VirCHEW Reality: On-Face Kinesthetic Feedback for Enhancing Food-Intake Experience in Virtual Reality

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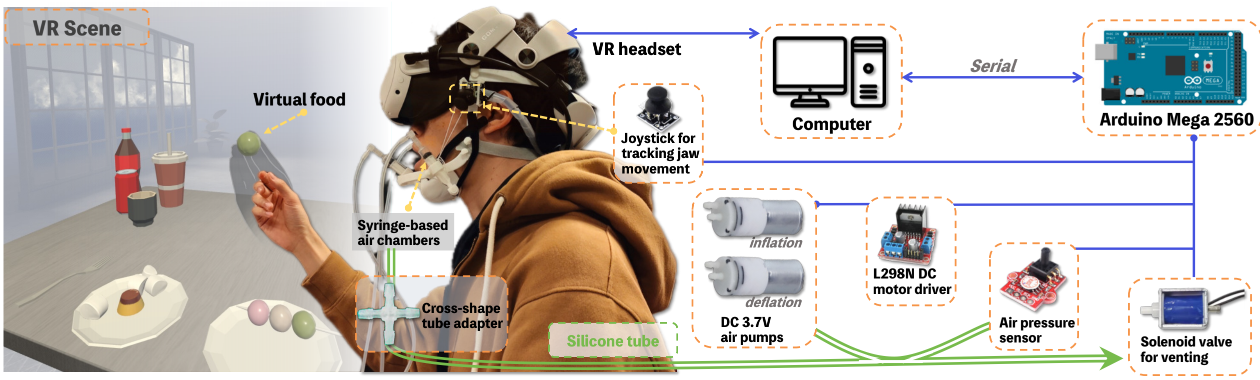

Fig. 1. System Diagram of *VirCHEW Reality*.

While haptic interfaces for virtual reality (VR) has received extensive research attention, on-face haptics in VR remained less explored, especially for virtual food intake. In this paper, we introduce *VirCHEW Reality*, a face-worn haptic device designed to provide on-face kinesthetic force feedback, to enhance the virtual food-chewing experience in VR. Leveraging a pneumatic actuation system, *VirCHEW Reality* controlled the process of air inflation and deflation, to simulate the mechanical properties of food textures, such as hardness, cohesiveness, and stickiness. We evaluated the system through three user studies. First, a just-noticeable difference (JND) study examined users' sensitivity to and the system's capability of rendering different levels of on-face pneumatic-based kinesthetic feedback while users performing chewing action. Building upon the user-distinguishable signal ranges found in the first study, we further conducted a matching study to explore the correspondence between the kinesthetic stimuli provided by our device and user-perceived food textures, revealing the capability of simulating food texture properties during chewing (e.g., hardness, cohesiveness, stickiness). Finally, a user study in a VR eating scenario showed that *VirCHEW Reality* could significantly improve the users' ratings on the sense of presence, compared to the condition without haptic feedback. Our findings further highlighted possible applications in virtual/remote dining, healthcare, and immersive entertainment.

CCS Concepts: • **Human-centered computing** → **Virtual reality**; **Haptic devices**.

Additional Key Words and Phrases: Virtual reality, Haptic devices, Food Texture

ACM Reference Format:
Qingqin Liu, Ziqi Fang, Jiayi Wu, Shaoyu Cai, Jianhui Yan, Tiande Mo, Shuk Ching Chan, and Kening Zhu. 2025. VirCHEW Reality: On-Face Kinesthetic Feedback for Enhancing Food-Intake Experience in Virtual Reality. In *Special Interest Group on Computer Graphics and Interactive Techniques Conference Conference Papers (SIGGRAPH Conference Papers '25), August 10–14, 2025, Vancouver, BC, Canada.* ACM, New York, NY, USA, 12 pages. https://doi.org/10.1145/3721238.3730694

1 Introduction

In recent years, researchers have explored a wide range of haptic devices to simulate real-world touch sensation and enhance the multi-sensory experiences in virtual reality (VR) environments [Cai et al. 2024, 2020; Fleck et al. 2025; Gao et al. 2024; Huang et al. 2023; Ke et al. 2023; Luo et al. 2024; Pacchierotti et al. 2017; Zhang et al.

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SIGGRAPH Conference Papers '25, August 10–14, 2025, Vancouver, BC, Canada
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ACM ISBN 979-8-4007-1540-2/2025/08
https://doi.org/10.1145/3721238.3730694

2022a,b; Zhu et al. 2019]. Among the various real-world experiences, food intake/eating stands out as a fundamental activity for survival, being one of the most common experiences in daily life [Edemekong et al. 2024; Gayler et al. 2022; Katz 1983]. During eating, our experience is shaped by multiple simultaneous sensations - from the visual appearance and aromatic cues to the tactile feedback in our hands and mouths [Spence 2016; Spence and Piqueras-Fiszman 2014; Weidner et al. 2023]. Enhancing and simulating these multisensory eating experiences through human-computer interaction (HCI) could potentially contribute to improve health through better food choices and enrich social interactions and sensory enjoyment [Mueller et al. 2023; Wang et al. 2025].

However, creating satisfying virtual eating experiences remained challenging due to the complexity of feedback modalities. Research has explored different approaches to simulate or enhance virtual eating experiences by leveraging different modalities, such as visual overlay in augmented reality [Narumi et al. 2011a,b], on-tongue electrical stimulation [Ranasinghe and Do 2016], thermal feedback on the lower lip [Ranasinghe and Do 2016], chewing sound [Kleinberger et al. 2023], and kinesthetic feedback on handheld linkages [Iwata et al. 2004] or jamming-based proxies [Sasagawa et al. 2018]. Among these work, there is still lacking the exploration of wearable devices with kinesthetic feedback for simulating eat experiences, which potentially render food texture properties (e.g. hardness and stickiness) in virtual eating [Guo 2021].

The perception of food texture (e.g., hardness, cohesiveness, and stickiness) is a critical yet particularly challenging aspect in creating virtual eating experience [Peng et al. 2021]. Food texture encompasses the rheological and structural attributes, which could be perceived through mainly tactile receptors [ISO 2009]. The tactile sensations in the mouth not only contribute to immediate sensory pleasure but also play a pivotal role in shaping our overall perception of food quality and satisfaction [Rosenthal and Chen 2024]. To simulate food texture in virtual eating scenarios, some researchers have proposed using electrical stimulation on the masticatory muscle [Niijima and Ogawa 2016a,b], oral tissue [Iwahama et al. 2023], or tongue [Mukashev et al. 2023].However, such these methods may raise concerns on hygiene and user safety (e.g., electric shock). Alternatively, some studies have explored cross-modal interaction, such as visual face deformation [Suzuki et al. 2018] or modified chewing sounds [Kleinberger et al. 2023; Koizumi et al. 2011; Wang et al. 2024], to alter virtual food-texture perception, but these methods lacked the physical force feedback needed for a realistic experience. While existing approaches have demonstrated potential in food texture simulation/modification, it is still unclear how force or kinesthetic feedback contribute to food texture rendering and enhance virtual eating experiences in VR.

In this paper, we present *VirCHEW Reality* (Fig. 1), a face-worn haptic interface that simulates food textures in VR through controllable pneumatic signals. The pneumatic signals further provided on-face force feedback while users are moving their jaws to perform the chewing motion. This was to simulate the mechanical properties of various food textures during chewing experiences. We evaluated the system through three user studies. We first conducted a psychophysical study to evaluate the just-noticeable difference (JND) of the pneumatic force feedback generated by *VirCHEW Reality*. The results demonstrated that our system could provide three distinguishable levels of force stimuli during both jaw-opening and jaw-closing phases, respectively. The following matching study showed the correspondence between force stimuli and real food textures in terms of hardness, cohesiveness and stickiness, respectively. Lastly, the user study in a VR eating scenario showed that our system yielded significantly higher ratings on the sense of presence compared to the condition without haptic feedback.

2 Related Work

Our work lies in the key areas of VR eating experience, food texture simulation and on-face haptic devices.

2.1 Virtual Eating Experiences

The research show that eating experience involves multiple perceptual channels, such as visual, auditory, olfactory, gustatory, and tactile cues, collectively shaping food perception and satisfaction [Prescott 2015; Sinding et al. 2023; Spence 2016; Verhagen and Engelen 2006]. This motivated researchers to enable VR eating from different modality perspectives. For example, research showed that changing visual appearance through augmented reality (AR) could affect perceived flavor of real cookies [Narumi et al. 2011b]. In addition, adding synchronous auditory cues during chewing allows to modify texture perception [Demattè et al. 2014; Zampini and Spence 2004, 2005], and deploying olfactory stimuli during eating can significantly enhance flavor intensity [Labbe et al. 2006; Liu et al. 2023; Spence 2022; Weidner et al. 2023]. Research also showed that applying electrical stimulation [Mukashev et al. 2023; Ranasinghe and Do 2016; Ranasinghe et al. 2015] or thermal modulation [Karunanayaka et al. 2018] allows to simulate perceived food properties. While these approaches allow for immersive virtual eating experiences, it is not trivial to rendering food texture perception during chewing in virtual eating [Rosenthal and Chen 2024; Szczesniak 2002; Ye 2019]. Our work focuses more on rendering eating experience in VR without needing physical food samples as proxies, by deploying kinesthetic force feedback directly on user's face to simulate food texture perception while users are performing chewing actions.

2.2 Haptic Devices for Food Texture Simulation

There have been several attempts on simulating food texture through haptic interfaces, particularly for its potential in enhancing the user experience in VR and AR. Studies have explored the feasibility of applying electrical stimulation on different facial and oral locations [Iwahama et al. 2023; Mukashev et al. 2023; Niijima and Ogawa 2016a,b] to induce non-mechanical sensory feedback. However, this technique may suffer from limited realism, as it cannot provide the force dynamics required for chewing interactions. Moreover, the on-face electrical stimulation may cause discomfort and potentially safety concerns [Efthimiou et al. 2022].

Mechanical systems, such as intra-oral devices with linkages [Iwata et al. 2004] or jamming-based systems [Sasagawa et al. 2018], have been developed to provide direct force feedback during chewing. These systems effectively rendered forces associated with food deformation and chewing resistance, offering higher realism than electrical stimulation. However, their bulky mechanical designs, hygiene challenges, and potential discomfort for intra-oral placement may hinder user experience, making them less suitable for wearable or long-term applications. Researchers also adopted vibrotactile feedback for rendering food texture perception, such as a straw-like interface that simulates the sensation of drinking [Hashimoto et al. 2006] or altering food textures through applying vibrations on the user's hand [Mizoguchi and Kajimoto 2023] or whole body [Nishi and Saga 2022] during eating. While these approaches can enhance food texture perception, they lack direct kinesthetic feedback, which is critically important during the chewing action. In addition, physical food proxies were needed for such devices.

Compared to those above-mentioned haptic interfaces for food texture simulation or VR eating experience, pneumatic haptic interfaces could be considered as an alternative for food texture simulation with kinesthetic feedback in chewing. Previous research shows that pneumatic devices could provide precise, controllable, and dynamic force rendering [Abad et al. 2024; Frisoli and Leonardis 2024], as lightweight, compact, and wearable pneumatic systems [Cai et al. 2024, 2020; Qi et al. 2023]. Inspired by this, our approach leverages pneumatic mechanisms to present controllable on-face kinesthetic force feedback simulating food texture perception to enhance food chewing experience in VR.

2.3 Haptic Devices for Mouths and Faces

Research showed that the skin areas around the head, such as face, mouth, forehead, and ears, are highly sensitive to haptic feedback [Corniani and Saal 2020]. To this end, there have been extensive research efforts on designing haptic interfaces that could be worn around the user's head. Early works explored the usage of around-head vibrotactile feedback as the directional cues for navigation in either real world [Mann et al. 2011] or virtual reality [Kaul and Rohs 2017]. Later, researchers investigated the usages of other modalities of haptics on users' faces, such as fan-based air flow [Watanabe et al. 2022], thermal effects [Peiris et al. 2017], and pneumatic chamber inflation [Günther et al. 2020], to enhance user experience in virtual reality. Researchers also studied applying electrical stimuli on the cheek muscles to trigger facial expression [Demchenko et al. 2023], and on the lip and the tongue to provide haptic notification [Mukashev et al. 2023]. Recently, research investigated the mid-air haptic feedback generated by the ultrasonic signal on users' face areas for VR [Howard et al. 2022; Lan et al. 2024].

Motivated by the high haptic sensitivity of human face and inspired by the existing research on on-face haptics, we developed *VirCHEW Reality*, leveraging the syringe-based linkage structure to provide on-face kinesthetic force feedback. By controlling the air pressure in the chambers during inflation/deflation, our system can provide the force that the face muscles encountered during the food-chewing process, and simulate different types of food texture.

3 Background: Food Texture Perception and Chewing Mechanics

Perceiving food texture could be influenced by visual, auditory, and kinesthetic tactile feedback during chewing [Chen 2009; Kohyama 2015; Szczesniak 2002]. Among these, kinesthetic feedback play an important role, as they provide critical information about food properties such as hardness, elasticity, and stickiness [Guo 2021; Kazemeini et al. 2021; Tonni et al. 2020]. These tactile feedback are perceived by the mechanoreceptors in the oral cavity and directed by the masticatory system, consisting of teeth, tongue, and jaw muscles [Miller 2017]. Specifically, during the process of chewing, the teeth break, crunch, and grind the food into smaller fragments, while the tongue works in tandem to manipulate and compress the food against the palate, facilitating effective mastication [Bourne 2002; Chen 2009; Rosenthal and Chen 2024]. A key contributor to texture perception is the activity of the masticatory muscles, which are responsible for generating the forces required for chewing by coordinating jaw movements such as opening, closing, and lateral shifts [Liu et al. 2017; Miller 2017]. The masticatory system consists of two muscle groups: elevator muscles (masseter, temporalis, medial pterygoid) that close the jaw and apply compressive forces, and depressor muscles (lateral pterygoid, digastric) that lower the jaw for opening during chewing. These coordinated muscle activities, guided by the temporomandibular joints (TMJ), adapt to the varying mechanical properties of food. For example, harder or chewy foods demand stronger contractions of the elevator muscles, whereas sticky foods require finer control of jaw movement and force to manage adhesion and facilitate opening. These oral activities could produce perceivable kinesthetic forces and render the information about the food's structural and mechanical properties [Chen 2009].

When eating solid food, such as a piece of biscuit, three mechanical properties — hardness, cohesiveness, and stickiness are core factors for food texture perception during chewing [Nishinari and Fang 2018]. Hardness refers to the force needed to deform or break food, ranging from soft (e.g., cream cheese) to hard (e.g., boiled sweets). It is primarily perceived during the initial bite and compression [ISO 2009; Rosenthal and Chen 2024]. Cohesiveness describes the internal strength of food, reflecting how well it holds together under deformation. It provides a spring-like resistance that increases as chewing force is applied. Generally, foods with high cohesiveness, such as those with chewy or gummy textures, resist fracturing, while low-cohesiveness foods, like crumble textures, break apart easily [Friedman et al. 1963; Szczesniak 2002]. Stickiness, or adhesiveness, is the force required to separate food from surfaces like the palate or teeth [ISO 2009]. This property contributes to the perception of sticky foods like toffee or peanut butter. These food textures are closely tied to the forces produced by masticatory muscles and detected by oral mechanoreceptors. Particularly, as illustrated in Fig. 2(a), hardness corresponds to compressive forces, cohesiveness reflects resistance to deformation, and stickiness involves the forces experienced during food separation and mouth opening [Boyd and Sherman 1975; Kazemeini 2024; Rosenthal and Thompson 2021].

4 *VirCHEW Reality*: System Design and Implementation

As shown in Fig. 1, *VirCHEW Reality* consists of two main components: the on-face wearable module (detailed in Fig. 3), which includes a support frame, a joystick for tracking jaw movement, three interconnected air chambers, and a jaw support; and the pneumatic actuation system, featuring DC air pumps for inflation/deflation, an air pressure sensor, a solenoid valve for venting, and an Arduino

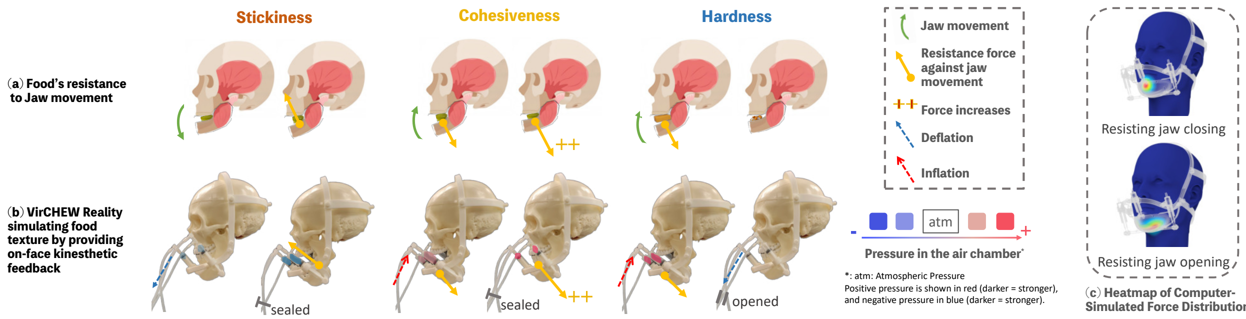


Fig. 2. The mechanism of *VirCHEW Reality* for on-face kinesthetic feedback. (a) Food texture properties, including hardness, cohesiveness, and stickiness, are represented as resistance forces against jaw movements. (b) *VirCHEW Reality* achieves these forces through inflation and deflation of air chambers. (c) Visualization of on-face force feedback intensity generated by *VirCHEW Reality*, with heatmaps indicating the distribution of force on the face during jaw-closing and jaw-opening phases.

Mega 2560 for control. By controlling the air pressure in the sealed chambers via inflation/deflation, our system can render different force profiles on the wearer's jaw area.

4.1 Pneumatic Actuation for Simulating Food Texture

Inspired by prior research on pneumatic haptic interfaces [Delazio et al. 2018; Ma et al. 2024; Uddin et al. 2016], we developed the *VirCHEW Reality* tailored to provide the kinesthetic feedback experienced during chewing. The system utilizes three syringe-based actuators, each repurposed from a 5 mL syringe barrel into an air chamber, with plungers and pistons ensuring uniform force application. YAMATE FL-935 lubricant was applied to reduce friction between the pistons and barrels. Three chambers are interconnected via a tube adapter and linked to a solenoid valve, which regulates airflow. The chambers are secured to the user's jaw using mechanical linkages, allowing a maximum swing angle of about 45°. When the air chambers are sealed, internal pressure is modulated by an inflate pump and a deflate pump (DC 3.7V micro air pump 370).

The pneumatic actuation system in the our device provides force feedback by controlling the air pressure in sealed air chambers. According to the specification of the air pumps, the air chamber operates within a pressure range of -50 kPa to +60 kPa. Here, the negative symbol indicates that the air pressure in the syringe/chamber is smaller than the external atmospheric pressure, while the positive sign refers to the in-syringe air pressure that is larger than the external. The cross-sectional area of a single air chamber, based on a circular shape with a diameter of 13.3 mm, is approximately $1.3893 \times 10^{-4}\,\mathrm{m}^2$. In the idle state, when no inflation or deflation occurs, the air chamber exhibits a static friction force that must be overcome to initiate movement. This static friction force, equivalent to a pressure of approximately 5 kPa, corresponds to a force of $F_{\mathrm{static}} \approx 0.70\,\mathrm{N}$ for a single air chamber.

Including static friction, the operational pressure range extends to -55 kPa and +65 kPa. Using $F = P \cdot A$, the force generated by a single air chamber ranges from $-7.64\,\mathrm{N}$ at -55 kPa restricting the jaw-opening motion, to $+9.03\,\mathrm{N}$ at +65 kPa that would resist the jaw-closing motion. Given that the device incorporates three air chambers positioned around the jaw, the total estimated force applied to the user's jaw ranges from $-22.92\,\mathrm{N}$ to $+27.09\,\mathrm{N}$. This allows the system to generate compressive or tensile forces to simulate chewing resistance during jaw closing and opening.

As shown in Fig. 2(b), our system aims to render the following aspects of food texture properties:

• **Stickiness**: To mimic the adhesion of chewing sticky foods, such as toffee or peanut butter, the system creates negative pressure in the syringes through deflation. Once the target pressure is reached, the solenoid valve closes, isolating the syringes to maintain a constant air pressure. When the user performs the jaw-opening motion, the negative pressure in the sealed syringes provides the resistance against the jaw-opening motion, to mimic how sticky foods adhere to teeth and oral surfaces.

• **Cohesiveness**: To simulate the resistance during biting down on cohesive foods, the system inflates to a target pressure that is larger than the external environmental air pressure and seals the syringes. When the user interacts with the inflated sealed syringes and performs the chewing motion, their jaw movement compresses the air within the sealed chamber, creating a natural increase in resistance that simulates the progressively increasing force experienced when chewing cohesive foods like gummies.

• **Hardness**: To render the sensation of biting into hard foods, the system first filled the syringes with a specific air pressure when user fully opened his/her mouth, creating resistance during chewing. When the user closes his/her mouth to 20% of the maximum opening—a threshold empirically determined through preliminary tests with three users—the system releases all pneumatic forces within a short time, replicating the sudden loss of resistance experienced when breaking hard foods like candies or crackers.

4.2 Mouth Movement Detection

To trigger the pneumatic control in real time, we installed a dual-axis joystick module (HW-504) on the side of the wearable support frame (shown in Fig. 3(b)) to detect the phases of jaw opening and closing. The analog signal from the joystick could reflect the jaw movement with a short responsive time, and indicate the process of chewing through the collision detection in VR.

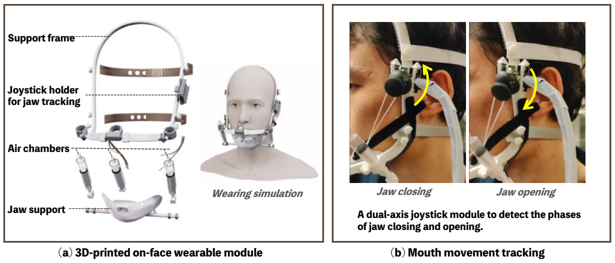


Fig. 3. (a) On-Face Wearable Module and (b) Mouth Movement Tracking.

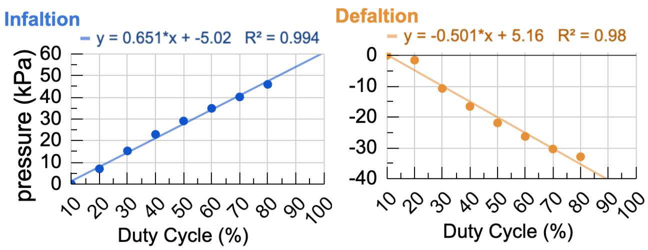


Fig. 4. The mappings between the input PWM duty cycles and the output pressure in the air chamber during inflation and deflation.

Due to the difference among different persons of their face-muscle strength and motion range, the joystick signal could vary across different users. To this end, each user went through a calibration process in which the analog joystick signals will be recorded when the user opened his/her mouth to the maximum extent and fully closed his/her mouth during chewing. The range between these two signal readings was used to determine the user's jaw state (fully opened/closed, opening/closing).

4.3 Technical Evaluation

To evaluate the performance of the *VirCHEW Reality*, we first conducted the technical assessment focusing on: the correlation between the Pulse-Width Modulation (PWM) signals and the pressure in the chambers. Specifically, we measured the pressure levels at duty cycles ranging from 10% to 80%, with increments of 10%, using an Arduino-based sensor system (air pressure sensor: XGZP6847A100KPGPN). For each value of duty cycle, the pressure in the air chambers was recorded and averaged on nine measurements of sensor recording. With the recorded data, we implemented a set of linear-regression models (Fig. 4), which mapped the PWM signals to the corresponding pressure levels.

Moreover, we evaluated the system response times for both inflation and deflation in achieving three reference pressure levels (10 kPa, 25 kPa, 40 kPa). Specifically, we assessed: (1) **Inflation/Deflation Time:** The duration required to reach the specific pressure levels from the idle state after triggering. (2) **Recovery Time:** The duration needed for the system to return to the idle status when the air chamber was vented to the atmosphere. The results are summarized in Table.1 in Appendix, which indicated that our system could rapidly reach the target pressure level for real-time interactions.

5 Study 1: Just-Noticeable Difference Evaluation

Unlike the mechanical properties measured by a food-texture analyzer, the human-perceived food texture could vary with non-linear characteristics depending on users' subjective feelings [Chen 2020]. To this end, we conducted a psychophysical just-noticeable difference (JND) experiment which has also been adopted by previous research to validate users' perception on wearable haptic interfaces [Jones and Tan 2013; Ke et al. 2023]. We aimed to investigate the human perception for on-face kinesthetic feedback which was previously unexplored according to the literature, and determine distinguishable stimulus levels. In the following sections, we referred to the joint-resisting forces experienced by the user during jaw opening and closing as the "haptic stimuli". All experimental protocols in this paper were approved by the university's ethics committee.

5.1 Participants

We recruited 12 participants (6 females), averagely aging 24.1 years (SD = 3.37). According to their self-reports, all participants had healthy chewing function, and were able to perceive varying chewing forces. None of them had prior experience with psychophysical perception experiments.

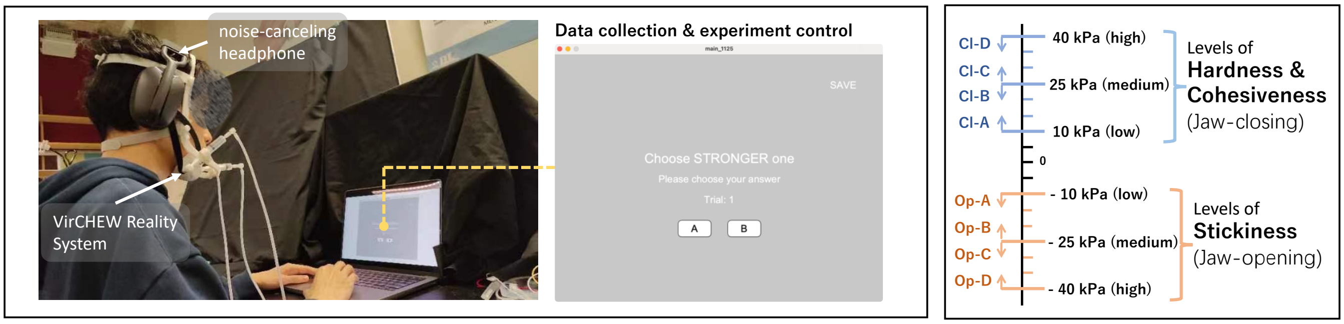
5.2 Apparatus and Stimuli

The experimental setup, as shown in Fig. 5, included the *VirCHEW Reality* and a laptop for experiment control and data collection. Participants sit on a chair and wore noise-canceling headphones playing white noise to minimize external distractions. A 14-inch monitor was used to display the graphical interface for guiding the participant and recording his/her responses.

Six reference stimuli were selected in accordance with the system's capabilities. The chewing process consists of jaw-opening and jaw-closing phases. For the jaw-opening phase, the reference stimuli were set as P1 = -10 kPa, P2 = -25 kPa, and P3 = -40 kPa. In the case of the jaw-closing phase, the reference stimuli were P4 = +10 kPa, P5 = +25 kPa, and P6 = +40 kPa. Negative and positive pressure values corresponded to resistances during jaw opening and closing, respectively. These six references led to eight stimuli intervals ("Op" for jaw-opening phase and "Cl" for jaw-closing phase) shown in Fig. 5(b). "Op-A" refers to the condition where the reference stimulus was fixed at -10 kPa, measuring the JND when increasing pressure from -10 kPa toward -25 kPa as the ending point. Similarly, "Op-B" had the reference stimulus fixed at -25 kPa, measuring the JND when decreasing pressure from -25 kPa toward -10 kPa. Other intervals followed the same definition pattern. During each trial, the participant wore the *VirCHEW Reality*, being seated, and experienced each stimulus for 5 seconds. Once the air pressure was stabilized, the participant performed chewing motions to perceive the stimulus.

5.3 Experiment Design

We employed a within-subject factorial design to measure the JNDs for above-mentioned six references stimuli generated by the *VirCHEW Reality*. The experiment used a two-alternative forced-choice (2AFC) paradigm [Green et al. 1966; Ke et al. 2023; Steinicke et al. 2010], where participants identified the weaker/stronger stimulus between



(a) Study environment and experimental interface for the JND evaluation **(b) JND intervals**

Fig. 5. Study 1: (a) Study environment and experimental interface for the JND evaluation. (b) JND intervals for the evaluation.

a reference stimulus (S) and a test stimulus (S ± ΔS) presented in random order.

We adopted a one-up two-down staircase procedure [Kollmeier et al. 1988], which adjusts stimulus intensity by decreasing it after two consecutive correct responses and increasing it after one incorrect response to converges at a 70.7% correct response threshold [Leek 2001; Levitt 1971]. We set the initial step size (ΔS) to 2.5 kPa, which was reduced to 20% (i.e., 0.5 kPa) after three reversals. Each interval ended after nine reversals, and the mean of the last six reversals was recorded as the JND values. The experimental order of eight intervals were counterbalanced across the participants using a Latin square design.

5.4 Procedure

Upon arrival, the participant was briefed on the procedure, assisted in wearing the *VirCHEW Reality*, and seated in front of the laptop for data collection, as shown in Fig. 5. A practice session was conducted to familiarize the participant with the process, allowing them to repeat training until confident.

Each experimental trial began with a 5-second countdown, followed by the activation of Stimulus#A for 5 seconds. Participants performed chewing motions to perceive the intensity while the stimulus was maintained. After another 5-second countdown, Stimulus#B was presented for 5 seconds. After each block (two trials), participants selected which stimulus felt stronger or weaker based on the interval type (i.e., weaker for increasing intervals, stronger for decreasing intervals). A 10-second break was provided between blocks, with a 1-minute break after every 10 blocks. Each interval consisted of 30–40 blocks, lasting 15–20 minutes, with a 5-minute break between intervals. In total, it took 2.5–3 hours for each participant to complete the study.

5.5 Results

Fig. 6 shows the distribution of JND values across the different interval conditions. Notably, as shown in Fig. 7(a)(b), the JND ranges for the jaw-opening and jaw-closing phases at their respective three reference levels showed no overlapping, indicating the device could produce potentially distinguishable force feedback.

Taking the interval condition as the independent factor, the repeated-measures ANOVA revealed a significant main effect of Interval

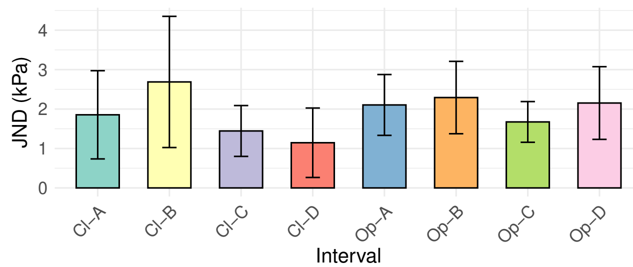
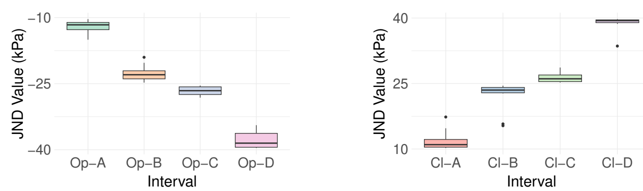


Fig. 6. JND Values Across Intervals.



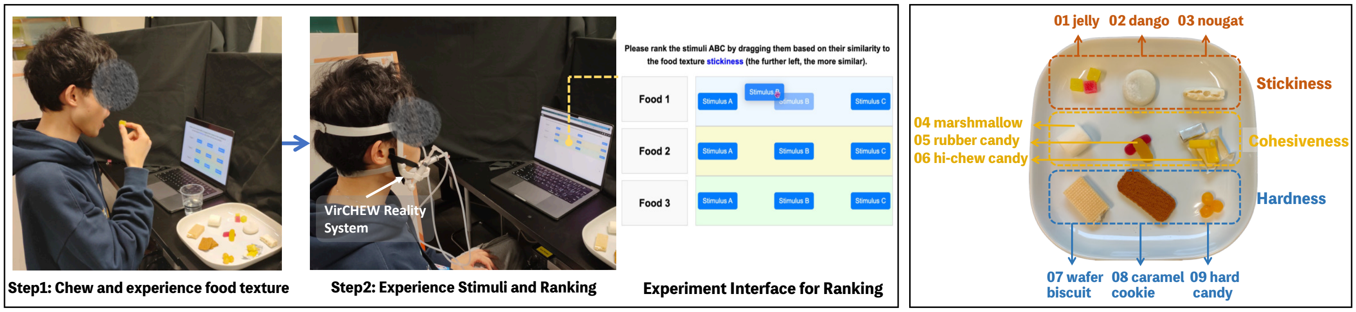
(a) Jaw-Opening Intervals (b) Jaw-Closing Intervals

Fig. 7. Distribution of JND Values for Jaw Opening and Closing Intervals

on JND values for both phases of jaw opening ($Op : F_{(3,33)} = 548.19, p < 0.0001, \eta^2 = 0.975$) and closing (($Cl : F_{(3,33)} = 340.29, p < 0.0001, \eta^2 = 0.955$)). Post-hoc pairwise comparisons with Bonferroni correction indicated significant differences between all interval pairs within the jaw-opening phase ($p < 0.001$) and the closing phase (($p < 0.05$)), as shown in Tab. 6&7 in Appendix. Additionally, we did not find any correlation between references and JND values both in Cl and Op. This suggested that the device's ability to produce distinguishable feedback was not strongly affected by the baseline force level in current setting.

5.6 Discussion of Study 1

Based on the results from Study 1, the non-overlapping JND values across different intervals suggested that the *VirCHEW Reality* is capable of generating distinguishable kinesthetic feedback for users during both jaw-opening and jaw-closing phases. Furthermore, the significant differences observed between all the interval pairs highlighted the resolution of human perception in detecting changes in



(a) Study setup for matching the on-face force Stimuli to food textures

(b) Food sample list

Fig. 8. Study 2: (a) Study setup illustrating the two-step process. (b) Food sample list categorized into three texture attributes.

on-face kinesthetic force intensity, which provided valuable insights for designing kinesthetic interfaces tailored for chewing scenarios. For example, when designing rendering food textures for medium softer foods (10 kPa - 25 kPa) in VR, we can adopt larger differences between two kinesthetic feedback levels, as JND values for Cl-B were significantly higher than other jaw-closing intervals. The JND values derived from this study not only quantified the perceptual granularity of *VirCHEW-Reality* system but also offered guidance for optimizing the force feedback for more immersive and precise chewing simulation in VR. Compared to the previous research on JND values for wearable kinesthetic haptic interfaces, *VirCHEW Reality* is the first to study the on-face force sensitivity which could potentially inspire the future research for on-face wearables.

6 Study 2: Matching the On-Face Force Stimuli to Food Textures

Building upon the validated stimulus levels in Study 1, we conducted a matching study to investigate how users may subjectively match the on-face force feedback provided by *VirCHEW Reality* to different food perceptions in terms of hardness, cohesiveness, and stickiness, which could guide the further feedback design in VR.

6.1 Participants

We recruited 12 participants (5 females) with an average age of 25.8 years (SD = 2.93). All had healthy chewing function and had not participated in the previous study.

6.2 Apparatus and Stimuli

As shown in Fig. 8(a), the experimental setup for Study 2 is similar to Study 1, with an added tray for holding food samples. To evaluate the ability of the *VirCHEW Reality* to replicate real food textures in terms of stickiness, cohesiveness and hardness, we selected three foods for each dimension, representing from low, medium, and high stimuli intensities, as shown in Fig. 8(b). Specifically, we selected jelly (Food 01), dango (Food 02), nougat (Food 03) for stickiness, marshmallow (Food 04), rubber candy (Food 05), Hi-Chew candy (Food 06) for cohesiveness, and wafer biscuit (Food 07), caramel cookie (Food 08), hard candy (Food 09) for hardness. Selection criteria prioritized common, recognizable foods that simulate varying intensities across texture dimensions. To minimize flavor influence on texture perception, foods with similar sweetness levels were selected based on packaging-reported sugar content. Additionally, food texture profiles were measured by a Texture Analyser TA.XT PlusC[1], as detailed in Table.2, Appendix A.2. To reduce the impact of food size and thickness on texture perception, all food samples were prepared to a uniform size, suitable for being placed entirely in the mouth in a single bite.

For the haptic feedback provided by *VirCHEW Reality*, we used the discriminable reference stimuli identified in Study 1 for both jaw-opening and jaw-closing actions. Specifically, the stimuli were listed as follow:

- **Stickiness:** -10 kPa, -25 kPa, -40 kPa (jaw opening)
- **Cohesiveness:** +10 kPa, +25 kPa, +40 kPa (jaw closing)
- **Hardness:** +10 kPa, +25 kPa, +40 kPa (jaw closing)

6.3 Experiment Design and Procedure

At the beginning of the experiment, the participant was briefed on the goal of matching haptic stimuli generated by *VirCHEW Reality* to the food textures across three abovementioned dimensions. He/she then went through the process of joystick calibration mentioned in Section 4.2. The experiment consisted of three groups of food samples, each targeting one texture dimension. For each group, the participant first consumed all three food samples to familiarize themselves with the targeted texture property.

During each matching trial, the participant first consumed a food sample for 5 seconds, then rinsed their mouths with plain water to neutralize residual flavor. He/she then experienced three haptic stimuli (low, medium, and high intensity) in randomized order, each lasting 5 seconds, while performing chewing motions guided by visual cues. A 10-second break was provided between stimuli to minimize sensory adaptation.

After experiencing all three haptic stimuli, the participant rated them based on their similarity to the food's texture, from 3 (most similar), 2, and 1 (least similar). This similarity-ranking task adopted in Study 2 was widely used in sensory evaluation on customer-perceived food properties [ISO 2006; Watts et al. 1989]. A 1-minute break was given between food samples, and each participant took a 5-minute break between groups. The order of the three texture groups was counterbalanced by a Latin square, and the order of

[1] https://www.stablemicrosystems.com/taxtplus.html

Texture Group	Food No.	Type	Low Stimulus Mean Score	Medium Stimulus Mean Score	High Stimulus Mean Score
stickiness	1	**Jelly**	2.58	1.83	1.58
	2	**Dango**	1.83	2.50	1.67
	3	**Nougat**	1.58	2.00	2.42
cohesiveness	4	**Marshmallow**	2.58	1.58	1.83
	5	**Rubber Candy**	2.00	2.42	1.58
	6	**Hi-Chew Candy**	1.50	1.92	2.58
hardness	7	**Wafer Biscuit**	2.42	2.17	1.42
	8	**Caramel Cookie**	1.75	2.58	1.67
	9	**Hard Candy**	1.58	1.92	2.50

Fig. 9. Study 2: Matching results of the on-face force stimuli to food textures.

food samples within each group was randomized to reduce potential biases. The total experiment duration was about 40 ∼ 50 minutes.

6.4 Results

The matching ratings of different types of foods under these three texture properties are descriptively shown in Fig. 9. Taking the stimuli levels as the independent factor for each texture properties and the participants' matching ratings as the dependent variables, we analyzed the results using the Friedman test followed by the post-hoc pairwise comparison using the Dunn's post-hoc test[Elliott and Hynan 2011]. Key findings are summarized below:

- **Stickiness.** We observed the significant effect of intensity levels on the matching ratings for the stickiness of Food 01, jelly ($\chi^2(2) = 6.5$, $p = 0.0388$), with low-intensity stimuli rated significantly closer to the texture than high-intensity stimuli ($p_{\text{adj}} < 0.01$). For dango (Food 02; $p = 0.097$) and nougat (Food 03; $p = 0.125$), no significant differences on the stickiness-matching ratings were found across different intensity levels, though medium- and high-intensity stimuli were generally rated as closer matches.

- **Cohesiveness.** For cohesiveness, the Friedman Tests revealed significant effect of the intensities levels on the matching ratings for marshmallow (Food 04; $\chi^2(2) = 6.5, p = 0.0388$) and Hi-Chew candy (Food 06; $\chi^2(2) = 7.17, p = 0.0278$). Low-intensity stimuli was rated with significantly better rating for matching with the cohesiveness of marshmallow ($p_{\text{adj}} < 0.01$), while high-intensity stimuli matched significantly better for Hi-Chew candy ($p_{\text{adj}} < 0.01$). No significant differences across the intensity levels were observed for matching with the cohesiveness of rubber candy.

- **Hardness.** There was a significant effect of the intensity level on the matching ratings for the hardness of wafer biscuit (Food 07; $\chi^2(2) = 6.5, p = 0.0388$) and caramel cookie (Food 08; $\chi^2(2) = 6.17$, $p = 0.0458$). Low-intensity stimuli received significantly higher matching ratings for wafer biscuit ($p_{\text{adj}} < 0.01$), and medium-intensity stimuli was rated significantly higher for matching with caramel cookie ($p_{\text{adj}} < 0.05$), in terms of the food hardness. No significant difference across the intensity levels was found for matching with hard candy.

6.5 Discussion of Study 2

Study 2 revealed that the on-face force feedback provided by *VirCHEW Reality* could be mapped to different categories of food texture, particularly for medium and high pneumatic stimuli, such as nougat (stickiness), Hi-Chew candy (cohesiveness), and caramel cookie (hardness). Overall, medium- and high-intensity stimuli were generally rated as better matches for firmer and stickier textures, while low-intensity stimuli were associated with softer textures. Moreover, larger between-subject variation was observed for certain cases, such as dango (stickiness), rubber candy (cohesiveness), and hard candy (hardness), possibly leading to the non-significant differences among stimuli for these food. Consistent with previous studies [Christensen 1984; Shupe et al. 2019; Zhou et al. 2021], the between-subject variability in Study 2 suggested that the effectiveness of haptic feedback depends on users' sensitivity of tactile perception. Future research should investigate how individual differences in tactile sensitivity may influence the perception of simulated food textures and explore how to accommodate users with varying sensitivity levels. Such efforts could facilitate the development of personalized haptic feedback systems[Malvezzi et al. 2021] that enhance texture realism for a diverse range of users.

7 Study 3: VR User Experience with *VirCHEW Reality*

Building on the findings of previous studies, we conducted a third user study in a VR eating scenario. This study aimed to evaluate how *VirCHEW Reality* may influence VR eating experiences.

7.1 Participants

We recruited 12 participants (4 females) with an average age of 27.75 years (SD = 1.48). All participants self-reported having healthy chewing function, balanced chewing ability, and the ability to perceive varying chewing forces. None had participated in the previous studies. Eight participants had prior experience with VR interaction, but only two had used VR combined with on-face haptic feedback.

7.2 Apparatus and Stimuli

Fig. 10 shows the experimental setup. The study utilized a VR eating scenario (shown in Fig. 10(b)) developed with Unity, running on a desktop computer equipped with an NVIDIA Quadro M4000. A Meta Quest 3 headset was used to provided immersive visual and auditory feedback as well as hand-tracking interaction.

Haptic feedback was delivered via the *VirCHEW Reality*, which was worn on the participant's face. The joystick on the device monitored participants' chewing actions and was synchronized with a collision box in the VR environment representing the user's virtual jaw. In the VR scene, the participant's hand motion was tracked to grab virtual food and perform a feeding motion to simulate placing the food into the participant's mouth. When the VR program detected that the virtual jaw was about to "chew" the virtual food (via the collision box), the pneumatic system triggered the corresponding haptic feedback for the tactile sensations of chewing.

There were three conditions used in this experiment: 1) an idle state in which the face-worn *VirCHEW Reality* was not turned on with no haptic cue (denoted as VC_{idle}), 2) the device provided randomized haptic stimuli unrelated to the virtual food (denoted as VC_{rand}), and 3) the device provided haptic stimuli corresponding to the virtual food textures (denoted as VC_{corr}). The haptic stimuli were selected based on the matching results in Study 2. Each participant experienced all three conditions, with their order counterbalanced using a Latin square design.

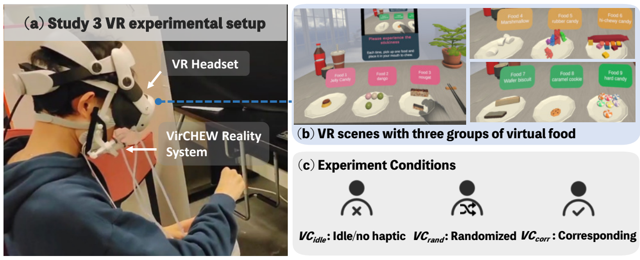


Fig. 10. Study 3: (a) The VR experience setup.(b) VR scenes displaying a selection of foods with varying textures. (c) Experiment conditions

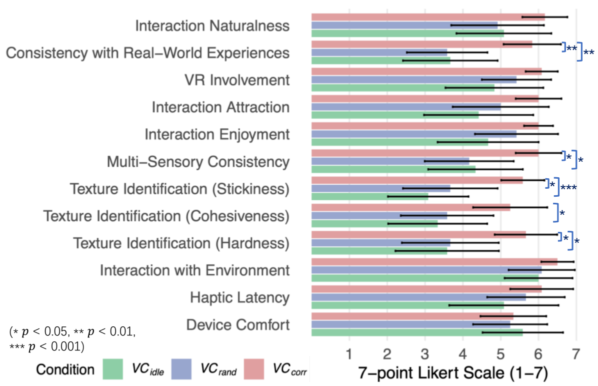


Fig. 11. Participants' Ratings of VR Experience in Study 3.

7.3 Task and Procedure

Similar to Study2, each participants went through the process of joystick calibration before all the trials. Before the main experiments, participants underwent a training phase to familiarize themselves with the virtual environment and interactions through exploring the VR eating scene without wearing the *VirCHEW Reality*. After that, participants were then engaged in three sessions corresponding to the three experimental conditions (VC_{idle}, VC_{rand}, and VC_{corr}) with the *VirCHEW Reality*. Within each session, participants experienced three groups of virtual food items. Each group was designed to reflect one of the three texture dimensions identified in Study 2 (e.g., stickiness, cohesiveness, hardness, see in Section 6.2). Each group contained three distinct virtual food items, resulting in nine items per session, as shown in Fig. 10(b).

To ensure comprehensive exposure, participants interacted with each virtual food item at least three times, with the presentation order of food groups and items randomized within each session. The duration of each session was approximately 10 minutes, including time for participants to experience all food items and haptic feedback. After each session, the participant took off the device, and filled out a questionnaire designed to evaluate their experience (see Supplementary Appendix A.3). Upon completing all three sessions, the participant was engaged in a semi-structured interview, to provide deeper insights into their subjective experiences. The entire procedure lasted approximately 50 minutes.

7.4 Results

7.4.1 Subjective Ratings of User Experience. The Fig. 11 shows the subjective rating results. The Friedman Test revealed that the stimulation condition significantly influenced participants' ratings on several questionnaire items, including realism of haptic feedback (Q02: $\chi^2(2) = 11.1, p < 0.01$), attraction (Q04: $\chi^2(2) = 12.1, p < 0.005$), enjoyment (Q05: $\chi^2(2) = 6.0, p < 0.05$), naturalness of chewing feedback (Q06: $\chi^2(2) = 8.22, p < 0.05$), and the ability to distinguish texture dimensions (stickiness, cohesiveness, hardness) (Q07a: $\chi^2(2) = 11.4, p < 0.005$, Q07b: $\chi^2(2) = 11.3, p < 0.005$, Q07c: $\chi^2(2) = 7.19, p < 0.05$). No significant effect of the stimulation condition was observed for other items (e.g., latency of feedback, controllability, and comfort). Conover's post-hoc comparisons revealed that there were significant differences between the realism of haptic feedback (Q02), the naturalness of chewing feedback (Q06), the stickiness (Q07a), the hardness (Q07c), where the VC_{corr} mode outperformed both than other two modes (all $p < 0.05$). For cohesiveness(Q07b), the VC_{corr} yielded higher rating comparing to the VC_{idle} mode ($p < 0.05$). For more details, please see Appendix.A.4.3.

7.4.2 Qualitative Feedback. **VR Eating Experience.** Most participants (n = 10) mentioned that eating in VR is an interesting and new experience. For example, P7 commented that "I have never imagined eating without real food." When asked about the enjoyment of the VR eating experience under different conditions , participants tended to find VC_{corr} more realistic in replicating the sensation of chewing thus more engaging and joyful in overall. This preference was attributed to the fact that VC_{corr} offered a more accurate force feedback, in contrast to none (VC_{idle}) or less consistent feedback (VC_{rand}). As P11 stated, "The mismatched feedback sometimes decreased the realism of the eating experience."

Perception with Food Textures. Participants' perceptions of the three food texture attributes — hardness, cohesiveness, and stickiness—varied. Five participants (P1, P2, P8, P9, P12) reported that the simulation of hardness and stickiness closely resembled real food, while six participants (P3, P4, P5, P6, P10, P11) found cohesiveness to be the most realistic. This divergence in responses may reflect individual differences in sensitivity to specific texture attributes.

Comfort & Social Acceptance. When asked about the device's comfort, the majority of participants (n = 9) reported no discomfort during the 30-minute experiment. One participant (P10), however, mentioned experiencing mild fatigue, potentially due to excessive jaw movement during the VR chewing interaction. Seven participants explicitly expressed no concerns about the social acceptability of the device as a VR headset accessory. P4 expressed anticipation that future VR eating could "let friends share the mouthfeel of the food they eat". However, P3 mentioned that she would feel somewhat self-conscious using it in highly public settings.

Mismatched Feedback as a Catalyst for Engagement. Three participants (P1, P2, P6) mentioned that VC_{rand} could be, in fact, more fun compared to VC_{corr}. For instance, P1 shared that during the VC_{rand} condition, she noticed a mismatch between the haptic feedback and the visual representation of the virtual food. She found this mismatching intriguing, as it offered an experience unavailable with real food, driving her to explore this "bizarre" sensation.

7.5 Discussion of Study 3

Overall, the results indicated that the synchronized haptic feedback (VC_{corr}) significantly enhanced participants' ratings on perceived realism, naturalness, and texture discrimination in VR eating experiences, compared to the other two conditions. These findings revealed the importance of synchronized multi-sensory integration in creating immersive and realistic VR food taking interactions.

The post-experiment interview in Study 3 identified several potential applications of *VirCHEW Reality* suggested by our participants. First, the system holds potential for social eating and sharing in VR, enabling not only the remote sharing of tactile characteristics of food but also the potential to evoke and share the emotions associated with eating experiences [Jiang et al. 2014; Macht and Simons 2000]. Additionally, its ability to provide various force feedback suggests applications in healthcare and rehabilitation, such as assisting the elderly or patients with weak/impaired chewing functions in recovery or supporting dietary behavior correction [Eertmans 2001]. Furthermore, the participants pointed out the potential value of *VirCHEW Reality* for diabetes management in which the patients may need to avoid sugar consumption and the device could offer a safe alternative while satisfying their cravings. Given these findings, *VirCHEW Reality* further exhibits potential for integration with other sensory modalities, such as olfaction, gustation, and thermoception. Aligning with multisensory integration theories [Spence 2016], future iterations of the system could amplify immersion by incorporating additional modalities, including olfactory (e.g., scent diffusion for "freshly baked" textures) or thermal feedback (e.g., nuanced mouthfeel of chocolate under warm or cold conditions).

8 Limitation

We observed several limitations in our current system. First, our approach focused on solid/semi-solid foods and was limited to the initial chewing phase, overlooking the dynamic changes in texture perception over time. Future work should explore adaptive force feedback, such as real-time modulation of pneumatic pressure or texture patterns based on chewing intensity or duration, to simulate the gradual transformation of food from solid to semi-solid or liquid states. Second, the between-participant perception variation, particularly in Study 2, pointed to the future research on how individual differences in tactile sensitivity influence the perception of simulated food textures. Additionally, long-term usability concerns, such as user fatigue, comfort, and hygiene, should be addressed, especially considering the potential for prolonged use in real-world applications. Future iterations should prioritize lightweight, ergonomic designs to minimize physical strain, ensuring both practicality and comfort for extended or repeated use.

9 Conclusion

In this paper, we present *VirCHEW Reality*, a face-worn haptic device to provide on-face kinesthetic force feedback, for simulating the chewing experience with the food of different hardness, cohesiveness, and stickiness. The on-face force was produced by controlling the process of air inflation and deflation. Our user studies showed that *VirCHEW Reality* could generated distinguishable levels of kinesthetic forces that could be further matched to different food textures. More importantly, our system could significantly improve user experience in taking virtual food in VR. Our findings highlighted the potential of on-face kinesthetic feedback to enrich virtual eating experiences, leading to possible applications in virtual/remote dining, healthcare, and immersive entertainment.

Acknowledgments

This research was partially supported by the Centre for Applied Computing and Interactive Media (ACIM) of School of Creative Media, City University of Hong Kong. This work was also partially supported by the National Natural Science Foundation of China (Project No. 62172346), and the Innovation and Technology Fund (Project No. ITS/106/22). This project is supported by the Ministry of Education, Singapore, under the Academic Research Fund Tier 1 (FY2024) Award 25-0156-A0001.

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