Influence of Fluid Effect on Virtual Simulation of Otolith Movement

Lingyi Kong1,2, Jun Wu2, Mingjie Feng3, Zhaobang Liu3 and Xiaoguo Yang1,*

1Department of Neurology, Wenzhou People’s Hospital, The third affiliated hospital of Shanghai University, Wenzhou, Zhejiang, China;  
2Department of College of Information Engineering, Yangzhou University, Yangzhou, Jiangsu, China;  
3Department of Medical Imaging, Suzhou Institute of Biomedical Engineering and Technology, Chinese Academy of Sciences, Suzhou, Jiangsu, China;  

*Corresponding author email: 52025403@qq.com

Abstract. More and more physics engines are used to simulate the dynamics between two rigid bodies. However, it is still unknown whether physics engine is suitable for computing the physical information of objects with fluid effect, such as the trajectory and collision dynamics of otolith in semicircular canal in benign paroxysmal postural vertigo (BPPV). The purpose of this study is to determine whether the fluid effect in Bullet physics engine has an impact on the movement data of otoliths in semicircular canal. Based on the experimental data obtained previously, we discuss the position and trajectory of the otolith when it falls in the Dix-Hallpike test. Root Mean Square Error (RMSE) is used to evaluate the static position of otolith under two conditions, and the RMSE is 0.716. We found that the initial position of otolith is affected by fluid effects, but the final static position and trajectory of otolith is similar (x=-5.838±0.294, y=19.348±0.143, z=-9.540±0.635). The experimental results show that the fluid effect does not affect the experimental results of the Dix-Hallpike test, and it has sufficient applicability for the evaluation of BPPV diagnostic methods.

1. Introduction
Benign paroxysmal postural vertigo (BPPV) is a common clinical disease of the peripheral vestibular system, which is ascribed to otolithic debris that becomes detached from the maculae of the otolithic organs and enters one of the semicircular canals[1]. Early research work has used clinical analysis to classify the nystagmus response of different otolith positions[2]. In 1952, Dix and Hallpike proposed the Dix-Hallpike test to diagnose BPPV. Now, the Dix-Hallpike test is considered as the gold standard for the diagnosis of BPPV in the posterior semicircular canal (benign paroxysmal positional vertigo of posterior semicircular canal, PSC-BPPV)[3]. In 1985, McClure proposed the Suprine roll test for the treatment of horizontal semicircular canal BPPV[4]. And in 2014, Califano proposed the straight-head-hanging positioning test for the treatment of superior semicircular canal BPPV[5]. All these studies emphasize that the corresponding relationship between nystagmus and otolith position must be considered.

Computer-based physical simulation technology has a rich history in supporting the development of medicine. Computer simulation for the treatment of human diseases has increased the choice of treatment methods, and has also increased opportunities and challenges for modern medicine. Clinically, Jean-Marc Schwartz expanded a non-linear viscoelastic model to simulate the characteristics of liver tissue to assist surgical treatment[6]. D. Périé proposed the scoliosis bracket simulation to study and...
verify the method of correcting scoliosis[7]. Recently, with the progress of 3D simulation technology, the Bullet physics engine developed by Erwin[8] has begun to be used in the production of various games and movies. And with the introduction of friction factors and fluid effects, Bullet's simulation results will make the research on BPPV diagnosis and treatment techniques more intuitive.

This study uses the Bullet physics engine to simulate the changes in the falling position and trajectory of otoliths after fluid effects are added. Take the Dix-Hallpike test as an example to evaluate the applicability of the Bullet physics engine in the auxiliary diagnosis of BPPV. In the following sections, we discuss the related work. In section 2, we describe how the Bullet physics engine work, including collision detection and graphics display. In Section 3, experiments with different parameters are carried out. In section 4, we discussed the test results and discuss the influence of fluid effects on simulation. Finally, in section 5, we present our conclusions and possible improvements, and give a brief overview of our future work.

2. Proposed Simulation Approach
Bullet physics engine is a real-time simulation engine of physics environment developed by C++ with good cross-platform and precise collision detection. It can simulate and display each frame of the rendered scene through Open Graphics Library (OpenGL)[9], use Graphics Processing Unit (GPU)[10] to complete physical simulation calculations, and continuously update entities.

2.1. Composition of Bullet
The main task of the physics engine is to perform collision detection, resolve collisions and other constraints, and provide updated world transform. The main components of Bullet physics engine include linear mathematics memory and container module, collision detection module, rigid body dynamics module, software dynamics module, multi-threading module, and some additional tool support modules.

The main work of this paper is to construct a simulation world, place physical objects such as semicircular canals and otoliths. Then it can set the mass, inertia and other physical properties of the objects, and calculate the physical properties of semicircular canals and otoliths to physically simulate each frame of the scene. According to the object's motion state and force direction, collision detection is performed to simulate the displacement conversion of the object.

2.2. Collision Model
The semicircular canal model in the experiment is imported from an external file and set as a concave model. In the previous work, we obtained the model of the bone semicircular canal through segmentation[11]. We have established the spatial direction of the membrane labyrinth, and established the standard spatial bone semicircular canal model, as shown in Figure 1. Figure 2 shows the use of spherical convex bodies to simulate otoliths.

2.3. Dynamics Modelling in Bullet
Bullet uses pulse-based simulation[12], which is characterized in that it can accurately calculate the contact points between colliding objects, so that the moment of collision can be calculated. In the process of dynamic collision, gravity and friction always act on the object. The Bullet physics engine can analyze
the force in real time to track the position of the object. 

*Dynamic simulation in Bullet.* The calculation of rigid body motion in the Bullet physics engine refers to the multi-rigid body-dynamic simulation\[^{13}\]. An effective numerical method for solving complementarity problems (LCPs) is proposed to reduce simulation errors in an iterative manner. It can be expressed in mathematical form as equation (1). Where \(k\) is iteration. When \(k\) approaches infinity, the function will converge to \(x^*\). In classical mechanics, the Newton-Euler equation is used to describe the motion of an object. The collision of rigid bodies during the movement will affect the angular velocity \(\omega\) and linear velocity \(v\) of the object.

\[
x^{k+1} = f(x^k) \quad (1)
\]

Fluid effects in Bullet. First, the Bullet physics engine can calculate the resultant force acting on the mass point and update the (temporary) velocity of the object. Specifically, it is divided into three parts: 

- a. Calculate the deformation measurement of the current object, such as Force (F), Moment of Inertia (J), Constant (C), Trace (tr(C)), etc. 
- b. Calculate the resultant force acting on the node. 
- c. Calculate the speed value of the node, as equation (2).

\[
\text{node.m}_v += f / m \quad (2)
\]

d. Update the (temporary) location of the node, as equation (3).

\[
\text{node.m}_q = \text{m}_x + \text{m}_v \times dt \quad (3)
\]

On this basis, the influence of fluid effects on the movement of otoliths in the Dix-Hallpike test is simulated.

2.4. Experimental Design

In the experiment, the rotation of the semicircular canal model is controlled by the input angle, where \(\alpha\) represents the angle of rotation around the x-axis, \(\beta\) represents the angle of rotation around the y-axis, and \(\gamma\) represents the angle of rotation around the z-axis. The semicircular canal model is established based on the right-handed coordinate system. Figure 3 (a) shows the semicircular canal coordinate system in the simulation.

*Figure 3.* The semicircular canal coordinate system.

The Dix-Hallpike test is a classic PSC-BPPV test. It involves turning the patient's head 45° to the right for testing, and then quickly causing the patient to lie down and lean back 30°. Figure 4 describes the movement of otoliths in the semicircular canal during the Dix-Hallpike test through collision detection in Bullet. The simulation experiment process can be summarized as follows: 

First, the semicircular canal is rotated to the corresponding angle. 

Secondly, the otoliths start to move under the action of various mechanics.
Finally, the movement of the otoliths at the bottom end is stationary, and the influence of gravity will cause nystagmus.

![Figure 4](image)

**Figure 4.** (a) Original state, (b) Turn 45°, (c) Lean back 30°.

The movement process of the otolith is similar to the record in the previous experiment[14]. It is worth noting that usually the contact points of the Bullet model are produced by the linear velocity and the angular velocity. This means that the movement of the otolith is affected by the semicircular canals. Figure 3 (b) The linear velocity of the middle otolith is controlled by its own gravity and the movement of the center of gravity of the semicircular canal, and the speed is updated with the update of the angular velocity of the semicircular canal.

Since the size of otoliths is about 3μm*5μm*5μm, which is very small, the otolith parameters in this paper need to be as small as possible. Table 1 lists the main parameters of each instance.

### Table 1. Main parameters.

| otolith | Mass (g) | Friction | Air density (Kg/m³) | Water density (g/cm³) |
|---------|----------|----------|---------------------|-----------------------|
| Example 1 | 0.02 | 0.1 | 1.0 | 0.1 |
| Example 2 | 0.02 | 0.2 | 1.0 | 0.2 |
| Example 3 | 0.02 | 0.5 | 1.0 | 0.2 |
| Example 4 | 0.008 | 0.1 | 1.2 | 0.1 |
| Example 5 | 0.008 | 0.2 | 1.2 | 0.2 |
| Example 6 | 0.008 | 0.5 | 1.2 | 0.6 |
| Example 7 | 0.1 | 0.1 | 1.5 | 0.1 |
| Example 8 | 0.1 | 0.2 | 1.5 | 0.2 |
| Example 9 | 0.1 | 0.5 | 1.5 | 0.6 |
| Example 10 | 0.5 | 0.1 | 2 | 0.1 |
| Example 11 | 0.5 | 0.2 | 2 | 0.2 |
| Example 12 | 0.5 | 0.5 | 2 | 0.6 |

### 3. Result

We took two experiments. In the first experiment, the object is not affected by fluid effects, and in the second experiment, the object is affected by fluid effects.

In the first experiment, we find that in the Dix-Hallpike test, under the influence of different parameters, the standard deviation of the z-axis coordinates changed relatively greatly when the otolith is at rest after 45° rotation (9.525±1.869). But after leaning back 30°, the final resting position of the otoliths is similar, as shown in table 2.

In the second experiment, we can find that the coordinates of the otoliths are similar when they are at rest regardless of whether it’s turning 45° or leaning back 30°.

As a result, the z-axis coordinates of all data in Experiment 1 and Experiment 2 are quite different (11.067±2.031) after turning 45°. But after leaning back 30°, the coordinates of the otoliths at rest are still similar. Therefore, we can find that the fluid effect does not affect the final coordinates of the otolith falling.

Figure 5 shows the trajectory of otoliths from (a) to (b) in Figure 4 under different parameters. All steps should be rested long enough to ensure that the otolith is still before the semicircular canal moves. From Figure 5, we can find that the trajectories of the lower otoliths in the two experiments are roughly similar. And otoliths will not change the trajectory of movement under the influence of fluid effect.
this to confirm that the fluid effect does not affect the ability of the physics engine to simulate the complete process of BPPV diagnostic technology.

![Figure 5](image-url)  
**Figure 5.** (a) the trajectory of otoliths without fluid effects. (b) the trajectory of otoliths affected by fluid effects.

|                        | Experiment 1 | Experiment 2 | Experiment 1 and 2 |
|------------------------|--------------|--------------|--------------------|
| **Turn 45°**           | (-9.341±0.345,8.273±0.266,9.525±1.869) | (-8.781±0.010,8.708±0.003,12.610±0.038) | (-9.061±0.371,8.491±0.287,11.067±2.031) |
| **Lean back 30°**      | (-6.039±0.240,19.273±0.153,10.005±0.519) | (-5.637±0.178,19.422±0.081,9.074±0.322) | (-5.838±0.294,19.348±0.143,9.540±0.635) |

### Table 2. Coordinates at rest.

4. **Discussion**

Peng once formulated the movement behavior of otoliths, the purpose is to study the visualization of otolith movement\(^ {15} \). Todd M and others built a mathematical model to assist in the treatment of BPPV \(^ {16} \). But their research is based on the calculation of complex mathematical formulas. However, in the Bullet physics engine, the calculation can be directly called and combined with the graphics engine, which simplifies the otolith simulation process and can control the movement of the model in real time.

Bullet physics engine uses fixed step algorithm\(^ {17} \). The movement speed of the otolith is calculated by the Bullet physics engine every 1/60s and the record is updated once. We use the root mean square error (RMSE) to study the difference between different parameters affecting the experimental results. Compared with other statistical methods, RMSE is more sensitive to extreme values, which makes it possible to measure the difference in the drop position of otoliths during the simulation process. The RMSEs equation of position is:

\[
RMSE = \sqrt{\frac{\sum_{n=1}^{11} ((x_{ns} - x_{nr})^2 + (y_{ns} - y_{nr})^2 + (z_{ns} - z_{nr})^2)}{12}} 
\]

\(x_{ns}, y_{ns}, z_{ns}\) represent the coordinates of otoliths at rest under the influence of fluid effects, \(x_{nr}, y_{nr}, z_{nr}\) represent the coordinates of the otolith at rest without the fluid effect.

RMSEs shows the influence of fluid effect on each simulation instance during the movement of otoliths in the Bullet physics engine. Through experiments, we can get that the RMSE of the otolith at rest position after turning 45° is 3.688, but it becomes 0.716 after being leaning back 30°.
The physical simulation test results of the Dix-Hallpike test show that the Dix-Hallpike test can induce a certain degree of movement of the otoliths in all semicircular canals. Locations where can see obvious movement of the otoliths and may induce vertical rotation nystagmus, including the movement of the right posterior semicircular canal away from the ampulla, the top posterior semicircular canal moves away from the ampulla or toward the ampulla and the otoliths in the left utricle enter the posterior semicircular canal[18].

At present, we do not know the biomechanics of the otoliths on the long arm side of the upper semicircular canal sliding from the bottom of the ampulla to the top. But according to our results, although the otoliths of the superior semicircular canal also move away from the ampulla, they are located at a short distance from the ampulla and the fluid effect is not obvious. That is, when the otoliths move in the semicircular canal, the fluid effect will not affect the degree of dispersion of the otoliths, and all otoliths will move toward the lowest point of gravity.

In fact, the type of nystagmus of BPPV is related to the concentration of otoliths[19]. Regardless of whether otoliths are affected by the fluid effect, the otolith will be deposited to the lowest point under the action of gravity and finally trigger the nystagmus at the corresponding position. The Bullet physics engine is sufficient to simulate the movement of otoliths in the semicircular canal with or without fluid effects, and assist the doctor to treat the patient according to the type of nystagmus.

5. Conclusions
The purpose of this research is to verify whether the fluid effect of the Bullet physics engine will affect the trajectory and falling position of the otolith when simulating the BPPV diagnosis and treatment technique. Although the movement time of the otoliths in the simulation may change due to the influence of fluid effects, the simulation results of the Bullet physics engine are consistent with the results of the trigger position of the nystagmus compared with previous experiments. In addition, if the simulation results are sufficiently accurate, it can assist doctors in verifying the feasibility of various BPPV diagnosis and treatment techniques. In future, we will further analyze the movement of otoliths in the semicircular canal such as whether the motion time and velocity of otolith will be affected by the fluid effect, and collect data clinically to determine the best experimental parameters. This will help to further understand the diagnosis mechanism of otoliths, then assist the doctor to determine whether the treatment method matches the type of BPPV and promote the advancement of BPPV diagnosis and treatment techniques.

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