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Research paper

Force Aware Haptic Rendering for Intubation Simulation

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Abstract

We introduce a new haptic rendering method for neonatal endotracheal intubation simulation. The challenging procedure involves multiple models of different material properties, and is performed in the narrow oral cavity involving multiple contacts with tongue, lips, and laryngoscope. Our method first sets up simple collision detection mechanism with adaptive inner sphere tree structure for deformable tongue tissue. Then a collision response is handled with a novel force aware projective position correction. Our method is proved to be effective for heterogeneous simulation environment, therefore can be applied to surgical simulation with similar difficult settings.

Keywords: *Collision handling, Force feedback, Haptic rendering, Surgical simulation.*

1. Introduction

Haptic interaction in complicated virtual environment involving deformable and rigid bodies is a challenging task [1]. Especially for medical simulation, which requires accurate, realistic, and real-time performance. Proper collision handling is a critical component in realistic haptic rendering, the detection and response must be done correctly and fast enough to reach an update rate of 1kHz.

Two challenging problems still persist given extensive studies in existing literature. First, most collision detection method implement different forms of bounding volume hierarchy (BVH), for example, the basic axis-aligned bounding boxes (AABB), oriented bounding boxes (OBB), and bounding spheres (BS) [2, 3, 4, 5]. They typically nest a complex object into a tree with root representing the whole object, and each leaf consists of a small subset, while collision is detected by top-down traversal. However, with deformable models, the tree may change fast with time, and the primitives at leaf level collision detection and response are computationally expensive. This severely slows down haptic feedback rate. Qian et al. [6] proposed an adaptive spherical collision handling method for deformable model based on local geometry feature. However, the method is integrated in Position-based Dynamics (PBD) solver, and it generates circumspheres locally for fast processing, which is not enough to preserve physical characteristics of deformable model, such as volume and stiffness. Second, relative low cost haptic device like Geomagic Touch X has smaller maximum force, unexperienced user can easily exert force beyond threshold. The simulation may deteriorate or even break down if no correction is enforced after haptic device lose track.

In this paper, we propose a simple and effective collision detection method for deformable models based on inner sphere tree concept, and a novel force aware position correction collision resolving method, which can maintain simulation stability after haptic device exceeding maximum force and lose track. We apply this method to simulate neonatal endotracheal intubation procedure, a very challenging task due to multiple contacts in a narrow oral cavity and with delicate force manipulation.

2. Related Work

Medical simulators have been widely studied both in medical field and Engineering field because they are advantageous compared to traditional medical training. Traditional surgical trainings are usually done by practicing over mannequins or cadavers, which are time consuming and expensive. Medical simulators lift the strict hour operation room restrictions, and provides abundant reusable datasets and level of difficulty settings.

Realism and real-time interaction are two important factors in simulator design. Faithful tissue simulation directly impacts the training or surgical planning results, while real-time interactive haptic rendering helps transferring the virtual skills onto real surgical situations. However, deformable tissue complicates haptic rendering especially when the surgical tool is not a simple geometric model. Deformation, multiple contacts, and force feedback have to be handled properly to reach a physically plausible and visually realistic simulation.

Correct force feedback is an important factor for realistic haptic rendering, yet has not been fully studied due to the complicated nature and oversimplified mapping between haptic device and its virtual avatar. Previous works have done extensive research on haptic interaction with rigid bodies [7, 8, 9]. However, for applications such as surgical simulation, the typical environment often involves soft bodies. Current literature on haptic device interacting with deformable models can be classified into two categories: realistic virtual environment simulation and smooth haptic rendering.

The first category emphasizes on complicated model deformation, and haptic device only acts as an agent to insert certain amount of disturbance to the system, its virtual model is simply mapped to symmetrical primitives. Simulators like needle insertion, suturing, and eye surgery fall in this group [10, 11, 12, 13, 14].

The second category involves more detailed haptic virtual model, such as scissors, and knives etc. However, the continuous contacts are very limited, and simplified deformable model is wrapped in high resolution texture mapping for better visual effect and fast haptic update rate [15, 16, 17, 18]. Therefore, simulators in both groups leave out the discussion of correct force feedback. Our force aware haptic rendering approach attempts to further improve simulation realism by providing efficient collision handling and proportional force feedback.

3. Method

Many surgical procedures involve haptic interaction with heterogeneous models, including rigid, soft bodies, even fluid sometimes such as blood. Previous works tends to emphasis more on realistic tissue deformation, and less on the accuracy of force feedback. However in some surgical procedures, force is an important indicator of success as in the case of neonatal endotracheal intubation shown in Figure 1. During the procedure, surgeon inserts laryngoscope into narrow oral cavity and presses down the tongue until trachea is in line of sight before inserting air tube. The most difficult part in this type of simulation is collision handling and correct force feedback. Our haptic rendering method provides a simple and effective solution for this challenging simulation. We first simplify collision detection with adaptive inner sphere tree-like structure, then implement a force aware position correction in collision response for stable simulation.

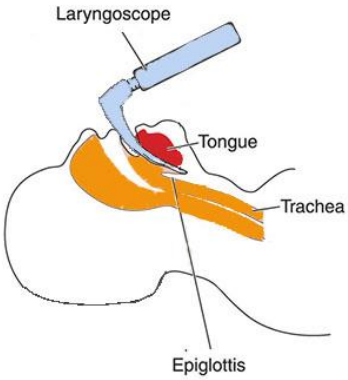


Fig. 1: Intubation procedure, first insert laryngoscope in oral cavity, press tongue and epiglottis until trachea is in sight, then insert intubation tube.

3.1. Collision Detection

We adapt collision detection algorithm from inner sphere tree [19], but more simpler and suitable for deformable model since IST is designed for rigid bodies. Physics-based Tetrahedron FEM is used for deformable model simulation [20].The goal is to fill this model with evenly distributed hierarchical spheres that can be barycentrically mapped to a small set of tetrahedron. The benefit is twofold: First, it is faster to conduct collision test with rotationally invariant sphere structure; second, the mapping between tetrahedrons and its enclosing spheres helps preserving volume by adding constraints on spheres distance. Moreover, fast collision handling improves haptic update rate, which usually drops dramatically in multiple contacts scenes.

3.1.1. Filling Spheres

The nature of deformable model prohibits sphere injection method that is used in IST, because the large internal spheres generated with greedy algorithm prevent model deformation unless we modify or rebuild the tree. Instead, we divide the model into evenly distributed grids, then fill each grid with a sphere. For model boundaries that do not pass sphere center, factorize the grid to 8 smaller grids and repeat the process as in Figure 2. The coarse level grid size or sphere can be arbitrary, but it is necessary to balance out between simplicity and realistic deformation. Our experiment indicates that the best result comes from sphere volume about 10 times of average tetrahedron volume.

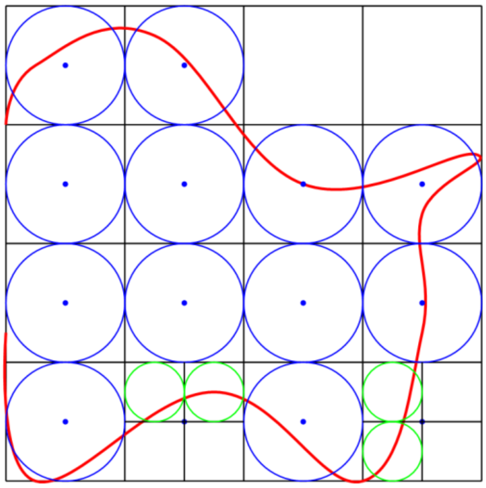


Fig. 2: Filling sphere in a deformable model (red), blue balls are the coarse level filler and green balls are the factorized finer level.

3.1.2. Mapping tetrahedron with sphere

Bounding volume hierarchy can be built the same way as IST. However, large deformation may require repeating the sphere filling and BVH building in runtime, this results in lower frame rate both for graphic and haptic rendering. Instead, we attach the sphere with its inner tetrahedron set using barycentric mapping, therefore the position of tree leaves may change, the relative relationship between them remains intact. It adds almost negligible cost to query the correct leaves in collision, but much faster than rebuild a tree. For the intubation simulation, the tongue is modelled as tetrahedron FEM and mapped to adaptive IST, the result is shown in Figure 3, where the two level orange spheres fill up the purple tongue wireframe.

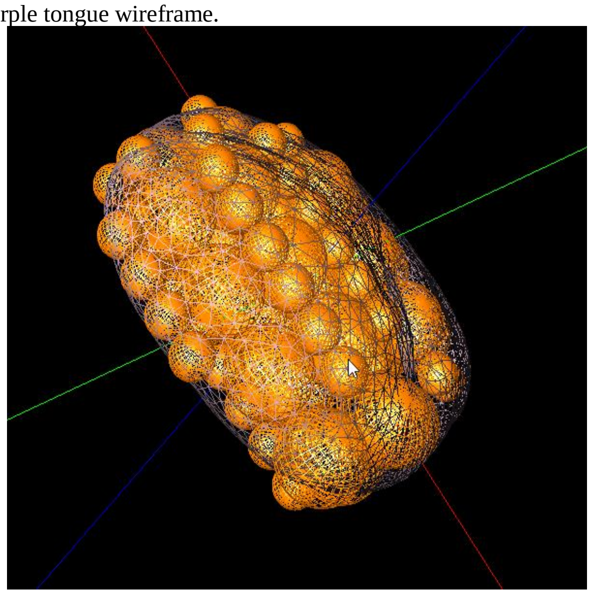


Fig. 3: Deformable tongue tetrahedron model (purple wireframe) is filled with adaptive IST collision detection structure (orange spheres).

3.2. Collision Response

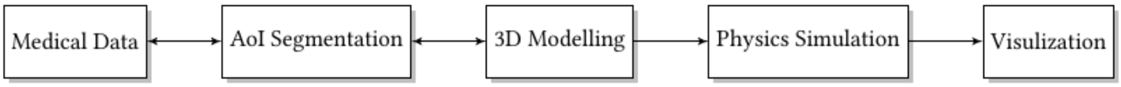


Fig. 4 Medical simulation stages: Medical data collection, area of interest segmentation, 3D tissue modelling, Physics-based simulation and simulation visualization.

Collision resolution is usually achieved by exerting penalty force or injecting impulse [21, 22], which basically works by correcting acceleration or velocity. Although physically plausible, it is computationally expensive and may generate oscillation effect under continuous contacts and increasing external force. For simulation with consistent contacts, directly editing position is more efficient and visually plausible.

In addition, haptic users usually cannot tell how much force they inject to the system without repetitive practice. When continually increasing force to the limit for a period of time, the haptic device loses track, its virtual model may keep exerting force to deformable model and break the simulation. We design a force aware position correction method that gracefully handle collision and maintain stable simulation when haptic device is out of track. We implement the method into implicit Euler solver.

$$\mathbf{p}^{n+1} = \mathbf{p}^{n} + h\mathbf{v}^{n+1} \tag{1}$$

$$\mathbf{v}^{n+1} = \mathbf{v}^{n} + h\mathbf{M}^{-1}\boldsymbol{f} \tag{2}$$

Where $\mathbf{p}^{n}$, and $\mathbf{v}^{n}$ are the position and velocity vector, respectively. $\mathbf{M}^{-1}$ is the inverse of mass matrix. $\boldsymbol{f}$ is the sum of all forces.

For the purpose of simple notation, the following discussion omits time step variable n unless otherwise specified.

The position correction works by adding a position correction vector $\mathbf{p}^{correction}$ to newly computed position after time integration.

$$\tilde{\mathbf{p}} = \mathbf{p} + \mathbf{p}^{correction}$$

The correction vector must meet the following projective constraint:

$$C_{(\mathbf{p})} = \begin{cases} (\mathbf{c}' - \mathbf{q}) \cdot \dfrac{\mathbf{c} - \mathbf{q}}{||\mathbf{c} - \mathbf{q}||} \geq 0 & \mathbf{f} \leq \mathbf{f}_{max} \\ \mathbf{c}' = \mathbf{c} & otherwise \end{cases}$$

Where $\mathbf{c}$ and $\mathbf{c}'$ are the old and new corrected position of sphere in collision after one time step, respectively. $\mathbf{q}$ is the nearest point on the surface of the colliding object. The new position will be project along the ray direction of the shortest distance between the current sphere center and the colliding objects, and the encapsulated tetrahedrons vertices position are updated along with it as shown in Figure 5.

The collision handling procedure is summarized in Algorithm 1.

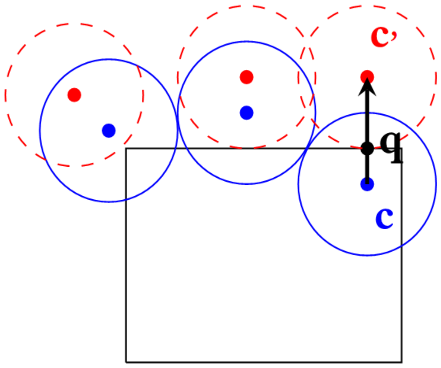


Fig. 5: Collision response with deformable model. Penetrating sphere (blue) center is projected along the shortest distance to the nearest surfaces direction.

Algorithm 1 Position Correction Implicit Euler Solver

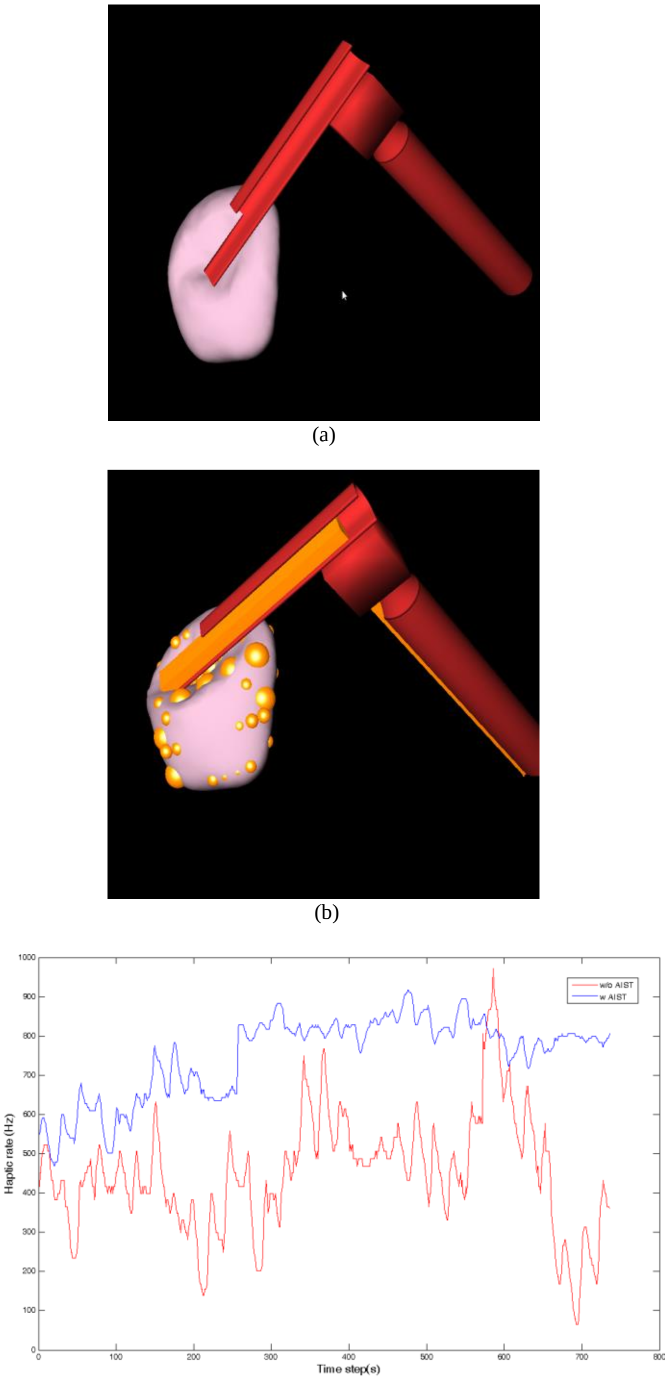
```
One step time integration :
        $\mathbf{v}^{n+1} \leftarrow \mathbf{v}^{n} + h\mathbf{M}^{-1}\mathbf{f}$
        $\mathbf{p}^{n+1} \leftarrow \mathbf{p}^{n} + h\mathbf{v}^{n+1}$
while $i \leq MaxIterationNumber$ do
    for AllContacts do
        $\mathbf{p}^{correction} = PositionProjectiveConstraints(\mathbf{C}_j, \mathbf{p}^{n+1})$

    end
    $\tilde{\mathbf{p}}^{n+1} \leftarrow \mathbf{p}^{n+1} + \mathbf{p}^{correction}$
end
$\tilde{\mathbf{v}}^{n+1} \leftarrow \frac{\tilde{\mathbf{p}}^{n+1} - \mathbf{p}^{n}}{h}$
```

4. Result and Discussion

We set up experiments for collision handling performance test and pilot neonatal intubation simulation. For medical simulation, the procedure typically involve 5 stages as shown in Figure 4: medical data collection, 3D segmentation, modeling, Physics-based simulation, and visualization. Data collection for this simulation includes neonatal oral cavity anatomy data, and laryngoscope. A Laerdal manikin is CT scanned, then tongue and face are segmented with MITK [23]. Tongue is modeled as soft body with tetrahedron FEM, Laryngoscope is 3D scanned and modeled as rigid body. Our collision handling and haptic rendering algorithm is implemented in SOFA [24], its modulized feature allows easy integration of new simulation techniques.

4.1. Performance

The main concern of haptic rendering is speed, low update rate can cause disparity between visual and tactile sensing. Moreover, in multiple contact environment, the force feedback is bumpy and unstable. Our adaptive inner sphere tree collision detection method reduce the computation complicity by taking advantage of rotational invariance of spheres, and simple barycentric mapping between sphere and its encapsulated tetrahedrons. In Figure 5, we show the continuous multiple contacts interaction between laryngoscope and deformable tongue. The comparison is made between direct primitive triangle level collision detection and our AIST method. From Figure 6(a), and 6(b), we can see there is not much visually difference between the two method. However, Figure 6(c) demonstrates our method has better performance in haptic update rated during persistent contacts, and has less turbulence over time. The proposed algorithm can improve simulation performance without down grading realism.



(a)

(b)

(c)

Fig. 6: Haptic interaction with deformable tongue model experiment. Collision handling comparison between direction primitive interactions (a) and our proposed adaptive inner sphere tree structure (b). (c) is the haptic update rate comparison between the two methods.

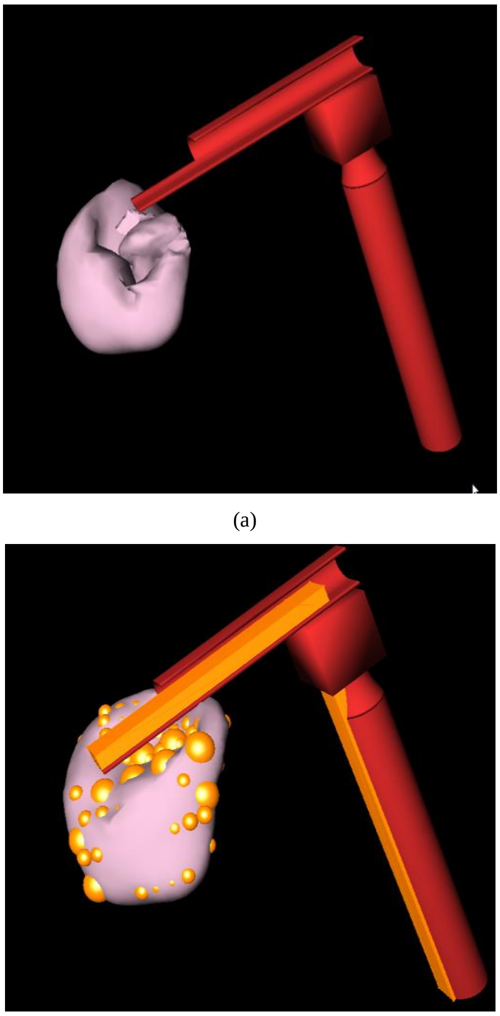
4.2. Stability

Our force aware time integration strategy provides a simple and effective solution to both collision response and haptic device overshooting. For collision response, direct position correction proves to be advantageous with multiple continuous contacts. Moreover, the level of correction is coupled with inserted force to maintain simulation stability. Users are usually not sensitive to small scale force and its incrementation over time. Especially when interacting with deformable model, the continuous deformation visual feed creates the illusion that the device can go further as shown in Figure 7(a), laryngoscope loses track after maximum force threshold is exceeded, and deformable tongue is not able to recover from the sudden disruption. With our method in Figure 7(b), the simulation remains stable, the tongue can recover to rest state.

Finally, we put all components together and run a pilot neonatal intubation simulation in Figure 8. User inserts laryngoscope into oral cavity and presses down the tongue in search for trachea opening. After adjusting laryngoscope for a better view angle, trachea colored in blue is largely visible, and a successful intubation procedure is completed. There are multiple contacts between lips, laryngoscope, and tongue, simulation is stable and realistic under this complicated environment. Figure 8(c) shows the method is effective and stable when haptic device exceeds maximum force and loses track, the grey sphere indicates the real position the haptic device should be at if there is no enforced overshooting position correction.

4.3. Future Work

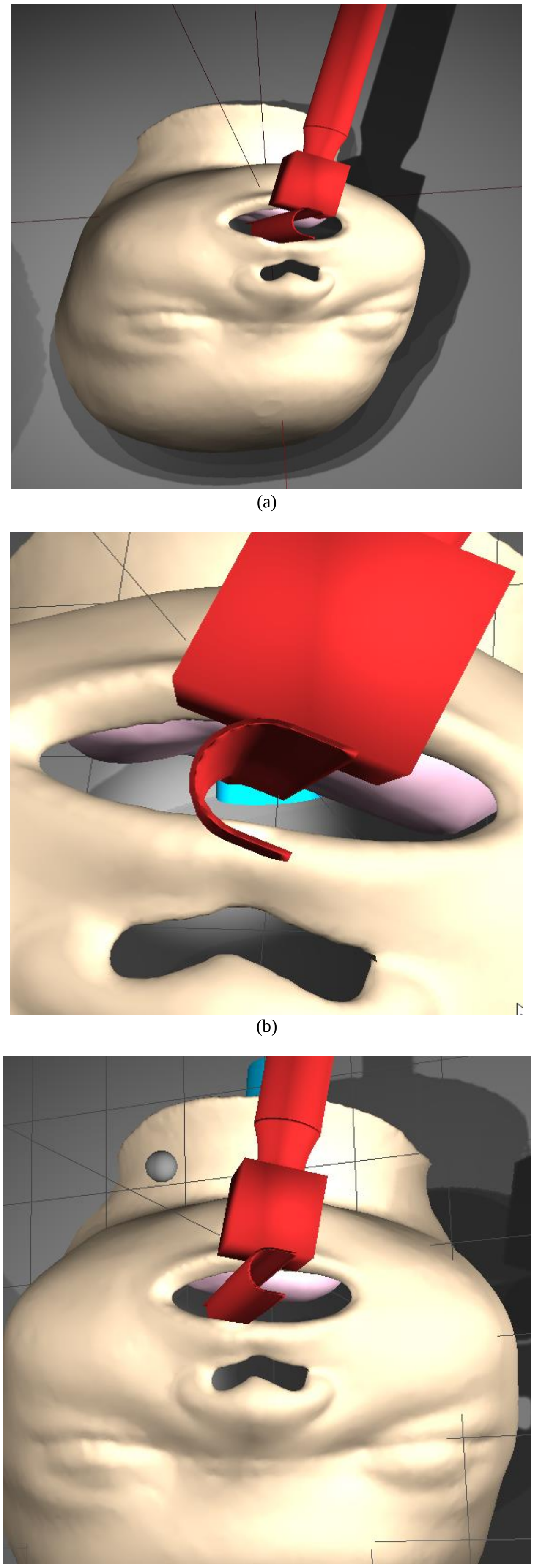
While our AIST and novel force aware haptic rendering method proves to be effective and an improvement on simulation environment with heterogeneous models. There are some limitations with it and room for further development. The AIST does not round up all the surfaces of arbitrary shaped model as shown in Figure 2, and fails collision detection test in these areas. It is possible to optimize the initial coarse level sphere generation with machine learning. There are also some promising future work with our pilot research, for example, adding constraints to achieve better deformable model volume conservation, and force prediction method to smooth out force feedback and keep up 1kHz rendering rate.



(a)

(b)

Fig. 7: Haptic interaction with deformable tongue model experiment. When haptic device exceeds force threshold and loses track, collision response with penalty force simulation breaks down (a), while our method remains stable (b).



(a)

(b)

(c)

Fig. 8: Neonatal endotracheal intubation simulation. Laryngoscope, trachea, and face surface are modeled as rigid bodies, and tongue as soft body. User inserts laryngoscope into oral cavity, and press down tongue until trachea (blue) is in sight. (a) The beginning of inserting laryngoscope into oral cavity. (b) Adjusting laryngoscope while pressing down the tongue until trachea is in line of view. (c) Simulation remain stable after haptic device reaches maximum force and loses track. The gray dummy indicates the real location of haptic device without overshooting position correction.

5. Conclusion

In this paper we introduce a new collision detection method, and a force aware position correction solver for deformable model. The collision detection is based on inner sphere tree algorithm developed for rigid body simulation, we adapt this structure and barycentrically map it to the underlying triangle primitives for computational efficiency. Then at the collision response stage, a position correction on the implicit Euler time integration result is performed based on inserted force. The results prove that our method is effective and stable. The new collision handling mechanism can be applied to complicated simulation environment with heterogeneous models, and we have successfully conduct tests on neonatal intubation procedure.

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