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Design and Modeling of an Ungrounded Haptic Gun that Simulates Recoil Using Asymmetric Force

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Abstract— **The lack of perception of recoil limits the immersion of virtual reality first-person shooting games in which users hold a gun in their hand. This paper presents the design and modeling of an ungrounded haptic gun that could simulate the recoil using asymmetric force, which is rendered by a voice coil actuator and produces directional force perception to users rather than vibration feedback. A magnet is driven by the electromagnetic force and moves forward inside the gun like a bullet does and the corresponding reaction force is perceived by users as a recoil. A spring is used to reset the position of the magnet, and a friction damper is used to prevent a collision when the magnet returns to its initial position that breaks the rendering of asymmetric force. We analyzed the dynamic model of the recoil. A user study was conducted to comparatively evaluate the perception of shooting recoil as well as the subjective preference of the proposed recoil rendering method. The results show that our proposed haptic gun with asymmetric force rendering could induce clear perception of shooting recoil, and could provide a more favored virtual shooting experience.**

I. INTRODUCTION

A considerable amount of applications of haptic feedback in virtual reality has been presented which shows the enormous potential [1]. Tedjokusumo et al. [2] shows that first-person shooting games in virtual reality are more favorable because of the immersive environment and a controller aiming for the target. However, the lack of realistic haptic rendering method of shooting restricts the immersion of first-person shooting games in virtual reality. Air guns can provide recoil feedback using an air pump with the disadvantages of unsustainable energy supply compared with electric power. Vibration is widely provided in virtual reality first-person shooting games [3](e.g. Oculus Rift and HTC Vive), but is less interesting due to the simple haptic feedback. Customized haptic shooting controllers have been developed(e.g. StrikerVR [4] and [5]). Recoil, a directional force feedback rather than vibration, is an essential part in haptic perception of shooting. We are engaged in developing a haptic gun to provide directional force feedback that simulates recoil, which does not shoot any objects out of the gun. On the basis of ground points, force feedback device can be divided into three types: grounded, body-grounded and ungrounded.

Grounded force feedback devices always have a base fixed to the point of the ground and are able to accurately provide a wide range of force feedback through a motor or a specific mechanism but restrict the movement of hands. The small workspace always limited their applications. Wei et al. [6] developed a firearm training system to simulate the recoil and trigger pull weight of shooting based on Phantom Premium.

Body-grounded force feedback devices need ground points on the body [7], [8]. Tsai et al. [9] proposed an arm-grounded device, ElasticVR, to present a continuously changed resistive force and an instant recoil upon the hand using an elastic band which is appropriate for various haptic applications.

Ungrounded force feedback haptic devices are usually easy to hold and laid down and are more appropriate for virtual reality, allowing free movement around the real world. Zenner et al. proposed a weight-shifting haptic controller, Shifty, providing an ungrounded force to enhance the perception of virtual objects in kinds of shape and weights. An ungrounded haptic gun allows users to experience the immersion of first person shooting games in virtual reality. Shooting with a real gun, bullets move tens of centimeters in the barrel and leave with a recoil to the user. However, it is difficult to design a controller that launches real objects to simulate recoil in virtual reality games. According to the non-linear sensory properties of humans, when the asymmetric force which includes a strong and sharp stimulus and a weak and flat stimulus is presented in proper order, the strong stimulus is perceived while the weak stimulus is neglected [10]. These studies are devoted to providing directional force feedback in an unground device using asymmetric force. Amemiya et al. [11] proposed a one degree of freedom (DoF) ungrounded device based on the slider-crank mechanism providing a 3Hz virtual force feedback during the period with rapid acceleration. Culbertson et al. [12] created a pulling sensation driving the actuator in one direction with maximum current, and slowly ramping down current for the return stroke. Pinching the actuator with the thumb, index finger, and middle finger, Culbertson et al. [12] and Tanabe et al. [13] considered the asymmetric vibration as a mass-spring-damper system introducing the finger dynamic character to the model. Shima et al. [14] developed a handheld device

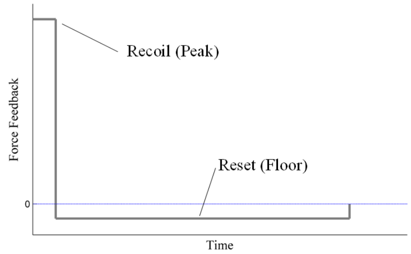

Fig. 1. Schematic diagram of force feedback induced by asymmetric force.

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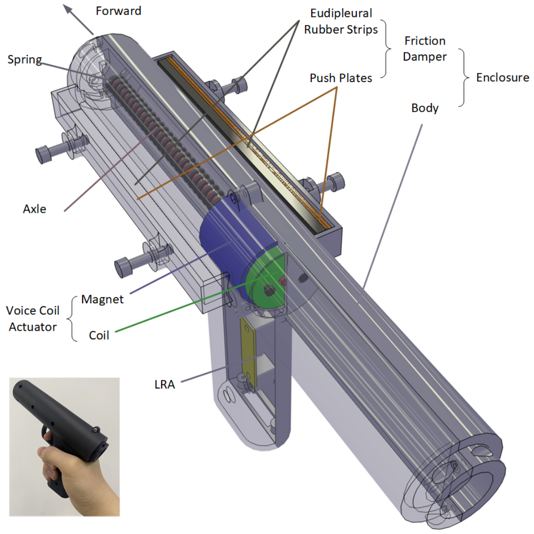


Fig. 2. The inner structure of the haptic gun. The upper-right figure shows the inner structure of the haptic gun used in user studies, and it was purposely made in a nearly symmetrical shape to balance the front and rear weight of the gun to avoid pre-identification of direction in user study that researches the perceived direction of shooting recoil without force feedback. The bottom-left figure shows a demo haptic gun used for VR games which shares the same inner structure as the one used in user studies, while has a shape more resemblant to that of a real gun.

including a voice coil actuator and a spring-mass system which collides with an acrylic unit to present force feedback.

This research is dedicated to developing an ungrounded haptic gun to provide directional force feedback that simulates recoil using asymmetric force rather than simple powerful vibration. Fig. 1 shows an example of force feedback induced by asymmetric force in ungrounded device without external forces. According to the law of momentum conservation in a closed system, the total momentum is constant, which means the integral of force feedback over the period in Fig. 1 equals to zero. Our proposed ungrounded haptic gun aims to provide a sharp recoil (positive force in figure) followed with a gentle reset (negative force in figure). Unlike [14], a damper is used to decelerate the magnet to avoid a later collision in order to provide a clear perception of directional recoil for one time. And a user study was conducted to evaluate the perceived direction in the condition that the subjects gripped the haptic gun with the whole hand rather than with two or three fingers as in [14] and [12] respectively.

II. HAPTIC RENDERING OF RECOIL

This section presents an implementation and dynamic model of our proposed ungrounded haptic gun. Modeling the system is an important part of the mechanism behind force feedback induced by asymmetric force.

A. *Design and Implementation of Haptic Gun*

The haptic gun is designed including a voice coil actuator (a magnet and coil), a vibration actuator (linear resonance actuator, LRA), a spring, an axle and an enclosure. The enclosure contains a friction damper and body, as shown in Fig. 2. The coil of voice coil actuator is screwed to the enclosure. The magnet, coil and spring are linked with an axle. The friction damper is designed to provide controllable sliding friction force during the movement of magnet, which is considered as a constant. The weight of the haptic gun is about 340.2g.

The haptic rendering of shot is divided into three stages: *recoil stage*, *bullet firing stage* and *resetting stage*, as shown in Fig. 3. During these 3 stages, the force feedbacks provided successively are *asymmetric* because the electromagnetic force is strong and steep but the elastic force and friction provided by spring and damper are weak and flat. In recoil stage, the reaction force provided by voice coil actuator simulates the recoil that is caused by the explosion of gunpowder. In bullet firing stage, magnet moving forward like a bullet. In resetting stage, like a self-loading system of gun, the magnet moves back so it is ready for the next shot. The shooting direction is considered as the direction opposite to recoil, which means when shooting forward, people will be presented with a recoil. For further analysis of the three stages of haptic gun, we present a dynamic model of our proposed haptic gun.

B. *Dynamic Model of Haptic Gun*

Our proposed ungrounded haptic gun is simplified to a mass, a spring and a friction damper. The elasticity of the human hand and wrist is ignored. A dynamitic model of the haptic gun is established, as shown in Fig. 4, where m is the mass of the magnet, x is the displacement of the magnet, F_m is the electromagnetic force applied by the coil to the magnet, k is the spring constant of spring, F_f is the friction applied to the magnet. According to the action-reaction law, when shooting forward, the force applied to the hand F is equal to the force applied to magnet:

$$F = m\frac{d^2x}{dt^2} = F_m - k(x - x_0) - F_f \tag{1}$$

where x_0 is the pre-tensioned length of spring. The movement and deformation of hand is ignored. Electromagnetic force F_m is calculated from the applied current as:

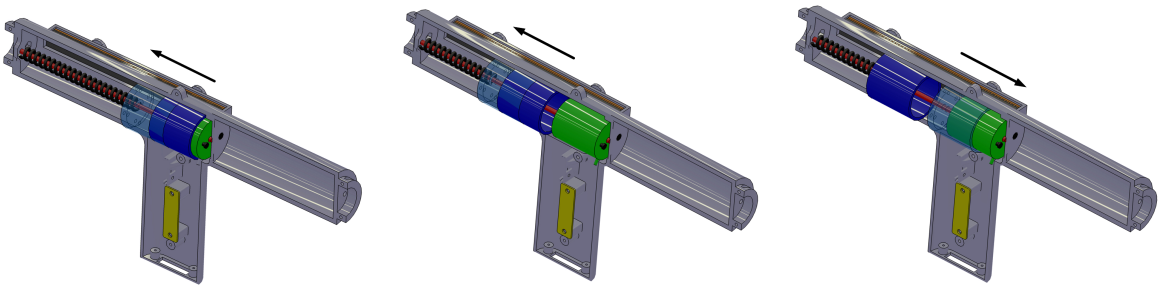
$$F_m = \begin{cases} \frac{x_c - x}{x_c} k_m i & x \leq x_c \\ 0 & x > x_c \end{cases} \tag{2}$$

where i is the applied current, x_c is the maximal displacement of magnet being controlled by coil, k_m is the actuator drive factor, and has the unit N/A [15]. The equivalent circuit model of voice coil actuator is

$$u = k_e\frac{dx}{dt} + iR + L\frac{di}{dt} \tag{3}$$

where u is the voltage of driving signal, R, L, and k_e are the equivalent resistance, equivalent inductance and back electromotive force constant of voice coil actuator respectively.

The parameters of voice coil actuator (VCAR0044-0075-00A, SUPT Motion) are: m=0.114kg, k_e=7.6V·s/m, R=2.9Ω, L=0.72mH, k_m=7.6N/A, x=0.0075m. The average values of other parameters are measured: k=14.0N/m, x_0=0.10m and F_f= 0.21N without friction damper using ATI Nano17 force



(a) (b) (c)

Fig. 3. Three stages of a shot using the haptic gun (a) Recoil stage. An electromagnetic force is generated by the voice coil actuator pushing the magnet moving forward from initial position to apply a reaction force to hand which grips the haptic gun (b) Bullet firing stage. The magnet moves forward with resistance from the spring and damper. (c) Resetting stage. The compressed spring pushes the magnet moving backward to the initial position and waiting for the next shot. Arrows indicate the moving direction of magnets. The opaque dark blue denotes the position of magnets at the beginning of stage and the transparent light blue denotes the position of magnets at the end of stage. The arrows show the direction of the moving magnet.

sensor and step motor. The actuator is driven by pulse signal, with 16V voltage, 10Hz frequency and 10% duty cycle.

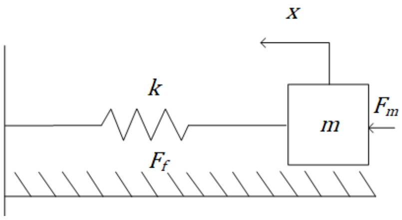


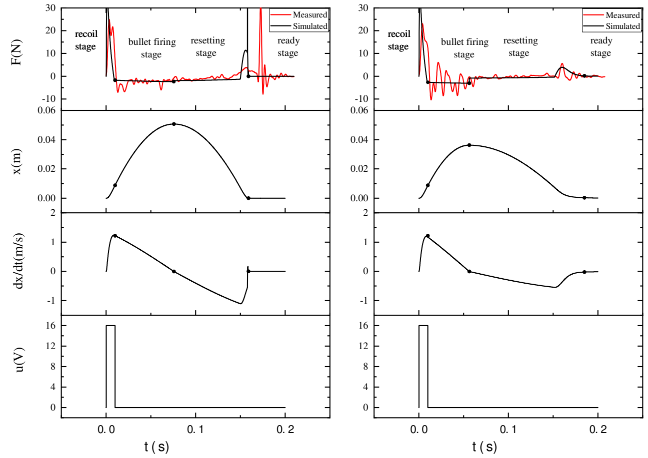
Fig. 4. Dynamic model of haptic weapon.

Fig. 5(a) shows the trends of simulated and measured force feedback F, displacement x, velocity dx/dt and input signal u over time (F_f =0.21N). To make it easier to understand and match Fig. 1, the force feedback that applies to the hand in the same direction as recoil is positive. A repulsive force rather than attractive force between magnet and coil (screwed to the enclosure) of voice coil actuator is generated by the input signal.

According to Fig. 3 and Fig. 5, we define the three stages of our proposed gun: recoil stage, bullet firing stage and resetting stage. We consider the stage when F_m firstly rises from 0 and then drops to 0 as recoil stage. After recoil stage, the magnet moves forward until dx/dt=0, which is defined as bullet firing stage. The stage of backward movement of magnet is defined as resetting stage until the magnet stops moving and is ready for the next shot.

The velocity dx/dt in Fig. 5(a) shows a problem: When the magnet approaches to the initial position ($x \to 0_+$) in resetting stage, the rest of velocity dx/dt at that time is not equal to zero which will induce a collision between the moving backward magnet and enclosure. In resetting stage, we assumed that when the magnet collides with the enclosure($x \to 0_+$) all the kinetic energy of magnet E_k is converted into deformation energy of enclosure E_p. The instantaneous acceleration is estimated.

$$E_p = \frac{1}{2}m\frac{d^2x}{dt^2}x_k = E_k = \frac{1}{2}m(\frac{dx}{dt})^2 \tag{4}$$



(a) (b)

Fig. 5. Comparison of simulated force feedback F for different friction. (a) F_f=0.21N (b) F_f=1.12N. Three stages are separated by solid circles with the ready stage in the end where the magnet stops moving and waits for the next shooting. In bullet firing stage, the force feedback provided by the spring and damper increases with the duration t and maximum displacement x decreased (b) compared with (a). In resetting stage, the magnet is in collision with the enclosure at higher speed (a) or stops slowly (b) which is shown in F as a pulse force.

where x_k is the deformation of enclosure due to the collision. We assume that x_k is submillimeter. As shown in Fig. 5(a) an excess pulse force feedback is provided which is inconsistent with our purpose: simulating the recoil using asymmetric force in Fig. 1. We recorded a slow motion 240 FPS (Frames Per Second) video of the moving magnet under the condition of Fig. 5(a). The haptic gun is placed on the table without any other obstruction. The video shows that the collision appears indeed and causes more than a dozen millimeters' movement for the enclosure. We consider that the second pulse force feedback F in Fig. 5(a) could distort the perceived direction of shooting recoil. To render recoil using asymmetric force, we should have weakened the absolute value of F in bullet firing stage and resetting stage. But to avoid the collision, a friction damper is developed to generate extra friction to reduce the rest of velocity dx/dt in both bullet firing stage and resetting stage. The extra friction F_{f_r} is provided by squeezing the magnet with two eudipleural rubber strips. The deformation of rubber is controlled by two push plates in the enclosure, as shown in Fig. 2. The movement of push plates depends on two pairs of screws and nuts. F_f applied to the magnet is

$$F_f = F_{f_0} + F_{f_r} = F_{f_0} + 2\mu\varepsilon\Delta V \tag{5}$$

where ΔV and ε is the deformation of one rubber strip and the elastic modulus respectively, F_{f0} is the measured average friction when the deformation ΔV=0 , μ is the dynamic friction coefficient. The increased friction F_f is 1.12N (average value we measured). Fig. 5(b) displays the trend of simulated and measured force feedback F, displacement x, velocity dx/dt and input signal u over time (F_f =1.12N). The second pulse force feedback F is decreased sharply with the increased friction on the assumption that the deformation of enclosure x_k is submillimeter. Fig. 5(b) matches the force feedback in Fig. 1 in trend. The friction damper decreases the absolute value of F in resetting stage, while increases it in recoil stage. A custom-made haptic gun with internal damper is developed as a demonstration, but is not used in the user study, as shown in Fig. 2.

We removed half of the enclosure and attached the BK, 4528-B accelerator to the magnet measuring the acceleration to validate our simulation. The other half of enclosure is fixed on the table. The F_f measures about 1.15N. The force data was calculated by acceleration data based on Newton's second law where the mass m is 0.114kg. We consider the profiles of simulated and measured force match and the haptic gun can provide asymmetric force to simulate recoil. The force feedback in Fig. 5(b) fluctuates during the bullet firing stage due to the unconstant friction force caused by both rough surface of rubber and nonuniformity of rubber deformation.

So far, the asymmetric force is induced simulating the recoil, firing bullet and resetting. In recoil stage, a backward pulse force is generated which is a reaction of electromagnetic force like the explosion of gunpowder rather than an impact of collision in [14]. In bullet firing stage and resetting stage the asymmetric force is respectively enhanced and decreased by the friction damper which eliminates the collision between magnet and enclosure.

III. USER STUDY

In this section, we describe two user experiments conducted to assess the perceived direction of shooting recoil and preference of haptic gun rendered by asymmetric force and vibration.

System: Three rendering methods are used in the experiments: *Vibration, Asymmetric Force I* (without damper, F_f=0.21N) and *Asymmetric Force II* (with damper, F_f=1.12N). The experimental apparatus was shown in Fig. 6. A voice coil actuator driver PAC-483A with a +24V DC power supply is used to generate the pulse signal. A Linear Resonant Actuator (LRA, ALPS) is utilized to provide vibration feedback for shooting as a reference. Waveform Library Effects ID No.1 of Drv2605 (Texas Instruments), LRA Driver is chosen. The micro controller unit(MCU) is STMF446. The acceleration of LRA is measured as we attached the accelerator used in Section II to the LRA. The waveform of acceleration is similar to several decaying sinusoidal waves with 1000m/s^2 peak value. The RMS(root mean square) of vibration is calculated: 257.54m/s^2. The duration of vibration is about 0.024s.

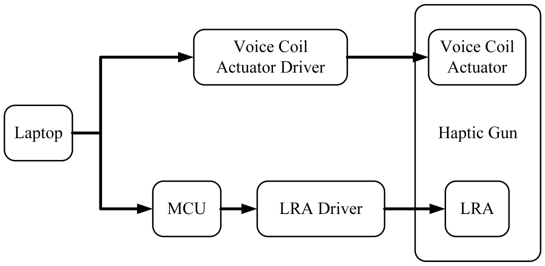


Fig. 6. Functional diagram of experimental system.

Participants: Fourteen right-handed participants whose ages ranged from 21 to 29 years (7 males and 7 females) were invited to the two experiments. Audiovisual information was suppressed by an eye mask and a noise-canceling headphone that output white noise. All participants had never seen the appearance and internal structure of the haptic gun, and gripped the haptic gun with their right hands. The experimental procedure was approved by the ethical committee of Jilin University. Fig. 7 shows an overview of the experimental environment.

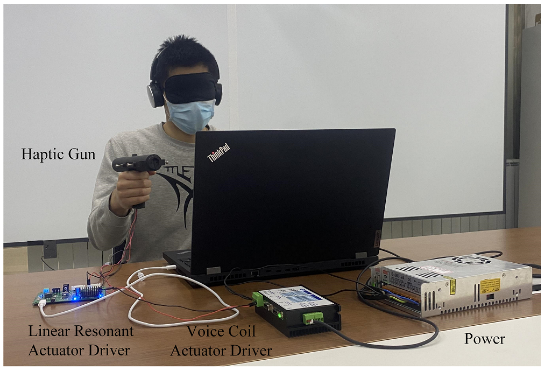


Fig. 7. Illustration of the formal experiment.

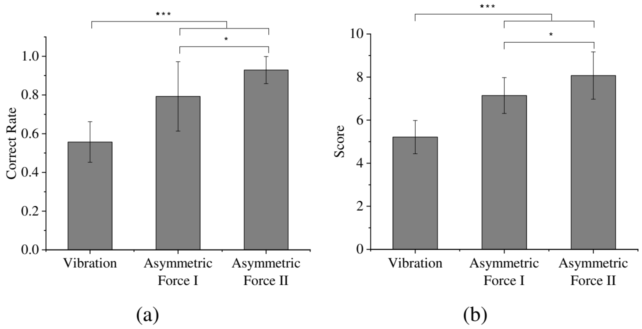
A. Experiment 1: Direction Recognition of Shot

A subjective experiment was carried out to comparatively assess the perceived direction of shooting recoil rendered by Vibration and our Asymmetric Force I and II. The shooting direction is considered as the direction opposite to recoil and was changed by the instructor manually. Vibration is a rendering method to show a contrast with Asymmetric Force I and II in the perceived direction of shooting and does not provide any directional force feedback. In this experiment, weights are used to keep the weight of haptic gun balanced to avoid pre-identification of shooting direction.

1) Method: Each participant sat in a chair in front of a desk while holding the haptic gun in right hand in a random shooting direction. The haptic gun was taken out from hand of the subject, set for the next shooting direction and given back to the subject by the instructor between each trial. After gripping it firmly, participants were presented with the haptic feedback. The experiment consisted of 3 sessions corresponded to three rendering methods randomly. Each session with one rendering method (Vibration, Asymmetric Force I or Asymmetric Force II) had 20 trials (4 sets × 5 repetitions)in which there are 10 trails with forward shooting direction and 10 trails with backward shooting direction, and the order is random. On each trial, participants indicated the shooting direction in terms of 'forward' or 'backward' using two alternative forced choice (2AFC). To address the fatigue of participants, they were given a 20-second break and a 5-minute break between every set and session respectively. The entire experiment took around 30 minutes on average. We performed one-way-ANOVA on forward correct rate using three rendering methods. Tukey's HSD test was conducted for post-hoc multiple comparisons. A Binomial Test was performed on the correct rate using vibration.

2) Results: The means of correct rate for detecting the shooting direction while shooting forward are plotted with their standard deviation in Fig. 8(a). The correct rate for each participant is calculated by $cor/10$, where cor denotes the times that the participant gave a correct answer and 10 is the number of trials. Only shooting forward is considered. The means of correct rate (14 participants) for Vibration, Asymmetric Force I and Asymmetric Force II are 55.7%, 79.3% and 92.9%, respectively.

Binomial Test (50%-50%) on the mean of correct rate and error rate of Vibration for shooting forward and backward was conducted. The results of Binomial Test showed that we cannot reject that the user's judgment on the shooting direction with Vibration rendering conforms to the 50%-50% binomial distribution (shooting forward and backward are p=0.205, p=0.673 respectively). Thus, we considered that the pre-identification that we worried about did not appear, which means the participants could not distinguish the shooting direction without recoil.



(a) (b)

Fig. 8. (a) Mean and standard deviation of correct rate of detecting the shooting direction(14 participants). (b) Mean and standard deviation of subjective preference for haptic feedback of shooting recoil(14 participants). (*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$)

The results of Tukey's HSD test showed that rendering method significantly affected correct rate ($F(2,26)$=28.45, $p<0.001$). The results of post-hoc Tukey HSD multiple comparison tests showed: The correct rate of Asymmetric Force was significantly higher than Vibration (both $p<0.001$). The correct rate of Asymmetric Force II was significantly higher than Asymmetric Force I ($p<0.05$). Our proposed haptic gun can provide a directional force feedback to simulate the recoil of shooting.

Some participants indicated that it is difficult to distinguish the direction of recoil rendered by Asymmetric Force I during Experiment 1 or after the entire experiment. It shows that the collision in the resetting stage may distort the perceived shooting direction.

"I can hardly recognize the shooting direction because I think I was presented with the force feedback twice successively sometimes in the same direction but sometimes not."(3 people, 21.4%).

B. Experiment 2: Subjective Preference of Haptic Gun

A subjective evaluation experiment was conducted to assess the preference of haptic gun rendered by Vibration and Asymmetric Force. Vibration is a rendering method to show a contrast with Asymmetric Force.

1) Method: Each participant sat in a chair in front of a desk while holding the haptic gun shooting forward in right hand. In each trial, participants were presented with one type of haptic feedback until giving a "next" signal. Three trials randomly corresponded to three rendering methods. After three trials, participants rated three types of haptic stimulus by answering the question using a 0 to 10 continuous scale:

How much do you like such haptic feedback for simulating shooting recoil in a first-person shooting game in virtual reality?

The 0 and 10 scores were defined as follows: 0: dislike very much and 10: like very much. A descriptive evaluation of three rendering methods should also be given based on the score. In order to obtain more comprehensive subjective evaluation, participants did not receive guidance from any aspects of the descriptive evaluation content. The entire experiment took around 8 minutes on average. The one-way-ANOVA was also performed on scores of preferences using three rendering methods. If there was a significant effect, Tukey's HSD test was conducted for post-hoc multiple comparisons.

2) Results: The mean of scores (14 participants) for three shooting rendering methods are plotted with their standard deviation in Fig. 8. The scores were significantly affected by rendering method: ($F(2,26)$= 33.810, $p<0.001$).

We conducted post-hoc Tukey HSD multiple comparison tests and the results showed: Asymmetric Force II with the highest score had a significant difference from Asymmetric Force I ($p<0.05$) and Vibration ($p<0.001$). Asymmetric Force I and Vibration had significant differences ($p<0.001$).

The descriptive evaluations given by users were analyzed. 100% of the participants gave lower scores for Vibration because

"It feels like a toy for children." (9 people, 64.3%)

"It does not like shooting with a gun." (5 people, 33.7%)
It indicates that the vibration is less favorable for rendering shooting. Some participants showed that they could not regard the vibration as a simulation of shooting without the experimental question. The main reasons for thinking that Asymmetric Force II is better are

"I can feel the recoil and the bullet firing is more obvious." (6 people, 42.9%)

"Shooting becomes more stable." (4 people, 35.7%)
It is worth noting that 6 people (42.9%) expressed that they felt the bullet firing using haptic gun rendered by Asymmetric force II. We consider that the increased force feedback F promote the subjective perception of moving magnet in bullet firing stage. The depleted velocity makes shooting stable. The reasons that the Asymmetric Force II is considered bad include

"It feels that the bullet is stuck." (1 person, 7.1%)

"It feels like shooting with a silencer." (1 person, 7.1%)
It shows that the friction damper may cause the perception that the bullet is stuck while shooting. The appropriate damper is a crucial factor in the subjective shooting experience induced by asymmetric force. Some participants could not distinguish between the latter two rendering methods and gave the same score (2 people, 14.3%).

C. Discussion

Our proposed rendering method of shot using Asymmetric Force I has good perception of recoil (mean of correct rate 79.3%), and the Asymmetric Force II rendering method significantly improves the direction sense of shooting (mean of correct rate 92.9%). Therefore, it is effective that asymmetric force simulates the recoil of shooting, a directional force feedback. In addition, our friction damper which depletes the velocity dx/dt of moving magnet in bullet firing stage and resetting stage to avoid the collision between magnet and enclosure influences the perceived shooting direction. The asymmetric force may also be used to render other impact or recoil like ballgame, whacking with a hammer, and being shot with a smaller actuator embedded in the controller or vest in virtual reality.

The maximum shooting frequency of multiple shots is about 5Hz for our implementation. The shooting frequency is capped by the friction coefficient of the damper according to the dynamic model.

In future work, a damper with anisotropic friction property that can provide damping during resetting stage but not during the bullet firing stage could be considered. The influence of user's hand should be taken into account to create a more precise model. The critical conditions of perceived directional force induced by asymmetric force are also worth studying.

IV. CONCLUSION

This paper proposes an ungrounded haptic gun rendered by asymmetric force. A dynamic model was also established dividing the process of shooting into three stages: recoil stage, bullet firing stage and resetting stage. A voice coil actuator is used to present the asymmetric force which is perceived as a directional force, recoil. A modified rendering method is proposed using a friction dumper. In order to evaluate the proposed rendering method, two user studies were conducted. Experiment 1 evaluates the subjective direction of recoil for our haptic gun. Results show that the proposed haptic rendering method has strong perception of shooting direction (means of correct rate are 79.3% and 92.9% (with damper), respectively). Experiment 2 evaluates the subjective preference of the proposed rendering method. Results show that asymmetric force has a significant improvement compared with vibration.

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