Exploring Physics Simulation Speed/Fidelity Trade-Off in Virtual Reality Environments

Lawson Fulton Vismay Modi Christine Murad

Abstract

The creation of compelling virtual reality environments necessitates worlds that are not just static, but respond to users presence in realistic ways. Physical simulation of materials enables this type of experience. However, there is a trade off between simulation speed and simulation fidelity, and the balance of these two features can affect the perception of realism when interacting with deformable objects in a virtual reality environment. In this paper, we describe a perceptual experiment in which participants compared meshes of various visual fidelity and speed in interaction, in order to explore the relationship between visual fidelity, speed, and perceptual realism of interaction with deformable objects in virtual reality. Participants, in general, found that they preferred a faster simulation over a simulation with more fidelity, and that a faster simulation created more realistic interaction.

1 Introduction

Interaction with a dynamic and physically plausible environment is a key factor in creating immersive virtual experiences. Numerical simulation of deformable bodies is one way of creating such environments for common compliant materials such as organic matter. However, there exists a trade-off between the speed of the physical simulation and it's fidelity. The higher a physical simulation's fidelity, the slower the interaction with the object will be. There remains a question of what the correct balance between these two factors is to create a realistic experience when interacting with objects in a virtual reality environment.

While there have been works to help improve physics simulations of deformable objects [1, 6, 8, 9], there is still little work on the evaluation of perceptual realism when interacting with these deformable objects. Existing work has focused on 2D environments [5, 7] or focused on perception of virtual reality using haptics [2, 3]. However, not as much has focused on the relationship between speed and visual fidelity and their effects on realistic interaction with deformable objects in virtual reality.

To explore this, we ran two iterations of a perceptual experiment in which participants interacted with a rectangular bar in a virtual reality environment, with varying levels of physical simulation resolution. The goal of the experiment was to investigate the relationship between simulation fidelity, speed, and perceptual "realism" of interaction in the virtual reality environment. We believed that the perceptual realism is constrained by model resolution, and computational speed, and that these are competing goals. We hypothesized that perceptual realism as a function of simulation resolution will be an inverted U-shaped response curve. We anticipated that the optimal mesh resolution for perceptual realism will be a trade-off between simulation accuracy, and interface responsiveness (speed of simulation). We found, however, that the most realistic interaction did not lie in the middle, with a balance between visual fidelity and speed, but lied on the preference of fast interaction. We also collected average number of milliseconds per time step for each mesh, in order to suggest an average frame rate that would be optimal for preserving perceptual realism.

2 Previous Work

2.1 Deformable Object Simulation and Interactivity

There has been much research in the simulation of deformable objects, both to make them realistic and easy to interact with. Xu [8] developed a new method to allow for designing material distributions for complex meshes, using pre-determined positions and elastic forces. Xu [9] also explored editing and modifying stress-strain curves in order to interact with different types of materials in an intuitive and visually pleasing way.

There is also research in incorporating haptics into deformable object interaction in order to increase their realism, particularly in virtual reality environments. Duriez [1] created a computer haptics algorithm using Signorini's contact law and Coulomb's friction law to enhance multi-object interaction and perception of haptics such as friction. Popescu [6] created a hand interaction model using a haptic glove in order to more realistically simulate contact with physical surfaces when working with deformable objects in virtual reality.

While there is existing effort in creating realistic and interactive physics simulations, there is still little research in evaluating user perception of interaction with these simulations of deformable objects - particularly in a virtual reality environment. The current work in this area is described below.

2.2 Evaluating Perceptual Realism of Physics Simulations

There have been several studies performed to evaluate perceptions of different physics simulations and animations that are meant to mimic their real-life counterparts. Um [7] ran crowd-sourced studies to evaluate the perception of fluid simulation, and exploring which methods of fluid simulation presented the most realistic simulation of liquid. O'Sullivan [5] ran studies with users to examine the effect of degradations and distortions in animations and their effect on the physical plausibility of the animations.

There have also been studies performed examining perceptual realism in virtual reality environments. Hoffman [3] looked at perception of realism in virtual reality environments, but explored the effect of touching a physical object, and how that effects the perception of realism of an object in virtual reality. Han [2] explored using checkerboard textures and different measures of spatial frequency and contrast, and performed user evaluations to evaluate their effects on users' perceived stiffness of a deformable object.

Though previous work has explored perceptual realism of physics simulations, our work looks particularly at perception of realism when directly interacting with a deformable object in virtual reality, and the effect of visual fidelity vs speed in the physics simulation.

3 Methodology

3.1 Participants

In Iteration 1, we had 15 participants (11 male, 4 female), and in Iteration 2, we had 9 participants (4 male, 5 female). Participants for both iterations consisted of University of Toronto Computer Science students, with 12 graduate students and 3 undergraduate students. 6 participants participated in both iterations of the study. All participants had 20/20 or corrected-to-20/20 vision.

3.2 Hardware and Software

The experiment was run on an Alienware laptop with a Intel Core i7-2820HK @ 2.90 GHz, with 32.0 GB of RAM, and an NVIDIA GeForce GTZ 1070 graphics card.

The HTC Vive VR platform was used for the experiment. This platform was chosen since it provides dual controller input, which will be the main mode of interaction with the virtual materials. The experiment was developed using the Unity game engine, and programmed in C#.

One of the constraints of using Unity for development is its support for only C# and Javascript languages. Since most high-performance simulation software is written in C++, we chose to use C# because of its ability to integrate with compiled code. The open-source simulation library GAUSS [4] was used to do simulation, with a series of custom wrappers we developed to interface with the main C# application.

3.3 Physics Simulation

In Iteration 1, there was a total of 5 meshes. The qualities of each of these meshes were:

	# of Vertices	# of Tetrahedra	# ms per timestep
Mesh 0	97	204	6.28
Mesh 1	191	460	15.65
Mesh 2	357	1051	42.83
Mesh 3	769	2543	130.2
Mesh 4	965	3471	179.62

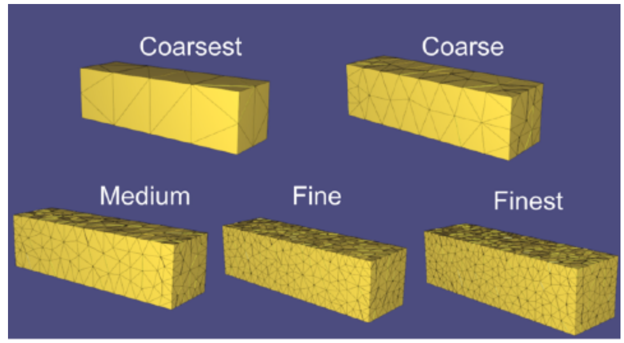

Figure 1: Visualization of meshes from coarsest (Mesh 0) to finest (Mesh 4)

One potential source of bias is the visual inconsistencies between different meshes with varying coarseness levels. Therefore, in Iteration 2 of the experiment, we avoid this bias by skinning all the test meshes for visual consistency. The finest mesh used in the tests is embedded onto all of the coarser meshes so that even the coarsest mesh appears to have just as many elements as the finest mesh. Skinning the meshes does not change the physical behaviour of the mesh, merely the appearance. We also corrected for numerical stiffness by manually choosing a Young's Modulus value for each bar that produced a visually identical displacement under gravity.

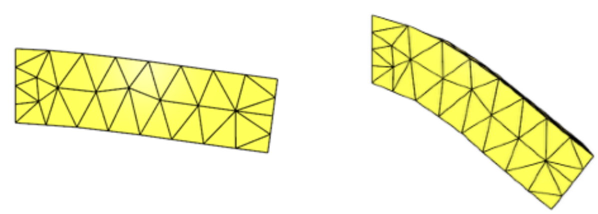

Figure 2: Before (left) and after (right) correcting for numerical stiffness

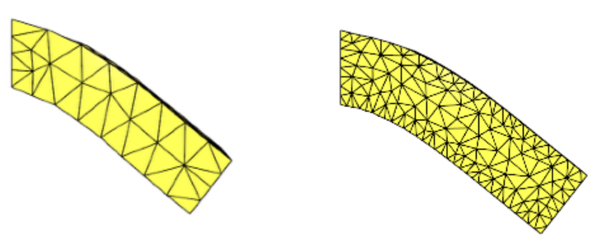

Figure 3: Low res (left) and high res (right) mesh with same Young Modulus value

Another aspect we wanted to explore was whether participants were choosing the faster meshes purely because of their speed, or whether participants truly felt that they were more "realistic". In order to explore this, we added two more meshes to the experiment in Iteration 2, which were duplicates of the two coarsest meshes (Mesh 0 and Mesh 1), but with an additional artificial speed delay of 100 ms. The qualities of each of these two extra meshes were:

	# of Vertices	# of Tetrahedra	# ms per timestep
Mesh 5	97	204	106.65
Mesh 6	191	460	116.12

3.4 Experimental Setup

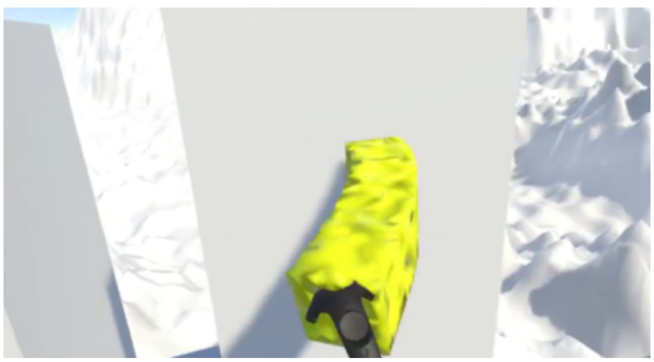

Figure 4: Participant view of interacting with mesh in the experiment

The experiment lasted between 10-15 minutes for each iteration. After participants had signed a consent form and had been instructed on the controls for the experiment, participants were shown pairs of meshes in succession in the virtual reality environment (counter-balanced between participants, and the order of pairs shown randomized to avoid learning effects), and were able to go up to the meshes and interact with them, either by bending them or stretching them. They were then asked to select which of the two meshes they felt were more "realistic" based on the interaction with them. Once they selected one, they were automatically shown the next pair. They did this for each pair of meshes until they had completed all of them.

4 Results

We used pairwise comparisons to analyze the results of our perception experiment. This involved pairing each candidate (mesh) with another head-to-head (with no repetition), and giving one point to the candidate that the participant chose as more realistic. The candidate with the most points was then declared the "winner" - in this case, the mesh that is the most realistic between the two.

4.1 Iteration 1

There were 10 pairwise comparisons between the 5 meshes used in Iteration 1. The results of the pairwise comparisons can be seen in Figure 5. The results show that the faster mesh, that contained less fidelity, was almost always preferred over the higher-fidelity, yet slower mesh. The only two cases in which the higher fidelity mesh was preferred was when comparing Mesh 0 vs Mesh 1, and Mesh 0 vs Mesh 2. These three meshes were all on the lower fidelity end of the scale, and were similar in speed.

	Mesh 0	Mesh 1	Mesh 2	Mesh 3	Mesh 4
Mesh 0	X	Winner: 1 By 9/15	2 By 9/15	0 By 9/15	0 By 11/15
Mesh 1	X	X	1 By 13/15	1 By 13/15	1 By 12/15
Mesh 2	X	X	X	2 By 13/15	2 By 12/15
Mesh 3	X	X	X	X	3 by 13/15
Mesh 4	X	X	X	X	X

Figure 5: Results of Pairwise Comparisons Analysis for Iteration 1

The total amount of times that a particular mesh was selected as more realistic was also calculated. A graph of these results can be seen in Figure 6. While there is a peak at Mesh 1 with the results lowering from there, we can see that Meshes 0-2 were selected most often as the more realistic mesh, with a steep drop for Meshes 3 and 4. From these results, we can see that people most often selected the faster mesh, though it contained less fidelity.

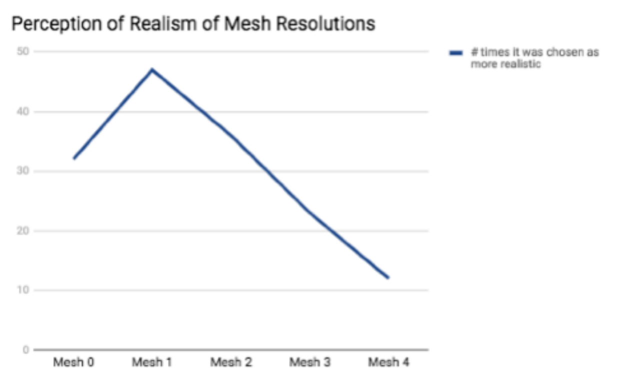

Figure 6: Number of times each mesh was selected as more realistic in Iteration 1

4.2 Iteration 2

There were 21 pairwise comparisons between the 7 meshes used in Iteration 1. The results of the pairwise comparisons can be seen in Figure 7. As was observed in the first iteration of the experiment, the faster mesh was almost always selected as the more realistic mesh to interact with. The only case in which the slower mesh was picked over the fast mesh was when comparing Mesh 3 and Mesh 6, where Mesh 3 was chosen more often as more realistic.

One difference between the results of Iteration 1 and Iteration 2 was the amount of times that Mesh 0 won in pairwise comparisons. While in Iteration 1, Mesh 0 won 2/4 times as the more realistic mesh, it won 4/4 times as the most realistic mesh between meshes 1-4, and it also was the more realistic mesh among the two new meshes that were added.

	Mesh 0	Mesh 1	Mesh 2	Mesh 3	Mesh 4	Mesh 5	Mesh 6
Mesh 0	X	Winner: 0 By 5/9	0 By 7/9	0 By 7/9	0 By 9/9	0 By 6/9	0 By 8/9
Mesh 1	X	X	1 By 7/9	1 By 9/9	1 By 7/9	1 By 7/9	1 By 8/9
Mesh 2	X	X	X	2 By 8/9	2 By 9/9	2 By 9/9	2 By 9/9
Mesh 3	X	X	X	X	3 by 6/9	5 by 7/9	3 by 6/9
Mesh 4	X	X	X	X	X	5 by 7/9	6 by 7/9
Mesh 5	X	X	X	X	X	X	5 by 5/9
Mesh 6	X	X	X	X	X	X	X

Figure 7: Results of Pairwise Comparisons Analysis for Iteration 2

When calculating the total amount of times that a particular mesh was selected as more realistic (Figure 8), we see that it is less of an inverted U-Curve, as both Mesh 0 and Mesh 1 have the highest number of selections (42). However the steep drop still remains from Mesh 2 to Mesh 3, and from Mesh 3 to Mesh 4. When looking at Mesh 5 and Mesh 6, although the amount of times they were selected in total is less than their non-delayed counterparts, they were still chosen more than both Mesh 3 and Mesh 4.

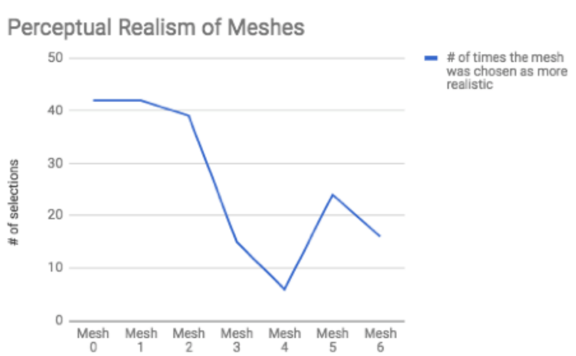

Figure 8: Total number of times each mesh was chosen as more realistic in Iteration 2

5 Discussion

As we showed above in the results, participants often chose the faster mesh as the one that felt more realistic when interacting with it. This was observed in both iterations of the experiment. This suggests that participants are willing to sacrifice more fidelity for faster interaction.

With the changes to the visual fidelity in the second iteration, Mesh 0 won more pairwise comparisons (even without consideration of the two added meshes), and was selected many more times in total. We also saw the number of times Mesh 3 and Mesh 4 were selected go down. However, the same general trend shows - participants selected the faster, lower fidelity mesh over the slower, high fidelity mesh, after interacting with it.

With the addition of the two extra meshes in Iteration 2, we found that with the extra 100ms delay, even though all the other qualities of the meshes they were duplicated from remained (Mesh 0 and Mesh 1), participants still chose the mesh with the faster speed. For example, when comparing with Mesh 2, Mesh 2 was picked over Mesh 5 and Mesh 6, while without the speed delay, Mesh 0 and Mesh 1 were picked over Mesh 2.

Based on the results of Iteration 1, we found that Mesh 1 was , on average, selected as the most realistic out of all the meshes. However, after the changes made in Iteration 2, it was found that Mesh 0 was, on average, selected as the most realistic out of all the meshes. This could be a factor of the skinning we added so that all the meshes visually looked the same - in Iteration 1, Mesh 0's material had visually less fidelity, even without interacting with it, so it would make sense that Mesh 1 would be slightly more realistic than Mesh 0 in Iteration 1.

From our study, we calculated the frame rate of the two most realistic meshes from both iterations. Mesh 0 ran at 159.2 frames per second, and Mesh 1 ran at 63.8 frames per second. We believe that in order to create realistic physical simulations for interactive deformable objects in virtual reality, these frame rates can be used as starting anchors for a minimal simulation speed.

6 Conclusion and Future Work

In this paper, we sought to explore perceptual realism of physics simulations and interacting with deformable objects in a virtual reality environment. We ran two iterations of perception experiment where we explored the relationship between simulation speed, fidelity, and perceptual realism of deformable objects. It was found that people tend to prefer faster interaction with deformable objects over visual fidelity.

There exists some limitations in this experiment. Some of the higher fidelity meshes were extremely slow to interact with, and when comparing meshes on opposite ends of the scale (such as comparing Mesh 0 with Mesh 4), participants expressed that is was a very obvious choice since Mesh 4 was very difficult to properly interact with. In the future, better hardware and meshes that were not drastically different from each other in interaction speed would help confirm whether people truly preferred the faster mesh, or whether the finest meshes were too slow to be properly comparable to the coarsest meshes.

References

[1] Duriez, C., Dubois, F., Kheddar, A., & Andriot, C. 2006. Realistic Haptic Rendering of Interacting Deformable Objects in Virtual Environments. *IEEE Transactions on Visualization and Computer Graphics* 12, 1: 36–47

[2] Han, D., & Keyser, J. 2016. Effect of Low-level Visual Details in Perception of Deformation. *Comput. Graph. Forum* 35, 2: 375–383.

[3] Hoffman, H. G. 1998. Physically Touching Virtual Objects Using Tactile Augmentation Enhances the Realism of Virtual Environments. In *Proceedings of the Virtual Reality Annual International Symposium* (VRAIS '98).

[4] Levin, D. I. W. 2018. GAUSS: Gaggle of Algorithms and Utilities for Simulating Stuff.

[5] O'Sullivan, C., Dingliana, J., Giang, T., & Kaiser, M. K. 2003. Evaluating the Visual Fidelity of Physically Based Animations. In *ACM SIGGRAPH 2003 Papers* (SIGGRAPH '03), 527–536.

[6] Popescu, V., Burdea, G., & Bouzit, M. 1999. Virtual reality simulation modeling for a haptic glove. In *Proceedings Computer Animation 1999*, 195–200.

[7] Um, K., Hu, X., & Thuerey, N. 2017. Perceptual Evaluation of Liquid Simulation Methods. *ACM Trans. Graph.* 36, 4: 143:1–143:12.

[8] Xu, H., Li, Y., Chen, Y., & Barbič, J. 2015. Interactive Material Design Using Model Reduction. *ACM Trans. Graph.* 34, 2: 18:1–18:14.

[9] Xu, H., Sin, F., Zhu, Y., & Barbič, J. 2015. Nonlinear Material Design Using Principal Stretches. *ACM Trans. Graph.* 34, 4: 75:1–75:11.