Simulating Ice Skating Experience in Virtual Reality

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Fig. 1: This figure shows a user who is skating in a virtual ice rink (left) through our proposed physics-based VR simulation approach through which the user can skate in a stationary boundary in real world by banding VR controllers on shoes (right).

Abstract—In this paper, we propose a physics-based approach to simulate the ice skating experience in virtual reality. While banding two VR controllers on the shoes, the virtual ice shoes will be tracked accurately in a virtual scene. As shown in the experimental results, when a user is sliding the shoes in a stationary boundary in the real world, the displacement of the shoes can be applied to apply force onto the virtual headset according to physics rules. So that through the vision rendered in the VR headset, the user can feel the motion in the virtual scene as if skating in a real ice rink. By demonstrating the simulation experimental results, we validate that our approach for simulating the ice skating experience in VR is realistic compared to the real ice skating experiences.

Index Terms—exertion game, ice skating, physics-based simulation, virtual reality

I. INTRODUCTION

In recent years, in order to fill the gap between virtual and reality, advanced simulation approaches are widely studied among human-computer interface (HCI) researchers. Especially, given the emerging technologies in computer vision and computer graphics, modern generations of virtual reality devices have the capability to track the user's head, hands, and controllers with very high accuracy. Such advanced improvements enable the accurate interaction between humans and computers and provide us with the possibility to simulate human-centered activities in immersive virtual environments. For example, users can use VR controllers to simulate the virtual experience for art designing, working in the virtual workplace, collaborating in virtual teams, virtual medical surgery, virtual training, studying in a virtual classroom, and even, exergaming in a virtual world.

Especially, exergaming in VR becomes extremely hot in recent years as people realize that virtual reality technologies open another dimension of entertainment for indoor exercise. Due to the introduction of highly immersive virtual environments with a wide range of varieties and the highly accurate interactions between users and VR exergaming devices, both incredible exercise effects and impressive gameplay experiences are achieved through VR exergames. Therefore, lots of VR exergaming researchers introduce high-level degrees of accurate simulation into VR exergaming. For example, researchers [1]–[5] have proposed virtual table tennis exergame simulators, Doi et al. [6] devised an VR American football simulator with cylindrical screen, Rojas et al. [7] proposed a full-body immersive VR soccer simulator for skill assessment, Bai et al. [8], [9] proposed a simulator for VR Volleyball Games, Tsai et al. [10], [11] proposed a simulator for basketball tactic training via virtual reality, Tsai et al. [12] designed an simulator using digital glove for virtual reality baseball pitch training, Ginja et al. [13] developed an VR simulator for training the para-badminton, Pan et al. [14] develop a small bowling machine based on VR simulation, De et al. [15] develop a billiard game VR simulator using a haptic interface, etc. However, none of above research has got a closer insight into simulating ice skating experience in VR.

Therefore, given this open opportunity for developing a simulator for ice skating in virtual reality, we take into consideration the physics rules for simulating immersive skating experiences according to the user's motion of feet which are tracked with the VR controllers banded on shoes. The contributions of our work include:

- We propose a novel research topic about simulating the skating experience in virtual reality. The full demo of the player's VR skating animation can be accessed by this link: https://youtu.be/Z1Sepm5LSZI.

(a) Player is in a boundary.   (b) VR controllers to VR shoes.   (c) Force analysis on VR shoes.   (d) Ice skating in a virtual scene.
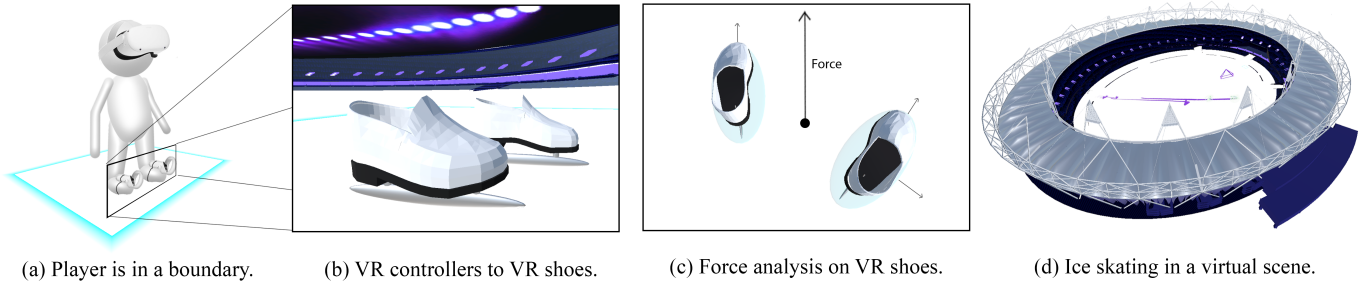
Fig. 2: Overview of our technical approach. (a) shows an abstract illustration of how the scene can be set up in a real-world environment for our approach: the blue square represents a stationary boundary in a real room. When the player is standing in the boundary with the VR controllers stably attached to their shoes using tapes or stickers as illustrated in the black box shown in (a), their shoe positions can be accurately tracked in VR and be mapped into the 3D virtual shoe model as shown in (b). Then given to the systematically composite force analysis proposed in our technical approach as shown in (c), the accelerations will be applied on the virtual camera of the user's headset as specified in the purple pyramid frame in (c). In the end, the player will move virtually in the virtual environment as shown in (d). In this case, the virtual environment is a 3D luxury ice skating rink. The purpose curves shown in (d) are the ice scratches simulated from the interactions between the ice shoe and the ice ground. Transparency of ice scratches decreases as time goes by.

- We propose the method to simulate the user's motion in virtual reality according to physics rules so that to achieve an immersive ice skating experience in the virtual scene.
- We implement the mathematical model of the ice skating simulator that we propose and demonstrate the simulation result to validate our proposed approach.

II. RELATED WORK

Except for those VR simulators for different types of VR exergame and VR sports mentioned in the previous section, there are also some academic research related to ice skating in VR, these works are very closely related to our work. For example, the SENSE ARENA team [16] has proposed a hockey sense training platform designed by innovative hockey leaders for professional players' training in VR. Through this VR app, users can wear ice skating shoes and feel the real experience in VR. However, this interface is location-specific and restricted to a small ice rink pre-setup in a room which requires lots of manual effort for professional scene setup in the real world, which is not convenient for players that only want to try ice skating in VR just for fun at the home. But setting up work for our proposed VR simulator is very easy and only need to attach VR controllers on the shoes simply using stickers or tapes which is easy to buy and also it is easy to achieve personally for most of the players at home.

At the same time, skating treadmills are also possible solutions for simulating ice skating experiences in virtual reality. Nobes et al. [17] conduct a study about comparing skating economy between on-ice and on the skating treadmill. Similarly, Koepp et al. [18] study on comparing VO2max and metabolic variables between treadmill running and treadmill skating. Similar comparison works between ice versus treadmill skating have also been done on physiological responses [19], plantar force distribution patterns [20], EMG activation patterns [21], etc. However, the common features of all treadmill skating programs are the complexity of the scene setup including safety-related considerations. Compared to all of these works, our approach is totally money-free, setup-free, and injury-free. This makes it possible for players to enjoy ice skating experience in VR without spending too much money on buying a skating treadmill which is really expensive.

However, we are not the first team to develop a setup-free and personal VR ice skating simulator. For example, in the SteamVR game store, there is an example game in VR that is simulating the hover skating experience in VR [22]. In this game, players can stand on a virtual skating board in VR which results in a realistic user experience. But the difference between our works is we are focusing on ice skating but that work is about board skating. In the meanwhile, there is another game application developed on Roblox [23] for the ice skating simulator. But unfortunately, this game is not developed on VR platforms also there is no consideration about the physics model to gather input from the players' shoe positions. Rather, their input is merely gathered from the mouse and keyboards. Unlike this work, our approach is not only based on VR interface but also we systematically study the physics behind the interactions between virtual shoes and virtual ice ground. So that compared to this work, our interface can give players more realistic virtual experiences in VR ice skating.

III. OVERVIEW

Figure 2 shows the overview of our technical approach for the ice skating VR simulator. As shown in subfigure (a), a user is standing within a stationary boundary in the real space, for example, a room. Then after attaching the VR controllers to the shoes, the VR controller will be mapped onto the ground in a virtual scene, in this case, is a luxury ice skating rink. During the attaching procedure, it needs to make sure that every controller is stabled on the shoe and correctly aligned to the shoe's forward direction. Then we attach the VR shoes

(a) Common mistake.   (b) Correct gesture.   (c) Friction force $\mathbf{f}_\mu(t)$.   (d) Composite force $\mathbf{f}_c(t)$.
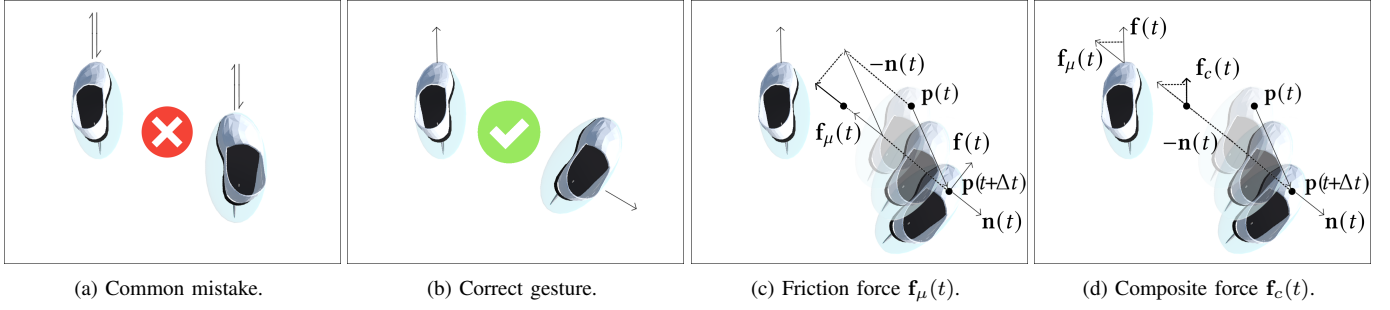
Fig. 3: Mathematical rules for physics-based ice skating simulations. (a) shows a common mistake that cannot make the player move at. In this case, the player is trying to slide their shoes forward and backward along their shoes' forward orientations. According to our daily experience, in this case, it can not move forward as the player is not able to generate any friction force through this motion. Rather, the correct way to push the player forward is moving the shoes as shown in (b). In this way, the friction force $\mathbf{f}_\mu(t)$ generated along the inward normal direction as shown in (c) can be delivered to the player so that a forward impulse will be acted on the player to increase the velocity. In the end, the player will move along the forward orientation of the shoe which is touching the ice floor as shown in (d) according to the composite force $\mathbf{f}_c(t)$.

to the game object of the VR controller which is contained in the Unity SteamVR asset package. In this way, there will be an accurate mapping from the real shoes to the virtual shoes as shown in subfigure (b). Then in the next step, by systematically analyzing composite force analysis proposed in our technical approach given to the accurate motion of the virtual shoes as shown in subfigure (c) and applying such composite force on the virtual camera of the user's headset as specified in the purple pyramid frame in (c), the virtual ice skating experience is simulated in the virtual ice rink as shown in subfigure (d) where the player will move virtually in the virtual environment as shown in (d). In this case, the virtual environment is a 3D luxury ice skating rink and the purple path is the ice shoe scratches simulated from the interactions between the ice shoe and the ice ground. Noted that in order to achieve a more realistic visual effect, the transparency of ice scratches will decrease as time goes by.

IV. TECHNICAL APPROACH

According to the motion of the virtual ice shoes, the virtual ice skating experience can be simulated immersively by applying Newton's Laws of motion. According to our experiences in ice skating, there is one type of common mistake made by beginners is they are trying to walk on the ice. As shown in Figure 3 (a), this is a failure case that the player is not able to move in our proposed VR ice skating simulator. According to the physics rule, when a player is sliding their shoes forward and backward along their shoes' forward directions, there will result in a close-to-zero friction force acting on the shoe. Therefore, no reaction force will be acted on the players to push them moving forward. Rather, if the player moves their shoes along the direction which is perpendicular to their shoes' forward direction, which is called as the outward normal direction, the friction on that shoe will be maximized. Therefore, the correct way to move forward in our ice skating simulator is shown in subfigure (b).

Motion Formulas. During the simulation, we assume that if the player wants to accelerate, there must be one shoe touching and staying on the floor while another shoe touching and sliding on the floor. For simplification, we call the shoe touching and staying on the floor a staying shoe and the shoe touching and sliding on the floor a moving shoe. This assumption makes sense as this is almost the most professional gesture in ice skating, especially for high-speed ice skating. Then, in order to implement such a feature mentioned above in our VR simulator, we calculate the friction force as shown in subfigure (c). Give the displacement (relevant to player's body position) of the moving shoe form time t to time $t + \Delta t$ as $\mathbf{p}(t + \Delta t) - \mathbf{p}(t)$, where Δt is the updating rate of the CPU game engine calculator, or, typically called fixed updating rate in Unity Game Engine. Then we call outward normal direction of the moving shoe at time t as $\mathbf{n}(t)$ and forward direction of the moving shoe at time t is $\mathbf{f}(t)$, then there is $\mathbf{n}(t) = \mathbf{f}(t) \times (0, 1, 0)$ for the right shoe and $\mathbf{n}(t) = -\mathbf{f}(t) \times (0, 1, 0)$ for the left shoe. Then we have the friction force $\mathbf{f}_\mu(t)$ calculated though the projection of the displacement along the inward normal direction $-\mathbf{n}(t)$ according to the Impulse-Momentum Theorem:

$$\int_t^{t+\Delta t} \mathbf{f}_\mu(t) \mathrm{d}t = -\mathbf{n}(t) m \left(\frac{\mathbf{p}(t + \Delta t) - \mathbf{p}(t)}{\Delta t} \cdot \mathbf{n}(t) \right), \quad (1)$$

where m is player's mass and displacement divided by time is the velocity of the moving shoe, this results in an impulse due to the friction force and act on another shoe (staying shoe) which is touching and staying on floor.

As shown in subfigure (d), the last step of the simulation is to calculate the final acceleration of the player due to the composite impulse acting on it. The composite force $\mathbf{f}_c(t)$ is calculated by projecting the friction force $\mathbf{f}_\mu(t)$ from another shoe (moving shoe) along the forward direction of the

current shoe (staying shoe). Then referencing to the Impulse-Momentum Theorem, we can calculate player's updated velocity according to player's updated composite momentum:

$$\mathbf{v}(t + \Delta t) = \mathbf{v}(t) + \frac{1}{m} \int_t^{t+\Delta t} \delta(t)\mathbf{f}(t)\left(\mathbf{f}_\mu(t) \cdot \mathbf{f}(t)\right) \mathrm{d}t, \quad (2)$$

where $\mathbf{v}(t + \Delta)$ is the updated velocity and $\mathbf{v}(t)$ is current velocity. Besides, $\mathbf{f}_\mu(t)$ can be directly replaced by Equation 1, so that it doesn't need to be solved explicitly. In this way, by alternating the staying shoes and the moving shoe, players will keep accelerating themselves using the simulation approach proposed here which results in realistic motions. $\delta(t)$ is a Dirac unit impulse function which denotes the friction force detector.

Force Detection. In order to detect which shoe is the source of the friction force, we propose an approximation approach using mathematical formulas rather than relying on other force sensors that are requiring particular hardware configurations. According to the observation of skaters' motions, every time whenever there is a friction force applied on the shoe is whenever that shoe is touching on the ground. Therefore, in order to detect whether there is any shoe touching on the ground, we use a threshold to specify the elevation of the ice floor y_0. Whenever the position of the shoe $\mathbf{p}(t)$ is above the ice floor, there is no friction force applied; Otherwise, there is. As shown in Figure 4, we represent such friction force detector using a Dirac unit impulse function calculated as: $\delta(t) = 1$, when $\mathbf{p}(t) \cdot (0, 1, 0) \leq y_0$; Otherwise, $\delta(t) = 0$.

V. Experimental Results

We have implemented the proposed ice skating VR simulator using Unity 3D with the 2019 version. We have implemented this VR interactive interface using the Steam VR 2.0 plugin. We conducted the simulation experiments with the hardware configurations containing Intel Core i5 CPU, 32GB DDR4 RAM, and NVIDIA GeForce GTX 1650 4GB GDDR6 Graphics Card. The VR program developed for the ice skating VR simulator is configured on Oculus Quest 2.0 version.

Figure 5 shows the experimental results of simulating the ice skating experience in a virtual ice rink. Each subfigure is a screenshot of a new frame in the animation as time goes by. Purple lines are simulating the scratch of the virtual ice skating shoes. As time goes by, the transparency of the scratches will decrease. The player's camera is rendered with a pyramid frame to specify the player's head position and orientation. In this experiment, a scene camera is set up at a fixed position in the virtual environment so that we can see the player's motion from a location far away from the player. As shown in the result, the player is able to move forward by pushing one shoe backward and staying another shoe on the floor using the correct gesture as we specified. By switching the moving shoe and the staying shoe, the player can keep moving forward.

In order to test the robustness of our simulation approach, we also experiment with a special case in ice skating practice, backward ice skating, which is also called backward crossrolls

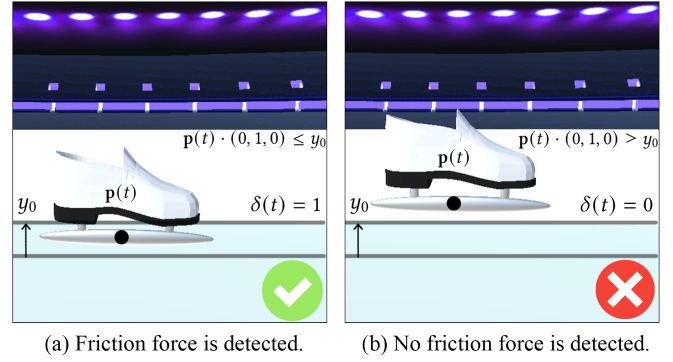(a) Friction force is detected.   (b) No friction force is detected.

Fig. 4: Friction Force Detection.

on ice. As we can see from the results shown in Figure 6, the effect looks real as if the player is really crossrolling on the real ice rink. Different from Figure 5, these figures are captured with the player's first person's view. In this case, the player is trying to draw "S" on the floor and switching the motion of two shoes periodically. Therefore, every time when one shoe is staying on the floor, another shoe is drawing "S" forward, the opposite friction force will push the player backward accordingly. By keep doing so, the player will keep moving backward. At the same time, when the player rotates the staying shoes slightly, the player's moving direction can be changed slightly according to the stating shoe as well. So the in this case, from the last subfigure, we can see a big curve of the player's navigation path. As one advantage of our simulator, players can practice moving backward in ice skating using our simulator and help understand better how the moving backward works during ice skating, it shows the potential of extending our approach for VR ice skating training.

VI. User Study

Procedure. We conducted a user study to test the users' experience in the ice skating VR simulator developed by us. We recruited 15 users, among whom 86.6% are male, 66.7% have learned ice skating before, and 13.3% tried VR games that are about VR ice skating. During the study, we ask users to put on the VR headset and put on the shoes prepared before the study. Those shoes are athletic shoes and are attached with VR controllers through plastic tapes. Then we run our VR simulator and let users try to slide their shoes on the floor within the safe boundary so that they can skate on the ice in the virtual since rink. After users' play the VR simulator for 5 minutes, we stop the trial and prompt users to submit a questionnaire about their virtual ice skating experiences.

Questionnaire. The questions in the questionnaire that are asking about their virtual ice skating experiences include: (1) Do you agree that the VR ice skating experience is realistic compared to the real-world ice skating experience? (2) Do you agree that the ice skating experience in the VR is comfortable? (3) Do you agree that the scene of the VR ice skating rink looks realistic and immersive? (4) Do you agree
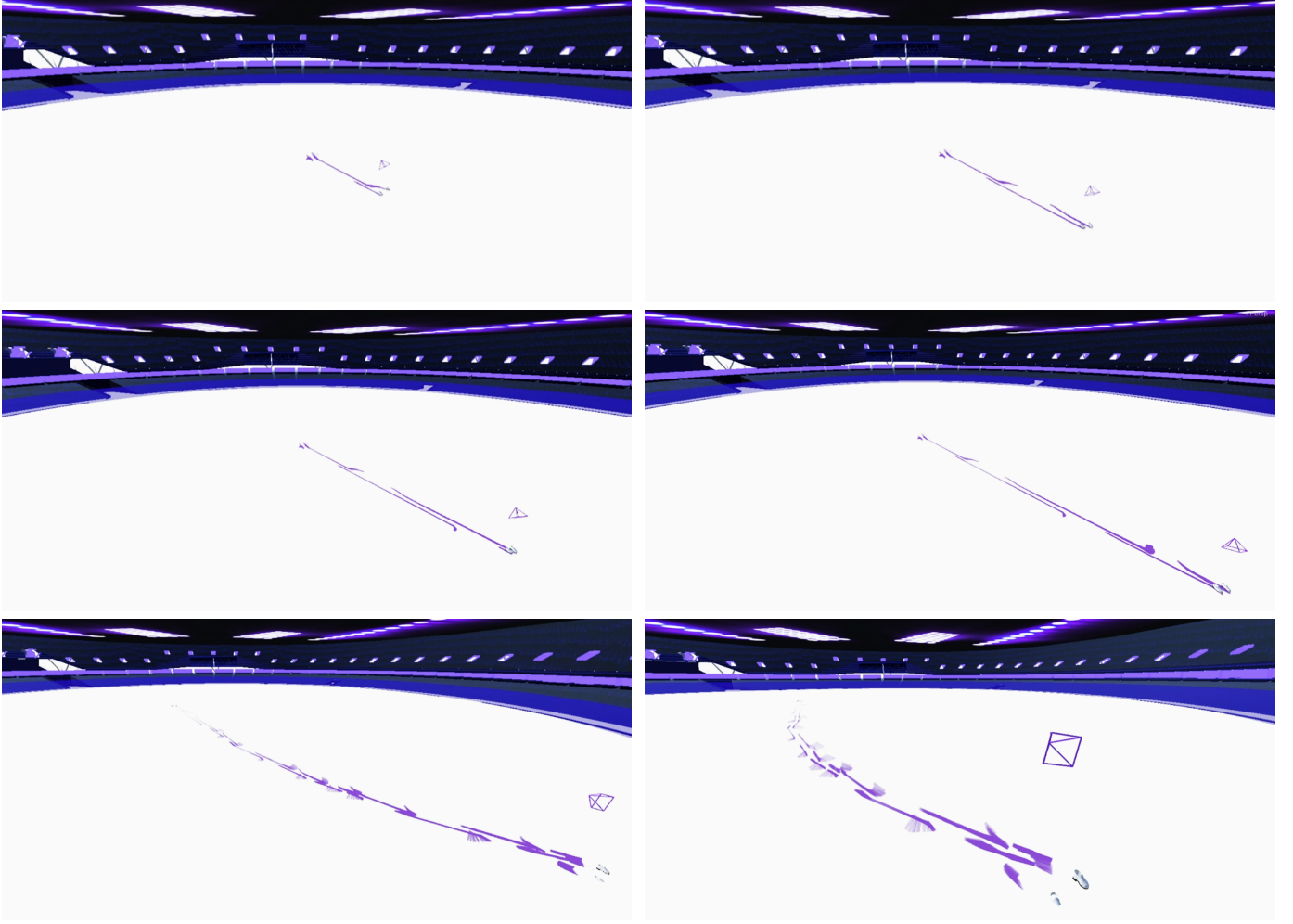
Fig. 5: Experimental results of simulating ice skating experience in a virtual ice rink. Different frames in the animation are rendered in this group of six subfigures according to chronological order. Purple lines plot the scratch of the virtual ice skating shoes built with a white 3D model. The purple pyramid polyline frame specifies the player's head position and orientation.

that the control of the VR ice skating experience is natural and comfortable? (5) Do you agree that the VR ice skating experience is fun? (6) Do you agree that this VR ice skating experience can help learn ice skating in the real world? All these six questions are prompting users to select a number between 1 and 5 where 1 stands for disagreeing and 5 stands for agreeing. At the end of the questionnaire, users are asked to provide some suggestions to improve the VR ice skating experience and make it feel more realistic.

Result. After collecting the answers from the user's feedback in the questionnaire, we got the scores (1-5) for evaluating our proposed VR ice skating simulator. In order to discuss the result more clearly, we abbreviate the questions in the questionnaire mentioned earlier using the short questions representations, they are: (1) Realistic? (2) Comfortable? (3) Immersive? (4) Natural? (5) Fun? (6) Helpful? As shown in Figure 3, we plot those scores using the box plots. Lower scores mean that the user tends to disagree, higher scores

means agree. The statistics of the scores for each question are concluded as below: (1) Realistic? (M=3.8 SD=0.77) (2) Comfortable? (M=4.13, SD= 0.83) (3) Immersive? (M=4.46, SD=0.51) (4) Natural? (M=4.06, SD=0.79) (5) Fun? (M=4.53, SD=0.63) (6) Helpful? (M=4.2, SD=0.77) Therefore, in general, we find users most agree that the scene of the VR ice skating rink looks immersive (M=4.46) and agree that the VR ice skating experience is fun (M=4.53). However, it seems that users least agree that the VR ice skating experience is realistic compared to the real-world ice skating experience (M=3.8). This makes sense as 33.3% of the users have never learned ice skating before, therefore, they are very confused about whether the VR ice skating experience is really similar to the real-world ice skating experience.

Suggestions. From the user's feedback in the questionnaire, we also collected some suggestions from users to improve the VR ice skating experience. We conclude those answers as (1) Adding other virtual characters to the ice rink as having more
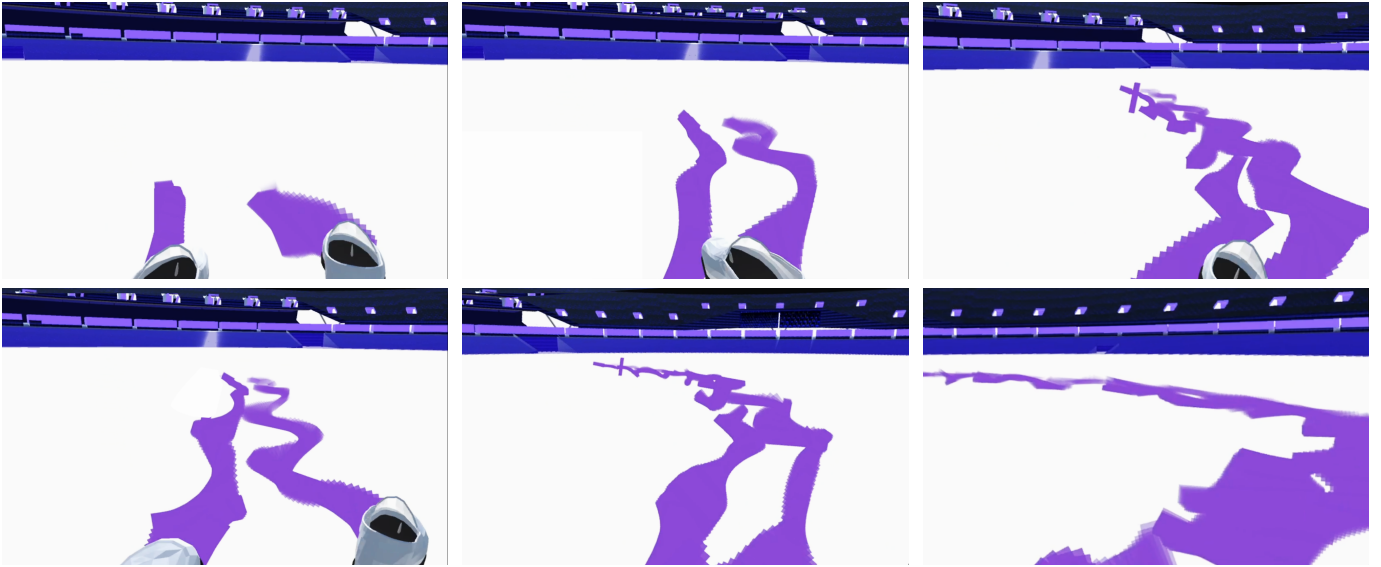
Fig. 6: Simulating virtual ice skating experience in moving backward. Different frames in the animation are captured in this group of six subfigures from the player's first person's point of view. In this experiment, we simulate players' backward ice skating motions by drawing crossing 'S' letters on ice with shoes.

people around would make the experience more immersive, this can also train players not to crash into others in real life when putting other people together. (2) The tracking of the feet sensors while in-game can be an illusion where it makes it seem like the user does not know what direction going in until looking at the stadium around. (3) Create the boundaries in the ice rink so that when players hit them can be bounced off. (4) Adding music that is played in ice skating rings that help people get immersed. (5) Add a virtual body of the player so that when looking down, players can see a body of themselves. (6) Enable users' playing with online competitors can make the game more fun. (7) Offering players the option to enable vibration feedback on the controllers to simulate natural feedback of the ice against the feet can potentially make the experience even more immersive. (8) Adding some simple instructions to start for people who have never been learned ice skating before. For example, adding the instructions on what the actual movement directions do in VR will be useful as they can then imitate the actual ice skating.

VII. CONCLUSION

In this paper, we propose a simple-to-set-up physics analysis-based ice skating simulator via virtual reality. By analyzing the friction forces caused by the motion of the ice skater's feet on the ice, and the composite force acted on the ice skater's body, we simulate the player's motion using physics law. Therefore, through our proposed approach, a user who is standing within a stationary boundary in the real space can move virtually in the virtual environment through an immersive ice skating experience simply by stabling two controllers on the shoes. As we can see from the experimental results, the simulation is realistic according to our daily life experience in ice skating.
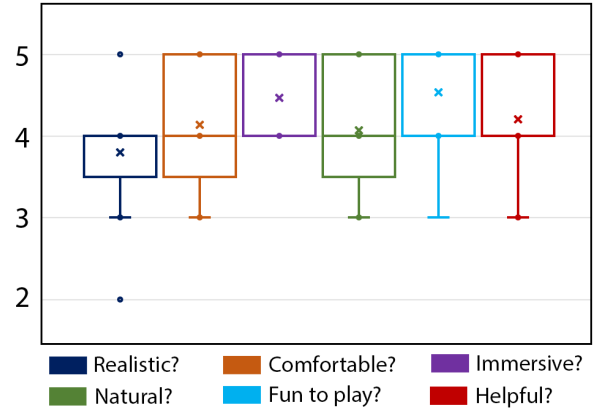

Fig. 7: User Study Result.

As future work, we will consider conducting a larger-scale user study to test our interface among different users including those who have ice skating skills and those who don't have. By statistically comparing the difference of users' feelings about the virtual ice skating experiences and the real experiences, we will give a more concrete statistical analysis of the validity of our proposed approach. We believe that if our work can show no significant difference between virtual experience and real experience of ice skating, we will claim that our approach can provide a definitely immersive ice skating simulator. We also believe that our work can shed light on interesting future research such as extending our simulator with more functionalities for ice skating entertainment and training through VR platforms. So that in the future, ice skating teaching and training can be easier and safer by familiarizing the players with a virtual ice skating simulator proposed by us.

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