석 사 학 위 논 문
Master's Thesis

힘 피드백을 통한 물리적 상호작용 구현이 되는 손목 착용형 햅틱 컨트롤러 연구

Enabling physical interaction through the wrist-mounted haptic controller with force feedback

2023

조 민 재 (趙 敏 材 Jo, Minjae)

한 국 과 학 기 술 원

Korea Advanced Institute of Science and Technology

석 사 학 위 논 문

힘 피드백을 통한 물리적 상호작용 구현이 되는 손목 착용형 햅틱 컨트롤러 연구

2023

조 민 재

한 국 과 학 기 술 원

문화기술대학원

힘 피드백을 통한 물리적 상호작용 구현이 되는 손목 착용형 햅틱 컨트롤러 연구

조 민 재

위 논문은 한국과학기술원 석사학위논문으로
학위논문 심사위원회의 심사를 통과하였음

2022년 12월 15일

심사위원장 윤 상 호 (인)

심 사 위 원 우 운 택 (인)

심 사 위 원 이 정 미 (인)

Enabling physical interaction through the wrist-mounted haptic controller with force feedback

Minjae Jo

Advisor: Sang Ho Yoon

A dissertation submitted to the faculty of
Korea Advanced Institute of Science and Technology in
partial fulfillment of the requirements for the degree of
in Culture Technology

Daejeon, Korea
December 15, 2022

Approved by

Sang Ho Yoon
Professor of Graduate School of Culture Technology

The study was conducted in accordance with Code of Research Ethics[1].

[1] Declaration of Ethical Conduct in Research: I, as a graduate student of Korea Advanced Institute of Science and Technology, hereby declare that I have not committed any act that may damage the credibility of my research. This includes, but is not limited to, falsification, thesis written by someone else, distortion of research findings, and plagiarism. I confirm that my thesis contains honest conclusions based on my own careful research under the guidance of my advisor.

MGCT 조민재. 힘 피드백을 통한 물리적 상호작용 구현이 되는 손목 착용형 햅틱 컨트롤러 연구. 문화기술대학원 . 2023년. 22+iii 쪽. 지도교수: 윤상호. (영문 논문)
Minjae Jo. Enabling physical interaction through the wrist-mounted haptic controller with force feedback. Graduate School of Culture Technology . 2023. 22+iii pages. Advisor: Sang Ho Yoon. (Text in English)

초 록

가상 현실에서 다양한 사용자 경험이 가능해지면서 보다 효과적이고 정밀한 촉각 피드백의 필요성이 대두되고 있다. 따라서, 본 논문에서는 가상 현실 안에서 발생하는 다양한 물리적 상호작용에 대해 직접적으로 피드백이 가능한 손목 착용형 햅틱 컨트롤러를 제안하고자 한다. 본 연구의 컨트롤러는 가상 물체나 환경의 물리적 특성을 구현하기 위하여 모터 시스템에 기반하여 힘 피드백을 제공하고, 힘 측정 센서를 적용하여 사용자의 손바닥 쪽에 가해지는 힘을 직접 측정하고 이를 통하여 제어기를 구성한다. 본 연구에서는 기존 모터 시스템 장치의 무겁고 약한 내구성의 한계를 최소화하기 위한 디자인을 적용함과 동시에 넓은 활동 범위를 제공하기 위하여 단일 링크 시스템만을 활용한 컨트롤러 디자인을 제시하였다.

핵 심 낱 말 햅틱 피드백, 웨어러블 기기, 햅틱 렌더링

Abstract

As various user experiences are possible in virtual reality (VR), the need for more effective and precise haptic feedback is emerging. Therefore, this thesis proposes a wrist-mounted haptic controller that can directly provide feedback on various physical interactions occurring within VR. The controller in this study provides force feedback based on a motor system to realize the physical characteristics of a virtual object or environment and applies a Force Sensing Register (FSR) to directly measure the force applied to the user's palm. In this study, a controller design using a single link system was explored to provide a wide range of activities while applying a design to minimize the limitation of heavy and weak durability of the existing motor system device.

Keywords Haptic Feedback, Wearable Devices, Haptic Rendering

Contents

List of Tables

List of Figures

Chapter 1. Introduction

The recent VR technologies make the user experience more realistic. Enhanced display and sound technology provide a more immersive experience visually and audibly in VR spaces. At the same time, novel controller technology works as output equipment as well as an input one, delivering a better haptic experience [1]. Recently, commercial VR devices [2] have a high usage and penetration rate, so general users have begun to experience a more immersive experience visually and audibly through VR head-mounted displays (HMDs). VR provides a realistic experience incorporating many types of sensory feedback [3]. Visual feedback is often given through HMDs which are recently being commercialized by a number of companies. However, few commercial VR products support haptic feedback, which is a key factor in improving the level of immersion and presence of VR experience [4]. This is mainly because existing haptic techniques almost exclusively rely on external mechanical devices which are generally expensive and complex [5, 6, 7].

Nevertheless, haptic VR controllers are essential devices to provide immersive virtual content. They have various shapes and functions, from the form of a general handheld controller [8] to the form of a haptic glove [9, 10]. Researchers have been introducing haptic controllers to implement various hand interactions, such as rendering textures [11], shapes [12], grasp [13], and squeeze [14]. Many VR controllers use vibration to remind the user that they have touched a virtual object when they interact with a virtual object [15]. It is difficult to rely on the vibration of the handle alone to provide users with a physical feedback perception. Therefore, in addition to vibration actuators mainly used in commercial controllers, haptic systems that can convey various haptic experiences by providing force feedback directly are also being studied [16]. Some researchers have proposed a haptic system that uses wire systems to distinguish the shape and size of virtual objects [17]. Other researchers suggest a handheld device to form the feeling and direction of impact force in VR situations using an air injection system [18]. One study suggests a handheld device that can reproduce rendering the thickness and slipping of a virtual object pinched between two fingers using a mechanism with rotational disks. [19]. Another study renders haptic shapes and enables users to touch, grasp, and interact with virtual and real objects with a controlling extender system [20]. However, there is a limitation in that it is inevitably an unnatural and bulky structure in order to be able to be applied in the presented specific situation.

There are several studies that apply a haptic system for precise force control with a simple structure for a wide range of applications. One study proposed a handheld controller in the shape of a wheel that rotates the contact for rendering fingertip haptic feedback when interacting with virtual surfaces [11]. Another study proposed a wearable device that combines a servo motor and brake-based locking slider system to simulate the grasping of rigid objects in a VR interface [21]. For providing ungrounded kinesthetic haptic feedback, a controller design with two double-gimbal control moment gyroscopes system was proposed [22]. They were lightweight and easy to use due to their simplified structure, but the shape of the hand must be fixed to receive the intended feedback.

To combine the benefits of both approaches, we propose a wrist-mounted VR haptic controller capable of implementing various force-based interactions. Our controller introduces a motor system to propose a 1-link manipulating design that can maximize a range of motion without losing precise control and structural advantages and force the center of the palm to feel detailed haptic feedback. This device is designed to allow users to finely implement the physical characteristics of objects or environments in virtual space. In other words, our haptic feedback sensation includes the direct perception of the physical properties of the virtual object, such as weight and stiffness, or indirect kinetic force, such as air resistance, and reflection from during the interaction. To fulfill the conception of this, the haptic force-generating functions need to be defined. First, our methods should help users distinguish objects with different force feedback. So, the proposed controller would make a noticeable difference when interacting with two objects which have noticeably different physical properties. Second, our method should do no or little destruction to the sense of experience. The haptic feedback perception is for simulating the actual experience in reality and making VR more realistic. The proposed methods should be natural during interaction with objects while providing force feedback to help users perceive the physical properties of virtual objects.

In the thesis, we develop a simplified 1- link manipulator motorized haptic VR controller design that ensures free hand posture and precise force control to use in various virtual reality scenarios while compensating for the problem of having the complex structure of existing motor-based wearable controllers. Then, minimum and difference thresholds of force feedback were investigated for recognizing and distinguishing the physical properties of a virtual object. Those are also helpful to figure out numerical criteria in haptic feedback design. all of these things were integrally connected so that they could be composed of one system for implementing various physical properties of virtual objects using the force feedback system.

Chapter 2. Related Works

2.1 Haptic devices for hand interaction in VR

In most VR applications, users interact with virtual objects using their hands. Therefore, it is common to give haptic feedback to a user's hand for an immersive experience. In other words, rendering haptic information through haptic devices is a general solution. Haptic devices can be divided into two categories: handheld and wearable haptic devices.

2.1.1 Handheld haptic devices

Handheld haptic devices are being studied as solutions to problematic setup and mobility problems. This type of controller typically provides haptic force feedback by holding the controller in the form of a bar, contacted in the user's palm or at finger level [11, 23, 24]. Their main strength is that they can be carried without restrictions on a large, fixed equipment. In addition, it is not cumbersome to use, so users can easily learn. With the above advantages, a number of handheld haptic VR controllers that render expressive haptic sensations have recently been studied. Some research proposed a handheld device that renders the shape of virtual objects through mechanically-actuated plate displacement [12, 25]. Some devices add haptic feedback mechanisms to tool-like devices to hold specific tools and focus on interacting with other objects [26, 27]. Some controllers install rotating devices to generate haptic feedback to the user through reaction torque [28, 29]. However, the disadvantage is that it always takes the user's hand during use. In other words, when an interaction between a user and a virtual object occurs in a VR space, they must hold the controller if they want to be provided with the appropriate feedback.

2.1.2 Wearable haptic devices

One of the design approaches of A wearable haptic device is a device that wraps around a user's hand and provides force feedback to the hand [30, 31]. These devices can accurately transmit forces directly to each finger joint, but for this purpose, it is difficult to guarantee durability because they have an excessively complex structure. To improve this, some haptic gloves deliver haptic feedback through a simpler structure using a thin form-factor electrostatic clutch [32]. There are also studies that separate complex power units from haptic gloves through vacuum pumps [33, 34]. However, a glove-type haptic device has been studied in the form of delivering haptic feedback to all five fingers, making it difficult to reduce the absolute size of the power source. For this reason, wearable devices in the form of concentrating and transmitting haptic feedback on the palm have been frequently studied. A wearable haptic interface that is able to generate haptic stimuli on the palm by 3-point support haptic display has been proposed [35]. By inflating air pockets in the middle of the palm, Other researchers have suggested inflatable devices for grasping interaction [36, 37]. Although this design concept has the disadvantage of not being able to transfer the force to the desired point other than the palm, our proposed controller is also designed in the direction of focusing haptic feedback on the palm for a simplified structure.

2.2 Rendering physical property of virtual objects

Along with other haptic effects, researchers suggest several methods that users can perceive various physical characteristics such as weight, stiffness, and fluid resistance when interacting with virtual objects. In other words, each haptic interaction can be divided into three physical properties from a dynamic perspective: inertia, elasticity, and viscosity.

$$F_i = M(g + a) \tag{2.1}$$

When lifting action is performed during interaction with a virtual object, the physical characteristic that can be felt even though there is no additional dynamic movement is weight. This interaction means the force of gravitational acceleration that is applied in the virtual world as in reality. If this is confirmed by the dynamic equation, shown as Eq. 2.1. G denotes the acceleration of gravity, a denotes the acceleration of an object, and M denotes the value of inertia of the object. Thus, F_i becomes a force by inertia, and haptic feedback is formed based on it. According to the above equation, it means changing the inertial value of the controller itself or rendering the force by the inertia can generate haptic feedback that the user can feel by weight. In the same way as the former one, some controllers physically move the center of gravity by moving the internal weight [38, 39, 40]. In the case of the latter one, several studies have suggested a haptic device that recognizes the weight of a virtual object by forming a shear force at the fingertips based on inertial forces [21, 41].

$$F_s = Kx \tag{2.2}$$

When the user directly presses the object itself, haptic feedback should vary depending on how much the object is pressed and how hard the object is. In other words, as shown in Eq. 2.2, a force, represented by F_s, proportional to the displacement of an object, represented by x, and its stiffness, represented by K, must be generated. In order to form haptic feedback by stiffness, some studies change the tension of the internal elastic component [42, 43, 44]. Other approaches include devices that directly generate force by elasticity through a motor system [45, 46].

$$F_v = B(v_{env} + v) \tag{2.3}$$

When a user interacts with a virtual object in an environment that directly affects an object such as wind or fluid, it might be delivered as haptic feedback as a force proportional to the speed of the object and fluid. This can be expressed as Eq. 2.3, where v_{env} denotes the velocity of a fluid in a given virtual environment and v denotes the velocity of a virtual object. F_v means the resistance force to the fluid, and B means the coefficient of fluid resistance or the viscosity coefficient of the fluid. In order to implement interactions with virtual environments such as fluids and winds, one study directly transformed resistance using a fan mechanism [47]. Other studies have rendered fluid resistance through propeller systems [48, 49].

$$F_{ref} = M(g + a) + B(v_{env} + v) + Kx \tag{2.4}$$

To present our controller capable of implementing all these various physical properties, we finally used a force feedback system where each element could be applied independently, as in Eq. 2.4.

2.3 Haptic perception characterization

Haptic perception can be characterized in various ways. A common metric used when performing psychophysical tests is Just-noticeable Difference (JND), which is the minimum difference between the two stimuli that allows the user to recognize the difference [50, 51]. Since JND differs as a function of the magnitude of the presented stimulus, it is generally normalized by the reference stimulus to calculate the Weber fraction. Previous work shows that with some exceptions [52, 53], the Weber fraction is relatively constant for haptic sensations [54, **?**, 55]. In our study, JND was used to find the minimum threshold of user perception and the threshold for the gap between the two forces in force feedback applied to the palm through our controller. In particular, we inferred whether the user felt about the stimulation caused by haptic feedback or noticed the difference through direct questions through the staircase method, used in the most widespread heuristic-based method, to produce high accuracy even with a small number of trials [56].

Chapter 3. Wrist-Mounted Haptic VR Controller

The design goal of our haptic controller is to provide dynamic interaction with rendering force and impedance. This dynamic interaction allows users to feel the inertia, viscosity, and elasticity of virtual objects, helping them to distinguish objects by haptic senses. It can also change to a certain force value for forming an arbitrary haptic feeling. Above all, these interactions must be configured to take place in mid-air. The main challenge is to secure maximum move space so that it can be used in various virtual environment scenarios. In addition, since the structure of the controller had to be simplified, the rotation axis was designated at the center of the wrist and the palm was designated as the operating point as shown in the concept design of the 1-link manipulator of Fig. 3.1.

3.1 Hardware implementation

We designed and built a haptic controller that can deliver dynamic interaction from the wrist to the palm. Fig. 3.1 shows the general appearance and mechanical movement. The controller is wearable on the wrist using a Velcro belt and is designed to generate rotational force from the mounted motor so that the force is transmitted to the 1-link manipulator through the u-belt system. The force generated at the end of the link can be calculated directly through the FSR mounted on the palm. In particular, the point of contact was set as the point where the index, middle, and ring fingers began. This is because it is one of the areas where sensitive parts of the palm are gathered [57], and it has advantages in terms of force recognition and amplification because it can take more distance from the wrist than the center. Arduino Portenta H7 is used as a microcontroller, and motor and encoder information are exchanged through an analog signal. In addition, the signal from the FSR is calculated through the internal ADC port, and the brake is controlled using a relay switch. Finally, all this information can be exchanged with the PC through Wi-Fi communication. The overall system configuration is shown in Fig. 3.2. Summarize our device specification as shown in Table. 3.1, our controller has several strengths: better back-drivability, stronger force, and faster velocity, this one because of the AC servo motor system with the belt-pulley system. However, because of that system, we have some weaknesses too. our controller consumes more power and it causes higher heat generation. To minimize this weak effect, the brake system is used for increasing the efficiency in the idle state.

3.2 Haptic feedback control

To deliver haptic feedback to users in real-time, a controller that forms constant inertia, viscosity, and elasticity is designed using motor force control, referring to the force calculated in the VR space as shown in Fig. 3.3. The physical characteristics of each virtual object were formed through a force according to the dynamic movement of the user. This calculation value is used to control the rotational force of the motor through the motor driver. As a result, through the motor rotational force generated at this time, the user is provided with haptic feedback suitable for each VR scenario, and the user's hand response is transmitted to VR through the LEAP Motion controller configured with HMD, and based on this, the user's dynamic movement is calculated.

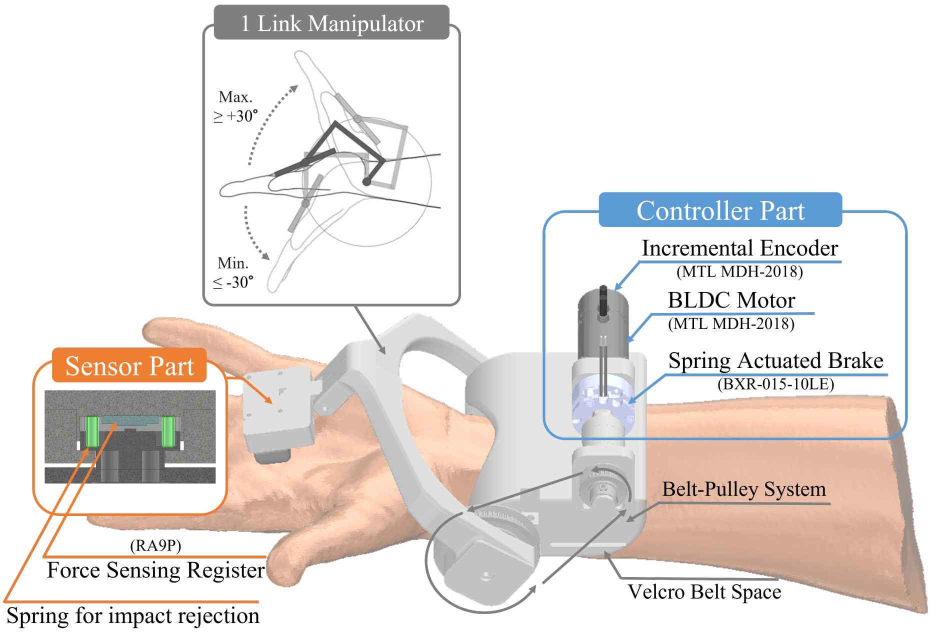

Figure 3.1: A brushless DC motor for precision torque control is used as a power source, and the torque generated here is amplified by the gear ratio (1:2.609) in the belt-pulley system after passing through the spring-actuated brake. The amplified torque is converted into a force through a 1-link manipulator and then driven to the palm, which is measured directly by the FSR. The sensor part includes an internal spring structure to operate like a switch and reduce the impact to be transmitted to the sensor.

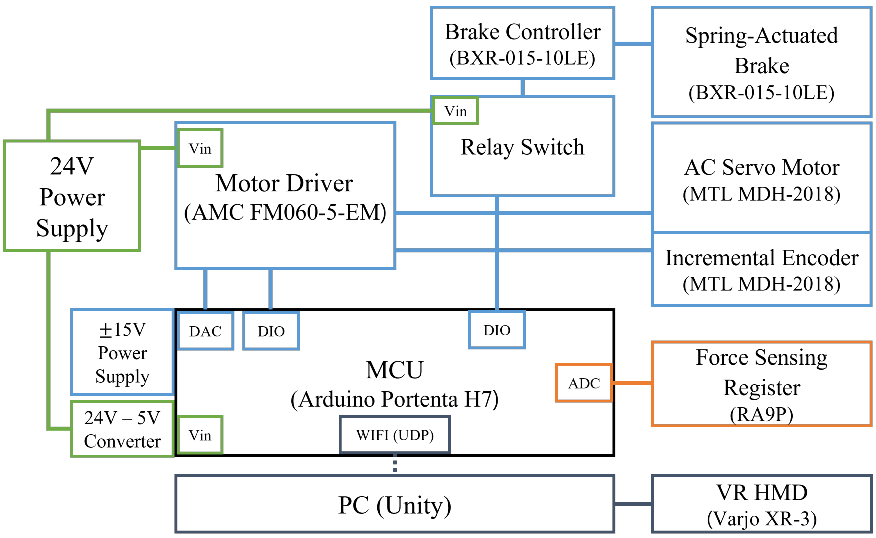

Figure 3.2: The motor is controlled by a motor driver, and the brake controller also operates independently. VR scene runs on an experimental PC, which is connected with VR HMD via USB, and all of this information is shared by the microcontroller through their own communication methods, such as analog, digital IO, and Wi-Fi.

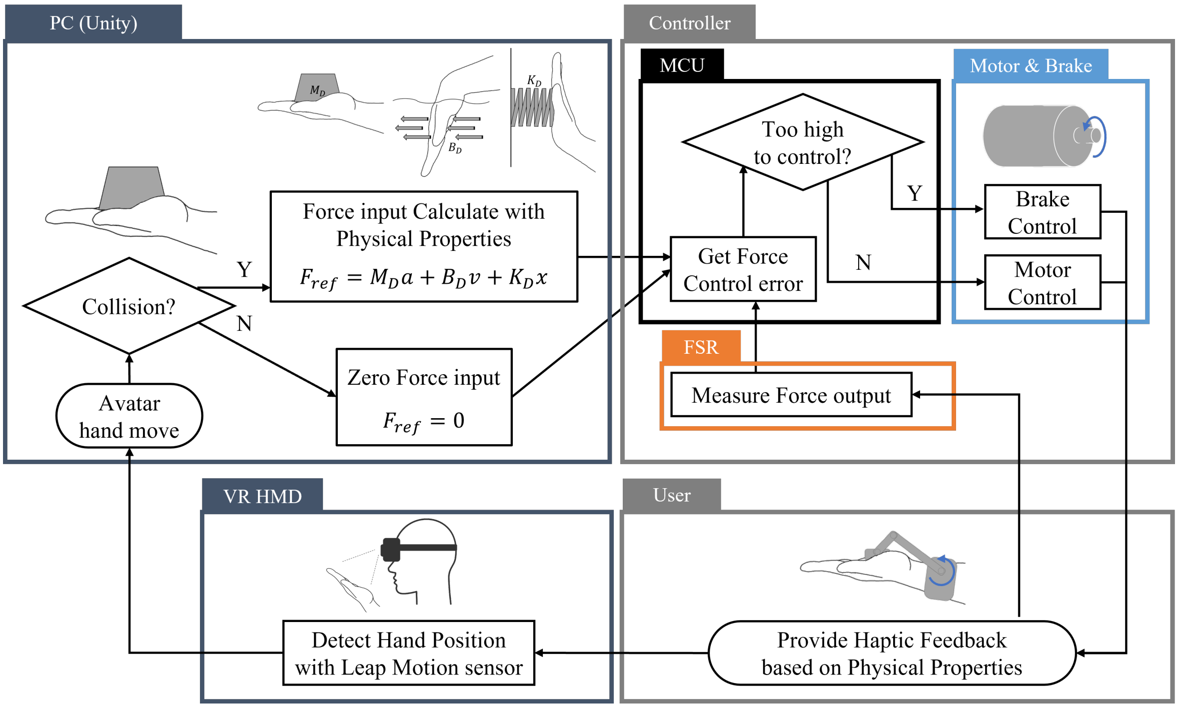

Figure 3.3: The flow chart was designed to be connected in closed-loop form by providing haptic feedback through the controller after calculating force feedback from the user's hand tracking using the internal Leapmotion controller of VR HMD.

Table 3.1: Overall Controller Specification

Weights	386 g
Operating Voltage	24 V
Rated / Peak Current	1.4 / 5.6 A
Torque Constant (Motor)	0.023 Nm/A
Rated / Peak Torque (Motor)	0.03 / 0.13 Nm
Rated Ang. Velocity (Motor)	157.08 rad/s
Gear Ratio	1:2.609
Rated / Peak Torque (After Gear)	0.078 / 0.34 Nm
Rated / Peak Ang. Velocity (After Gear)	60.21 rad/s
Distance from Gear to End-point	92.5 mm
Rated / Peak Force (End-point)	0.843 / 3.68 N
Rated Lin. Velocity (End-point)	5.57 m/s

Chapter 4. Experiment

In this thesis, in order to measure the performance of the proposed haptic system, we conducted an experiment to obtain the minimum threshold and the difference threshold of force feedback to measure the controller's own performance. Varjo's XR-3 with an internal hand tracking sensor was used as a VR HMD for estimating the location information of the user's hand. In addition, force feedback generated from interaction with virtual objects implemented within VR was measured through VARIENSE's FSE103 sensor, and the experimental environment was constructed as shown in Fig. 4.1.

4.1 Perceptive thresholds for force feedback

Since the controller in this study uses the palm as a force point when interacting with objects, an experiment should be designed to understand the impact on user perception, not just the magnitude of the force. Therefore, the purpose of this experiment is to find out the minimum threshold value that the user starts to feel stimulation when receiving force feedback through a haptic controller and the relative threshold value that is substantially different for a specific feedback stimulus. This is to find out the point where haptic feedback obtained through the controller is applied to the user in practice and the relative point of force that can be effectively distinguished when various physical feedbacks are given in the virtual environment.

Psychophysics is a classical framework for studying the relationship between the physical world and psychological concepts such as perception. The JND is a quantitative measure in psychophysics and is defined as the smallest change (DF) in the stimulus intensity (F0) that creates a change in the perception of that stimulus [58]. We investigated the minimum threshold and the difference threshold performed by human subjects.

4.1.1 Setup

Participants

We recruited 10 subjects with ages between 25 and 30. All participants had engineering or computer science backgrounds and were right-handed. We first introduced the purpose of the user study, the setup, and the scene. The participants were then equipped with the wrist-mounted haptic controller for the left hand. Each participant was then allowed to practice in a training scene until they were comfortable with the equipment and ready for the tests. Following the training phase, tasks 1, and 2 were started.

Task 1: Minimum threshold

Psychophysical experiments were performed to measure the human hand's force discrimination ability (e.g. JND) for low-intensity forces [54]. We used the three-down one up-staircase method. The reason we chose this method is to prevent accidental responses. In a three-down, one-up staircase the stimulus amplitude decreases after three correct responses and increases when one response was incorrect. Before reaching the first reversal, the 1 down method is used. This is related to reducing the number of trials. When many trials are conducted, participants feel fatigued in the wrist. After the first reversal, every second reversal occurs, the step size changes. We proceed with the experiment until 10 reversals occur

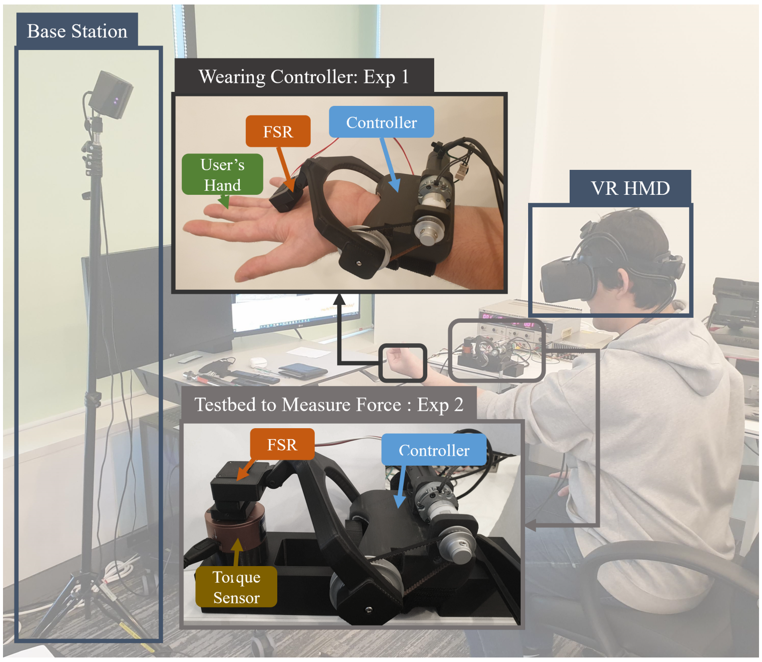

Figure 4.1: In estimating thresholds experiments, the user directly wears the controller, and only delivers opinions on feedback stimuli without any movement. In measuring the force of haptic feedback experiments, the user performs the interaction while wearing only the VR HMD, and measures the force generated by the torque sensor.

and set the 8 reversal values as the threshold value. We focus on force-feedback value in order to obtain more accurate estimates of the minimum threshold of force-feedback perception. We excluded extremely low, high values that disturbed the quality of experience. We will measure the minimum level of force-feedback value that can be detected. All participants started at $0.65N$ and proceeded with a three-down one-up staircase. When there are 'three yes responses', the force feedback value goes down, and when 'no' responses are given before 'three yes responses', the force feedback value goes up. The first step size was $0.19N$. The second and third step sizes were $0.13N$, and from then on, the step size was reduced by half.

Task 2: Difference threshold

The second experiment is to find a difference threshold. Participants were asked to move a wrist while wearing the device. Participants responded whether they perceived the difference of force-feedback or not, as compared to the previous value that the device pressed on the palm. If it can be distinguished from previous stimuli, they answered "Yes", otherwise they answered "No". To obtain the difference threshold, a three-down one-up staircase method was also used. At first, the step size was set to $0.32N$, but after 'three yes', the step size was reduced. If there is no response, we increase the step size again. All participants proceeded with 3 down 1 up staircase starting at $0.32N$. When there are 'three yes' responses, the gap value goes down, and if there is no response before 'three yes' responses, the gap value goes up. The starting value is $1.3N$, and the first step size is $0.32N$ As the trial progresses, the step size changes. The range of force-feedback values ranged from $1.3N$ (maximum output of the device) to $0.32N$ (minimum output of the device).

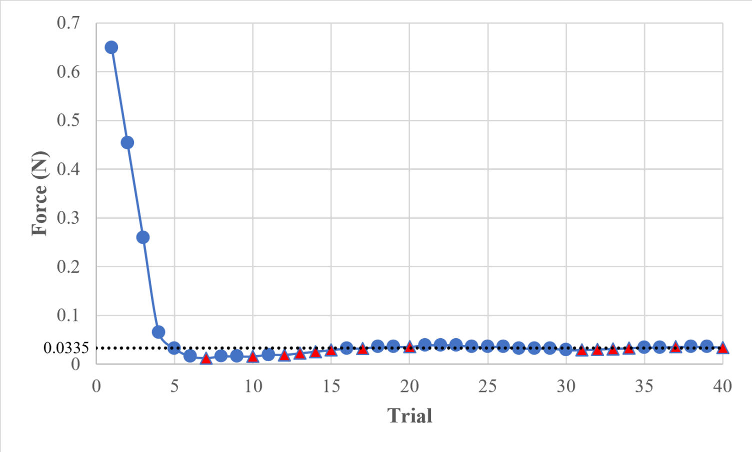

Figure 4.2: Subject 1's Result of minimum threshold experiments. In this graph, it can be seen that the threshold appears at 0.0335 N.

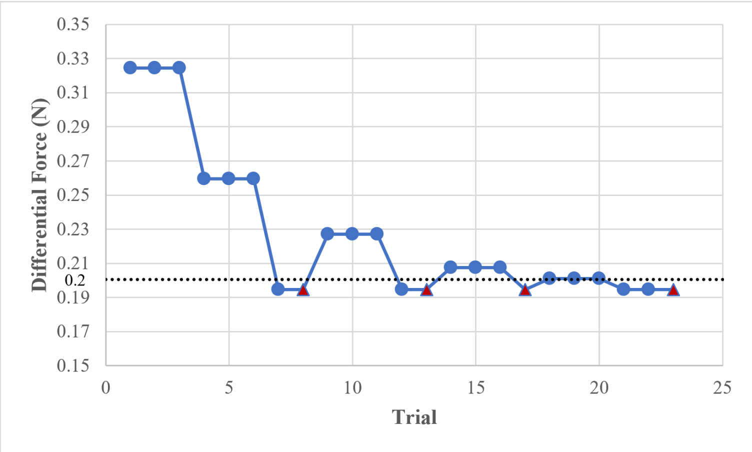

Figure 4.3: Subject 1's Result of difference threshold experiments. In this graph, it can be seen that the threshold appears at 0.2 N.

4.1.2 Minimum threshold

The results were derived through each attempt about 45 times, and the experiment was stopped when the estimated convergence value was continued about 10 times to derive an accurate result value in each experiment. Figure. 4.2. shows subject 1's minimum threshold. For four participants, the average minimum threshold value was 0.114 N (SD=0.155).

4.1.3 Difference threshold

The results were derived through each attempt about 30 times, and the experiment was stopped when the estimated convergence value was continued about 10 times to derive an accurate result value in each experiment. Figure. 4.3. is the result of subject 1 of the difference threshold. For 4 subjects, the average difference threshold value was 0.248N (SD=0.121).

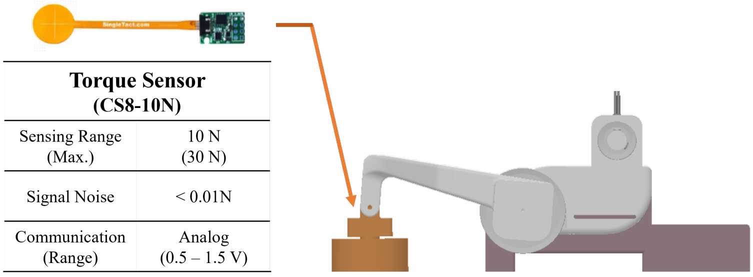

Figure 4.4: Designed to secure the device to the floor via a test bed and to position the torque sensor so that the force can be applied vertically. The table below the sensor represents the specification.

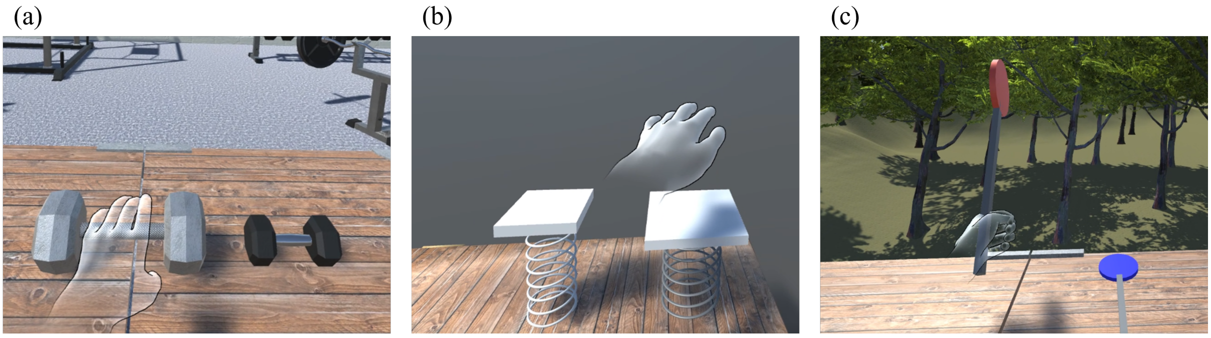

Figure 4.5: (a) Inertia Scenario: user lifting dumbbells, (b) Elasticity Scenario: pressing springs, and (c) Viscosity Scenario: Swinging the paddles. When interacting within these VR scenarios, physical characteristics are estimated by simultaneously measured hand movement and force.

4.2 Rendering physical properties in VR

Since the controller in this study forms a force according to each set property value when interacting with a virtual object or environment, an experiment should be designed to determine the magnitude of the force that changes according to each virtual environment situation. In other words, the purpose of this experiment is to find out whether force feedback symmetrical to the value of the physical properties of a given virtual environment can be effectively generated through the controller.

In this experiment, a more precise force measurement method is needed than the method using FSR configured in the device. So, we use a 3-axis torque senator to get precise force data for checking force sensing performance. we figure out Rendering performance at various levels. For accurate force measurement, the experimental table was designed to fix the controller like Fig. 4.4. The user's dynamic motion value, such as displacement, velocity, and acceleration, for checking the physical property rendering performance was measured through HMD in each simulation, which is shown in Fig. 4.5.

4.2.1 Weight reproduction through inertia rendering

As a scenario to implement the inertial value of a virtual object, an experiment was conducted to measure the difference between the force generated at this time with light and heavy dumbbells in an environment where the gravitational acceleration of $9.8m/s^2$ is applied downward. It was confirmed that the desired inertia value configured on the virtual object was 0.025 to $0.075Ns^2/m$, and a corresponding experimental inertia value of about 0.0252 to $0.0771Ns^2/m$ was applied as shown in Fig. 4.6.

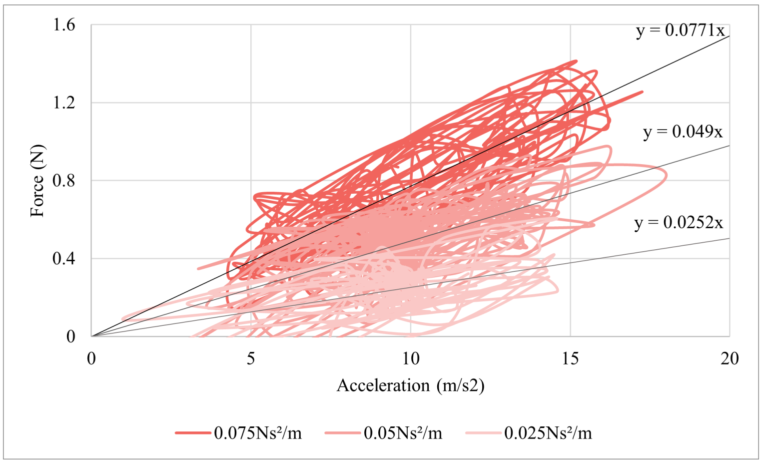

Figure 4.6: To obtain the results of inertia rendering, a force graph against acceleration is drawn. Each force feedback is generated in proportion to the desired inertia value, which is estimated by the gradient of each trend line.

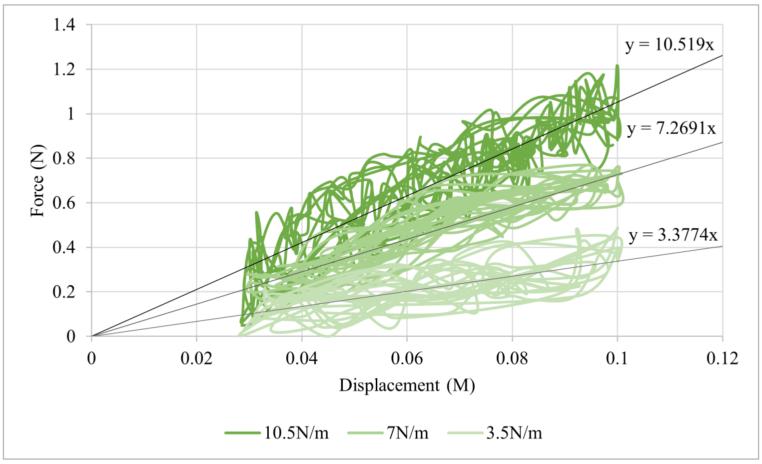

Figure 4.7: To obtain the results of elasticity rendering, a force graph against displacement is drawn. Each force feedback is generated in proportion to the desired elasticity value, which is estimated by the gradient of each trend line.

4.2.2 Stiffness reproduction through elasticity rendering

As a scenario that implements the elasticity value of a virtual object, an experiment was conducted to measure the force generated at this time and the difference between the spring with low hardness and the large spring. At this time, the maximum displacement of the spring is $0.1m$, which is rounded from the second decimal place to the value multiplied by the available angle of the wrist $60°$ and the average male wrist-to-palm distance $74.52mm$. It was confirmed that the desired elastic value configured on the virtual object was 3.5 to $10.5N/m$, and a corresponding experimental elasticity value of about 3.3774 to $10.519N/m$ was measured as shown in Fig. 4.7.

4.2.3 Wind resistance reproduction through viscosity rendering

An experiment was conducted to measure the force and difference generated when a paddle of a different area is directly held and swung in an environment in which a wind speed of $1m/s$, which is

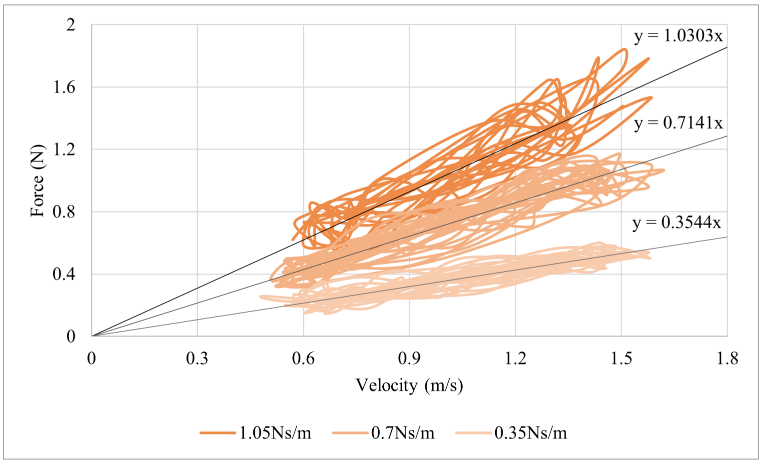

Figure 4.8: To obtain the results of viscosity rendering, a force graph against velocity is drawn. Each force feedback is generated in proportion to the desired viscosity value, which is estimated by the gradient of each trend line.

generally recognized by humans, is blowing from right to left. It is confirmed that the desired viscosity value given to the virtual object is 0.35 to $1.05 Ns/m$ and a corresponding experimental viscosity value of about 0.3544 to $1.0303 Ns/m$ is measured as shown in Fig. 4.8.

Chapter 5. Discussion

5.1 Design Guideline

Experimental results show that with a controller focused on haptic feedback on the palm, people can perceive the stimulus from force feedback of at least $0.114N$, and the next force feedback that can feel the difference is $0.362N$, which is as large as $0.248N$. Through force-based haptic feedback, design guidelines for implementing physical characteristics in a virtual environment can be organized. Most of the force-based haptic feedback controllers form force feedback proportional to the physical property value stored in the virtual object based on the user's expected dynamic movement value to implement physical properties in a virtual environment as haptic feedback. Therefore, based on the thresholds of the stimulus and the expected movement of the user, we present the physical properties rendering equation to generate proper force feedback like Fig. 5.1.

$$F_{obj_1}, F_{obj_2} > F_{min} = M_{min}(a_{user} + a_{env}) + B_{min}(v_{user} + v_{env}) + K_{min}(x_{user} + x_{env}) \tag{5.1}$$

$$|F_{obj_1} - F_{obj_2}| > F_{diff} = M_{diff}(a_{user} + a_{env}) + B_{diff}(v_{user} + v_{env}) + K_{diff}(x_{user} + x_{env}) \tag{5.2}$$

Substituting this guideline to a physical property rendering scenario, Given two interactive virtual objects(obj_1, obj_2), the force feedback from each object must be greater than the minimum threshold as Eq. 5.1. the difference in force feedback to distinguish each object is specified to be greater than the difference threshold as Eq. 5.2. if we try to interact with a cube with a side length of $0.1m$ in a virtual environment with a gravitational acceleration of $9.8m/s^2$ and wind speeds of $1m/s$, it must have the inertia of more than $0.0116Ns^2/m$, the viscosity of more than $0.114Ns/m$, and elasticity of more than $1.14N/m$. Inertia above $0.025Ns^2/m$, viscosity above $0.248Ns/m$, and a cube with elasticity differences above $2.48N/m$ can be said to be comparable. In this way, when our controller is used, from a user-cognitive perspective, it is possible to obtain help in inputting accurate physical properties and calculating haptic feedback.

5.2 Limitation & Future works

When the controller is directly worn, the force measurement results vary depending on the user's hand position due to the difference between the force caused by the sensor mass and the direction of the force to be generated by the motor. To improve this, we will improve haptic rendering through psychophysical user experiments as a follow-up study, and further research will be conducted on increasing experience immersion by providing various physical forces within VR through a force feedback system

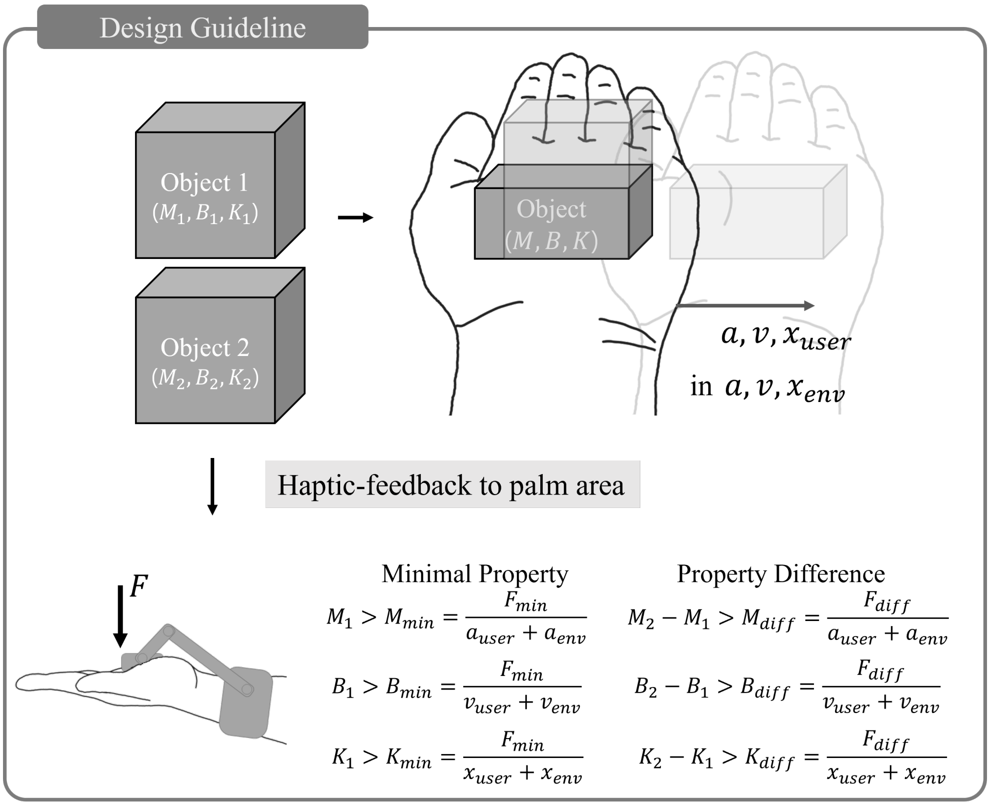

Figure 5.1: Within a given VR environment $(a_{env}, v_{env}, x_{env})$, when a user's dynamic movement $(a_{uesr}, v_{user}, x_{user})$ is estimated, the physical properties of any two objects $(M,\ B,\ K)$ are specified based on the minimum, difference threshold of the force feedback (F_{min}, F_{diff}).

Chapter 6. Conclusion

From the results of the physical property rendering experiment, our controller can form arbitrary inertial, viscosity, and elasticity, and this feedback confirms that the user can interact organically with the virtual environment. In particular, since the previously implemented physical property implementation scenarios can be implemented independently, it means that they can provide dynamic haptic feedback that can be utilized in a variety of VR content combined with inertia, elasticity, and viscosity. Furthermore, since they are based on real-world physical environments, we expect to be able to present intuitive precise force feedback formation methods to users as well as content designers. When configuring a force feedback-based controller, it is expected that it can help to form a virtual environment criterion that can be practically implemented through the minimum threshold value and the difference threshold value.

Based on the virtual environment haptic feedback criteria above, we will provide an in-depth basis for the design guidelines through experiments to determine whether the user could actually feel the intended sensation and to what extent there was a more effective contribution compared to visual feedback. We will also evaluate the performance and usefulness of force-based methods in forming haptic feedback, in addition to implementing physical characteristics such as collision detection and UI/UX design.

Unlike other digital platforms, VR controllers used with HMD frequently interact with what is not visible in addition to what is visible on the screen. This means that haptic feedback is an important part of virtual reality content. Thus, when designing feedback on interaction with virtual objects, presenting numerical standards and guidelines for haptic feedback could create easy and simple feedback formation methods for designers and help users intuitively understand virtual reality situations. It is also helpful to develop and research haptic controllers, being applied as a reference to the minimum performance to form appropriate feedback in mechanical design.

Bibliography

[1] Nannan Xi and Juho Hamari. Shopping in virtual reality: A literature review and future agenda. *Journal of Business Research*, 134:37–58, 2021.

[2] Meta. Oculus. https://www.meta.com./.

[3] Qian Janice Wang, Francisco Barbosa Escobar, Patricia Alves Da Mota, and Carlos Velasco. Getting started with virtual reality for sensory and consumer science: Current practices and future perspectives. *Food Research International*, 145:110410, 2021.

[4] Janet K Gibbs, Marco Gillies, and Xueni Pan. A comparison of the effects of haptic and visual feedback on presence in virtual reality. *International Journal of Human-Computer Studies*, 157:102717, 2022.

[5] Bruno Araujo, Ricardo Jota, Varun Perumal, Jia Xian Yao, Karan Singh, and Daniel Wigdor. Snake charmer: Physically enabling virtual objects. In *Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 218–226, 2016.

[6] Lung-Pan Cheng, Thijs Roumen, Hannes Rantzsch, Sven Köhler, Patrick Schmidt, Robert Kovacs, Johannes Jasper, Jonas Kemper, and Patrick Baudisch. Turkdeck: Physical virtual reality based on people. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, pages 417–426, 2015.

[7] Ryo Suzuki, Hooman Hedayati, Clement Zheng, James L Bohn, Daniel Szafir, Ellen Yi-Luen Do, Mark D Gross, and Daniel Leithinger. Roomshift: Room-scale dynamic haptics for vr with furniture-moving swarm robots. In *Proceedings of the 2020 CHI conference on human factors in computing systems*, pages 1–11, 2020.

[8] HTC Corporation. Vive pro controller. https://www.vive.com/.

[9] Haptix Inc. Haptix vr glove. https://haptx.com/.

[10] Plexus Immersive Corp. Plexus glove. http://www.plexus.im.

[11] Eric Whitmire, Hrvoje Benko, Christian Holz, Eyal Ofek, and Mike Sinclair. Haptic revolver: Touch, shear, texture, and shape rendering on a reconfigurable virtual reality controller. In *Proceedings of the 2018 CHI conference on human factors in computing systems*, pages 1–12, 2018.

[12] Hrvoje Benko, Christian Holz, Mike Sinclair, and Eyal Ofek. Normaltouch and texturetouch: High-fidelity 3d haptic shape rendering on handheld virtual reality controllers. In *Proceedings of the 29th annual symposium on user interface software and technology*, pages 717–728, 2016.

[13] Inrak Choi, Eyal Ofek, Hrvoje Benko, Mike Sinclair, and Christian Holz. Claw: A multifunctional handheld haptic controller for grasping, touching, and triggering in virtual reality. In *Proceedings of the 2018 CHI conference on human factors in computing systems*, pages 1–13, 2018.

[14] Jaeyeon Lee, Mike Sinclair, Mar Gonzalez-Franco, Eyal Ofek, and Christian Holz. Torc: A virtual reality controller for in-hand high-dexterity finger interaction. In *Proceedings of the 2019 CHI conference on human factors in computing systems*, pages 1–13, 2019.

[15] Jongyoon Lim and Yongsoon Choi. Force-feedback haptic device for representation of tugs in virtual reality. *Electronics*, 11(11):1730, 2022.

[16] Xupeng Ye. A survey on simulation for weight perception in virtual reality. *Journal of Computer and Communications*, 9(9):1–24, 2021.

[17] Cathy Fang, Yang Zhang, Matthew Dworman, and Chris Harrison. Wireality: Enabling complex tangible geometries in virtual reality with worn multi-string haptics. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pages 1–10, 2020.

[18] Ching-Yi Tsai, I-Lun Tsai, Chao-Jung Lai, Derrek Chow, Lauren Wei, Lung-Pan Cheng, and Mike Y Chen. Airracket: Perceptual design of ungrounded, directional force feedback to improve virtual racket sports experiences. In *CHI Conference on Human Factors in Computing Systems*, pages 1–15, 2022.

[19] Myung Jin Kim, Neung Ryu, Wooje Chang, Michel Pahud, Mike Sinclair, and Andrea Bianchi. Spinocchio: Understanding haptic-visual congruency of skin-slip in vr with a dynamic grip controller. In *CHI Conference on Human Factors in Computing Systems*, pages 1–14, 2022.

[20] Hsin-Ruey Tsai, Chieh Tsai, Yu-So Liao, Yi-Ting Chiang, and Zhong-Yi Zhang. Fingerx: Rendering haptic shapes of virtual objects augmented by real objects using extendable and withdrawable supports on fingers. In *CHI Conference on Human Factors in Computing Systems*, pages 1–14, 2022.

[21] Inrak Choi, Heather Culbertson, Mark R Miller, Alex Olwal, and Sean Follmer. Grabity: A wearable haptic interface for simulating weight and grasping in virtual reality. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*, pages 119–130, 2017.

[22] Julie M Walker, Heather Culbertson, Michael Raitor, and Allison M Okamura. Haptic orientation guidance using two parallel double-gimbal control moment gyroscopes. *IEEE transactions on haptics*, 11(2):267–278, 2017.

[23] Tomohiro Amemiya and Taro Maeda. Asymmetric oscillation distorts the perceived heaviness of handheld objects. *IEEE Transactions on Haptics*, 1(1):9–18, 2008.

[24] Tomohiro Amemiya, Hideyuki Ando, and Taro Maeda. Lead-me interface for a pulling sensation from hand-held devices. *ACM Transactions on Applied Perception (TAP)*, 5(3):1–17, 2008.

[25] Shigeo Yoshida, Yuqian Sun, and Hideaki Kuzuoka. Pocopo: Handheld pin-based shape display for haptic rendering in virtual reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, pages 1–13, 2020.

[26] Ginga Kato, Yoshihiro Kuroda, Ilana Nisky, Kiyoshi Kiyokawa, and Haruo Takemura. Hapsticks: A novel method to present vertical forces in tool-mediated interactions by a non-grounded rotation mechanism. In *2015 IEEE World Haptics Conference (WHC)*, pages 400–407. IEEE, 2015.

[27] Taku Hachisu, Michi Sato, Shogo Fukushima, and Hiroyuki Kajimoto. Hachistick: simulating haptic sensation on tablet pc for musical instruments application. In *Proceedings of the 24th annual ACM symposium adjunct on User interface software and technology*, pages 73–74, 2011.

[28] Hiroaki Yano, Masayuki Yoshie, and Hiroo Iwata. Development of a non-grounded haptic interface using the gyro effect. In *11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2003. HAPTICS 2003. Proceedings.*, pages 32–39. IEEE, 2003.

[29] Kyle N Winfree, Jamie Gewirtz, Thomas Mather, Jonathan Fiene, and Katherine J Kuchenbecker. A high fidelity ungrounded torque feedback device: The itorqu 2.0. In *World Haptics 2009-Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 261–266. IEEE, 2009.

[30] Mourad Bouzit, Grigore Burdea, George Popescu, and Rares Boian. The rutgers master ii-new design force-feedback glove. *IEEE/ASME Transactions on mechatronics*, 7(2):256–263, 2002.

[31] CyberGlove Systems. Cybergrasp. http://www.cyberglovesystems.com/cybergrasp/.

[32] Ronan Hinchet, Velko Vechev, Herbert Shea, and Otmar Hilliges. Dextres: Wearable haptic feedback for grasping in vr via a thin form-factor electrostatic brake. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, pages 901–912, 2018.

[33] Timothy M Simon, Ross T Smith, and Bruce H Thomas. Wearable jamming mitten for virtual environment haptics. In *Proceedings of the 2014 ACM International Symposium on Wearable Computers*, pages 67–70, 2014.

[34] Igor Zubrycki and Grzegorz Granosik. Novel haptic device using jamming principle for providing kinaesthetic feedback in glove-based control interface. *Journal of Intelligent & Robotic Systems*, 85(3):413–429, 2017.

[35] Daria Trinitatova and Dzmitry Tsetserukou. Touchvr: A wearable haptic interface for vr aimed at delivering multi-modal stimuli at the user's palm. In *SIGGRAPH Asia 2019 XR*, pages 42–43. 2019.

[36] Shan-Yuan Teng, Tzu-Sheng Kuo, Chi Wang, Chi-huan Chiang, Da-Yuan Huang, Liwei Chan, and Bing-Yu Chen. Pupop: Pop-up prop on palm for virtual reality. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, pages 5–17, 2018.

[37] Dhruv Jain, Misha Sra, Jingru Guo, Rodrigo Marques, Raymond Wu, Justin Chiu, and Chris Schmandt. Immersive scuba diving simulator using virtual reality. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*, pages 729–739, 2016.

[38] Jotaro Shigeyama, Takeru Hashimoto, Shigeo Yoshida, Takuji Narumi, Tomohiro Tanikawa, and Michitaka Hirose. Transcalibur: A weight shifting virtual reality controller for 2d shape rendering based on computational perception model. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pages 1–11, 2019.

[39] Colin Swindells, Alex Unden, and Tao Sang. Torquebar: an ungrounded haptic feedback device. In *Proceedings of the 5th international conference on Multimodal interfaces*, pages 52–59, 2003.

[40] Andre Zenner and Antonio Krüger. Shifty: A weight-shifting dynamic passive haptic proxy to enhance object perception in virtual reality. *IEEE transactions on visualization and computer graphics*, 23(4):1285–1294, 2017.

[41] Kouta Minamizawa, Souichiro Fukamachi, Hiroyuki Kajimoto, Naoki Kawakami, and Susumu Tachi. Gravity grabber: wearable haptic display to present virtual mass sensation. In *ACM SIGGRAPH 2007 emerging technologies*, pages 8–es. 2007.

[42] Neung Ryu, Woojin Lee, Myung Jin Kim, and Andrea Bianchi. Elastick: A handheld variable stiffness display for rendering dynamic haptic response of flexible object. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, pages 1035–1045, 2020.

[43] Tzu-Yun Wei, Hsin-Ruey Tsai, Yu-So Liao, Chieh Tsai, Yi-Shan Chen, Chi Wang, and Bing-Yu Chen. Elastilinks: Force feedback between vr controllers with dynamic points of application of force. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, pages 1023–1034, 2020.

[44] Neung Ryu, Hye-Young Jo, Michel Pahud, Mike Sinclair, and Andrea Bianchi. Gamesbond: Bimanual haptic illusion of physically connected objects for immersive vr using grip deformation. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pages 1–10, 2021.

[45] Yuqian Sun, Shigeo Yoshida, Takuji Narumi, and Michitaka Hirose. Pacapa: A handheld vr device for rendering size, shape, and stiffness of virtual objects in tool-based interactions. In *Proceedings of the 2019 CHI conference on human factors in computing systems*, pages 1–12, 2019.

[46] Mike Sinclair, Eyal Ofek, Mar Gonzalez-Franco, and Christian Holz. Capstancrunch: A haptic vr controller with user-supplied force feedback. In *Proceedings of the 32nd annual ACM symposium on user interface software and technology*, pages 815–829, 2019.

[47] André Zenner and Antonio Krüger. Drag: on: A virtual reality controller providing haptic feedback based on drag and weight shift. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pages 1–12, 2019.

[48] Seongkook Heo, Christina Chung, Geehyuk Lee, and Daniel Wigdor. Thor's hammer: An ungrounded force feedback device utilizing propeller-induced propulsive force. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pages 1–11, 2018.

[49] Tomoya Sasaki, Richard Sahala Hartanto, Kao-Hua Liu, Keitarou Tsuchiya, Atsushi Hiyama, and Masahiko Inami. Leviopole: mid-air haptic interactions using multirotor. In *ACM SIGGRAPH 2018 Emerging Technologies*, pages 1–2. 2018.

[50] Deane B Judd. Chromaticity sensibility to stimulus differences. *JOSA*, 22(2):72–72, 1932.

[51] Cara Gonzalez Welker, Steven H Collins, and Allison M Okamura. Human perception of wrist flexion and extension torque during upper and lower extremity movement. *IEEE Transactions on Haptics*, 2022.

[52] Naila Ayala, Gordon Binsted, and Matthew Heath. Hand anthropometry and the limits of aperture separation determine the utility of weber's law in grasping and manual estimation. *Experimental Brain Research*, 236(8):2439–2446, 2018.

[53] Mirela Kahrimanovic, Wouter M Bergmann Tiest, and Astrid ML Kappers. Discrimination thresholds for haptic perception of volume, surface area, and weight. *Attention, perception, & psychophysics*, 73(8):2649–2656, 2011.

[54] Seyedshams Feyzabadi, Sirko Straube, Michele Folgheraiter, Elsa Andrea Kirchner, Su Kyoung Kim, and Jan Christian Albiez. Human force discrimination during active arm motion for force feedback design. *IEEE transactions on haptics*, 6(3):309–319, 2013.

[55] Gustav Theodor Fechner. *Elemente der psychophysik*, volume 2. Breitkopf u. Härtel, 1860.

[56] Christian Hatzfeld. Haptics as an interaction modality. In *Engineering Haptic Devices*, pages 29–100. Springer, 2014.

[57] Charlotte Fransson-Hall and Åsa Kilbom. Sensitivity of the hand to surface pressure. *Applied ergonomics*, 24(3):181–189, 1993.

[58] Walter H Ehrenstein and Addie Ehrenstein. Psychophysical methods. In *Modern techniques in neuroscience research*, pages 1211–1241. Springer, 1999.