tool. Inefficient mesh generation results in element distortion in FEM. Thus, in that case convergence will not occur. Therefore, all complex anatomical features of the spine system will be accurately represented in the finite element model verified mesh [10][11]. Specific attention will be paid on the contact areas between nucleus and C4-C5 spine. The real in vivo situation between the curette and the nucleus has nonlinear contact nature. Therefore, the stiffness and damping parameters especially at contact regions are crucial for the realistic simulation. For these parameters, experimental input of experienced neurosurgeons by using tactile force feedback devices e.g. haptics will be acquired for tuning up the parameters. This phase is key component of the simulation. Otherwise, without a physically correct force feedback generation, plausibility of the simulator will drastically degrade.

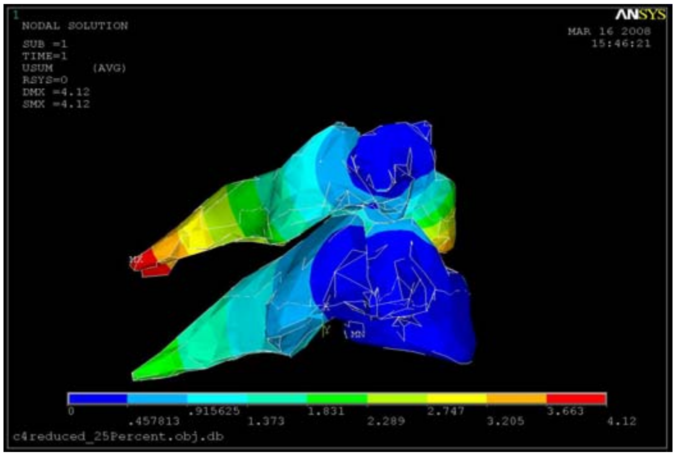

Figure 2. FEM model of C4 and C5 with displacement vectors

III. SURGICAL SIMULATION LOOP: CHALLENGES

One of the most important challenges –efficient mesh generation- and how it is handled was already introduced in the previous subtitle. In addition to this challenge, deformations, collision detections and responses, fluid dynamics, haptic rendering and graphical rendering calculations are involved in a typical surgical simulation loop (see Figure 3). Each of these computations is a separate realm. Each frame is generated as a result of all these concurrently running compute intensive operations. Since humans are more perceptive to space-time interpolations than physical reality in a virtual scene, real-time performance for all these computations is indispensable part of a surgical simulator [12]. Therefore, the most prominent challenge for surgical simulators is attaining at least 30 frames per second running time. Current computation power does not permit us to build real-time models that consist of hundred(s) of thousand(s) of polygons. The problem opens up as a research topic since algorithms are still a long away from the realism. This is especially true for deformation algorithms.

Deformations in surgical simulations are commonly modeled with two different physically based approaches e.g. Finite Element method (FEM), and Mass-spring Method (MSM). In the FEM, only a few material parameters (e.g. Young's modulus and Poisson ratio) are required. Even though the FEM results in more physically realistic deformations, a significant drawback of this method is its expensive computation cost and vulnerability to surgical procedures such as incision, suturing, and tearing. To simulate surgical operations with FEM, the inverse of the global K matrix (stiffness matrix) must be computed (for more information on K matrix and its computation, please see [21]). Explicitly inverting the matrix takes a considerable amount of time [13]. Hence, it is very difficult to attain real-time performance with the FEM. However, MSM is relatively computationally inexpensive and it is also physics based method. Because of the real-time surgical operations support of MSM, it is widely accepted by surgical simulation community. For FEM and MSM details, reader is referred to Halic et. al [14].

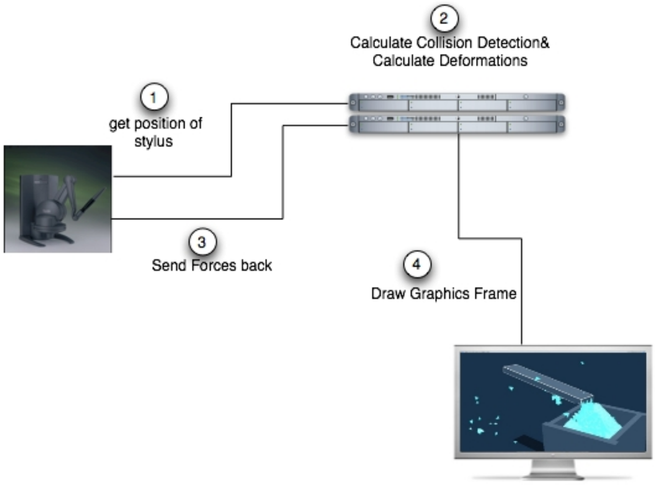

Figure 3. A typical surgical simulation loop

IV. THE PHYSX LIBRARY

Computer games and surgical simulations have a lot common enabling technologies such as graphics rendering, collision detections, deformation computations, and haptics. With proper design and development, game or physics engines can be used for surgical simulator development [19]. For instance, even though engagement intricacies are different, the scooping operation in the ACDR surgery is very similar to removing tuna from the fish can in a gaming environment. The main question is how we can use and enhance our gaming environment towards a surgical simulator development so that the user can have experience on a surgical procedure. Game or physics engines rise to answer this question. There are plenty of available physics engines. Some of them are commercial, e.g. Havok [15], PhysX [16] and some are freely available and open source e.g. Bullet [17], Box2D [18].

PhysX is a physics engine library which is initially developed by a company named Ageia and currently owned by NVIDIA Corporation. PhysX supports parallel processing on graphical processing unit (GPU) by using compute unified device architecture (CUDA) [20]. Since Physx provides rudimentary components such as rigid body physics, rigid bodies and soft bodies, joints, and fluid dynamics for early proof-of-concept scooping operation development, it is our choice of platform. PhysX and Bullets support parallel optimizations. Bullet's parallel optimization is based on SPU (synergistic processor unit) whereas PhysX supports parallel optimization for both PPU (Physics processing unit) and GPU (graphics processing unit). PhysX is chosen over Bullet and other engines due to its GPU support which in turn provides much higher parallel computation power. Therefore, PhysX have a better performance for multi object interaction scenes.

A. *Force Calculations for Scooping Action*

To have the feeling of taking the soft materials between two bones, the material in the box must be chosen carefully. The soft body in the box should have nearly same properties with shortening. Therefore, the soft body's viscosity has to be at least ~250.000 cP (250 Pascal-seconds) like shortening.

Haptic leads us to do some calculations for getting more accurate force feedbacks from the environment. During the simulation, the program needs to handle two force groups which affect the objects in the scene. The first group affects the rectangular prism (see Figure 6). This group contains three different forces; the force which is originated from the shearing stress between soft body and rectangular prism, the force which is originated from the haptic device and also mass of the rectangular prism. The second group affects the particles which compose the soft body. This group also contains three forces; the forces between two soft body particles, the force which is originated from shearing stress between the soft body particles and the rectangular prism, and finally the mass of each particle.

Analysis of the forces in the first group can be started with the force that is caused by the shearing stress between the rectangular prism and the soft body. Soft body consists of small particles that have fluid properties. During the simulation, whenever the rectangular prism contacts with the soft body, a shearing stress occurs at the contact location in the boundary of the rectangular prism. Thus, the general understanding of average shear stress is defined as:

$$\tau = \frac{F}{A} \qquad \text{(Eq. 1)}$$

where τ represents shearing stress, F represents the force applied, and A represents the cross-sectional area. The shear stress of a Newtonian fluid is expressed as in Eq. 2.

$$\tau = \mu \frac{du}{dy} \qquad \text{(Eq. 2)}$$

where μ is the dynamic viscosity of the fluid, u is the velocity of the fluid along boundary and y is height of the boundary. However, by combining Eq. 1 and Eq. 2 the effect of shearing stress in the contact point of rectangular prism can be calculated as in Eq. 3 where F represents shearing force at point A (see figure 4).

$$F = \mu \frac{A.du}{dy} \qquad \text{(Eq. 3)}$$

A force calculation for the scooping action includes three phases. In the first phase, the user tries to dig the rectangular prism into the soft body. For this situation vertical (*Fy,* total force at point A in figure 4) values of the haptic force feedback need to be calculated. While the rectangular prism is buried in the soft body, Buoyancy force will affect the rectangular prism at the contact position. Buoyancy force is:

$$F_{Buoyancy} = -\rho g V \qquad \text{(Eq. 4)}$$

where ρ represents the density of the fluid, g represents the gravitational acceleration, and V represents the volume. *Fy* value of the haptic feedback force can be calculated by (Eq. 5):

$$F_y = F_{Buoyancy} - m_{stick} g \qquad \text{(Eq. 5)}$$

In the second phase of scooping action, the user tries to belch the rectangular prism from the soft body. In this situation, the haptic force feedback (the force applied to point D in Figure 4) calculations are based on the moment in the contact point (C in the Figure 4) between the rectangular prism and the edge of the box).

In each frame cycle, it can be assumed that the rectangular prism is a rigid body and the system is in static equilibrium. In this system D is the point where the haptic force applied, B is the center point of the rectangular prism, which is also the rectangular prism's center of gravity, and *A* is the contact point. Then, the haptic force feedback (*F*) can be expressed using Eq. 6. (Total moment ($\sum M$) at the edge of the box (Point C) is 0).

$$F_{feedback} = \frac{\left(\frac{l}{2} - d\right).m_{stick} g + (l-d).\left(\mu.\frac{A.du}{dy}\right)}{d} \qquad \text{(Eq. 6)}$$

where l is the distance of the rectangular prism to the soft body, d represents the distance between point D and C.

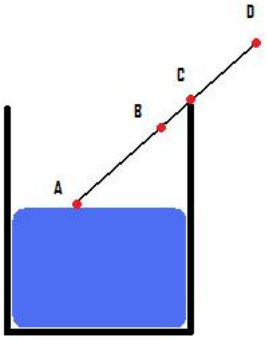

Figure 4. The second phase of the scooping action.

In the third phase of the scooping action, the user removes small amount of soft body from the box as illustrated in Figure 5.

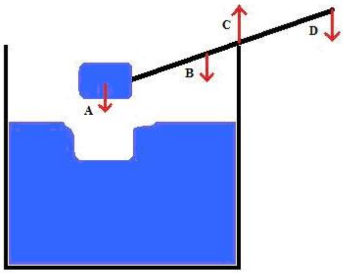

Figure 5. Soft body removal from the box

In this state, haptic feedback force can be determined for each cycle by assuming system is in a static equilibrium state and Eq. 7 is valid.

$$+\uparrow \sum F_y = 0 \qquad \text{(Eq. 7)}$$

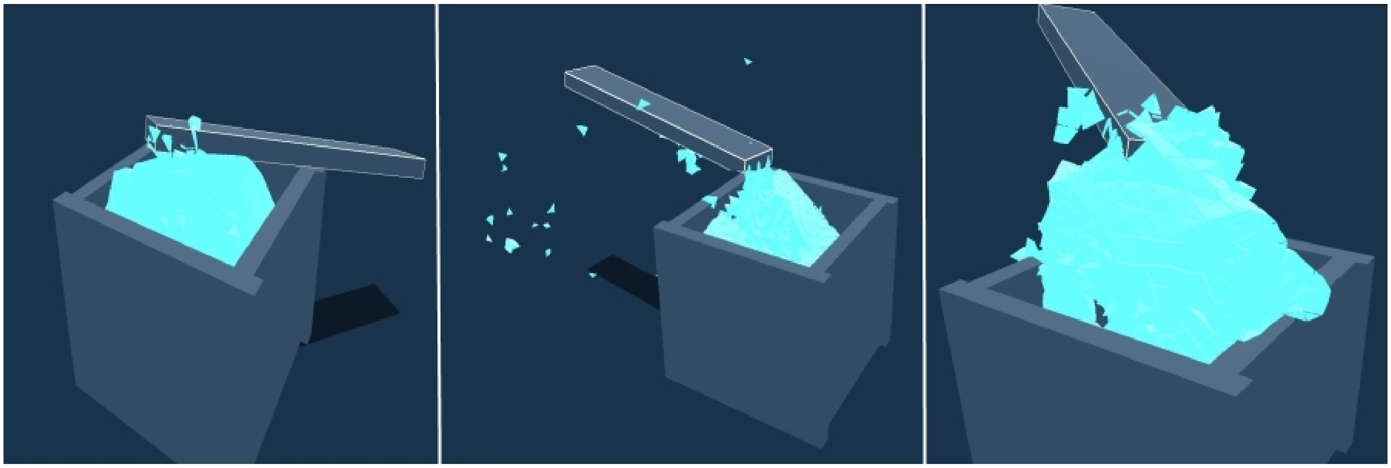

Figure 6. The scooping procedure from a box with rectangular prism and tetrahedral volume particles

where upper arrow indicates upper directional forces (positive) and lower direction is negative and also multiplication of all forces in y direction is 0. Fy of Haptic feedback can be calculated by using Eq. 8 which is derived from Eq. 7.

$$F_{y_{Haptic}} = m_{stick}g + m_{softbody}g \quad \text{(Eq. 8)}$$

While analyzing the second force group, it is important to understand the interactions of soft body particles. Soft body particles are connected to each other by using the spring model. The force that can disconnect two soft body particles can also be determined by using the spring model. Interaction of two particles can be controlled by three variables: the stiffness (k), the length of spring (L), and the maximum displacement (δ_{max}). The stiffness determines the deformation resistance of the soft particles, length of the spring determines the density of the soft body, and the maximum displacement determines the maximum deformation. Eq. 9 shows the connection between k, δ and P (force).

$$k = \frac{P}{\delta} \quad \text{(Eq. 9)}$$

By using Eq. 9, the minimum required force to disconnect two soft body particles can be calculated by Eq. 10.

$$P_{\min} = k.\delta_{\max} \quad \text{(Eq. 10)}$$

If the force that is applied by the rectangular prism is greater than P_{min}, then the soft body particles will be disconnected (it leads to soft body tearing).

In the third phase of the scooping action, there must be a static equilibrium state so that small amount of soft body stays on top of the rectangular prism (see Figure 5). Eq. 11 demonstrates the equilibrium conditions where x is number of connections on top of the rectangular prism and y is the number of soft body particles in one side of the rectangular prism. In this phase, there is a force that is resulted from shear stress which is already mentioned above.

$$\sum_{0}^{x} k.\delta_{\max} = \sum_{0}^{y} m_{soft\_body\_particle} \cdot g \quad \text{(Eq. 11)}$$

B. Implementation Details

Rigid bodies can be created in Physx as NxActor. Each NxActor is created with an NxActorDesc object which holds the information about the properties of object e.g. applied force to object, kinetic energy, linear velocity, linear momentum, and linear damping etc. Soft bodies can be created in Physx as NxSoftBody object. Each soft body is composed of the soft body particles which are tetrahedral meshes. Soft body object's properties are determined by NxSoftBodyDesc object. Although Physx supports the collision detections between soft body and rigid body, it does not support the collision detections between soft bodies. To overcome this discrepancy, small rigid bodies are inserted into the soft bodies.

In the simulation, as illustrated in Figure 6, there are four main objects. These are ground plane, soft body, rectangular prism, and a box. The rectangular prism, which is the rigid body object, is the only object that provides user interactions in the simulation and it is dynamic actor. Without that the scene is stationary. It is created as an actor which is a kinematic actor so that it can apply forces to other objects in the scene. However, during the simulation it does not get any force feedback from PhysX's calculations. The box in the scene is also an actor with five different actors; however, it is static actor. Its density is set to zero so that it is not affected by any other object in the scene. In order to represent a soft body (nucleus) in between C4-C5 vertebrae, the high viscosity fluid is used. Fluids in PhysX are represented by particles with density, stiffness, damping, viscosity parameters, etc. By using the SoftBodyDesc object, it is possible to create the soft body which has the similar properties with shortening. In the simulation, the rectangular prism which is controlled by the Phantom Haptic device scoops the high viscosity soft body and banishes some amount of soft body from the box. During the simulation, the collision detection algorithm takes place between vertices of interacting objects. The sensitivity of collision detection algorithm in PhysX is adjustable by manipulating thickness of the objects and/or collision response coefficients. Later, physicians' perception will be attained in order to obtain physically correct collision coefficients. Using the results of all these calculations, PhysX applies forces to the scene objects. As a result, exemplary proof-of-concept scooping action is illustrated in Figure 6.

The Phantom Haptic device integration to Physx library is implemented using OpenHaptics™ toolkit [22]. The haptic feedback is computed by the haptic rendering engine according to material properties (such as stiffness, damping, viscosity, etc.) of the active objects. Active objects in our case are the rectangular prism, the container box, and the soft body (tetrahedral particles) in the box. The rectangular prism is associated with the Phantom cursor and is modeled as a single PhysX convex rigid actor. The haptics rendering loop runs at 1,500 Hz and graphics rendering loop runs around 60 Hz at maximum frequency. This frequency difference rarely caused collision misses. This is resolved by increasing thickness of the objects. Current optimized collision detection method in PhysX is used in order to detect collisions. As mentioned in section 4 the reaction force vectors caused by collisions are calculated and carried out to the haptic cursor for haptic feedback.

V. CONCLUSION & FUTURE DIRECTIONS

The complete ACDR surgery is very complex and under development. One of the most important phases of the ACDR surgery –scooping action- is target of this proof-of-concept study. The available technologies such as NVIDIA PhysX made possible for us to implement framework for realistic scooping action simulation. The Phantom haptic device is also integrated in to the PhysX environment towards increasing plausibility of the simulation. There are many advantageous of PhysX engine for surgery simulation development. These advantageous are also outlined in the study. The nucleus (soft body) in between C4-C5 vertebrae is represented as small particles that have fluid properties. The scooping actions are represented by rectangular prism which is being interacted via the haptic cursor.

As a future work, the scooping action will be validated by surgeons or residents from the Neurosurgery Department at University of Arkansas for Medical Sciences. The stiffness and damping parameters especially at the nucleus and the vertebra contact regions are crucial for the realistic simulation. To adjust these parameters, neurosurgeons' input by using haptics will be acquired.

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