TouchMark: Partial Tactile Feedback Design for Upper Limb Rehabilitation in Virtual Reality

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Fig. 1. A: Patient was instructed by the experimenter and therapist in the virtual tutorial process; B: Four steps of virtual soup preparation: engaging with tangible handles to mirror cutting, pouring, adding, and stirring actions using corresponding virtual utensils with *TouchMark*; C: Four types of tangible handles with different *TouchMark* designed for virtual tasks.

Abstract—The use of Virtual Reality (VR) technology, especially in medical rehabilitation, has expanded to include tactile cues along with visual stimuli. For patients with upper limb hemiplegia, tangible handles with haptic stimuli could improve their ability to perform daily activities. Traditional VR controllers are unsuitable for patient rehabilitation in VR, necessitating the design of specialized tangible handles with integrated tracking devices. Besides, matching tactile stimulation with corresponding virtual visuals could strengthen users' embodiment (i.e., owning and controlling virtual bodies) in VR, which is crucial for patients' training with virtual hands. Haptic stimuli have been shown to amplify the embodiment in VR, whereas the effect of partial tactile stimulation from tangible handles on embodiment remains to be clarified. This research, including three experiments, aims to investigate how partial tactile feedback of tangible handles impacts users' embodiment, and we proposed a design concept called *TouchMark* for partial tactile stimuli that could help users quickly connect the physical and virtual worlds. To evaluate users' tactile and comfort perceptions when grasping tangible handles in a non-VR setting, various handles with three partial tactile factors were manipulated in Study 1. In Study 2, we explored the effects of partial feedback using three forms of *TouchMark* on the embodiment of healthy users in VR, with various tangible handles, while Study 3 focused on similar investigations with patients. These handles were utilized to complete virtual food preparation tasks. The tactile and comfort perceptions of tangible handles and users' embodiment were evaluated in this research using questionnaires and interviews. The results indicate that *TouchMark* with haptic line and ring forms over no stimulation would significantly enhance users' embodiment, especially for patients. The low-cost and innovative *TouchMark* approach may assist users, particularly those with limited VR experience, in achieving the embodiment and enhancing their virtual interactive experience.

Index Terms—Virtual rehabilitation, embodiment, body ownership, agency, self-location, tactile sensation

1 Introduction

Using various virtual reality (VR) scenes in different contexts has become more prevalent nowadays, and VR allows the simulation of conditions that are difficult to achieve in the real world, especially in rehabilitation [1, 2]. The rehabilitation tasks of the physical world may carry certain risk factors; for instance, patients undergoing upper limb rehabilitation need to regain their ability to perform activities of daily living (ADLs), including cooking tasks. Performing this task in the physical world often involves the use of dangerous kitchenware and open flames, both of which pose significant risks [3, 4]. Using VR technology can provide patients with a safe and immersive environment for practical training [4, 5].

Users' interactive experiences in VR can be enhanced by haptic feedback, with traditional VR controllers frequently serving as the primary source of tactile stimulation for users [6]. It has been discovered that haptic feedback significantly contributes to aspects of motor coordination in upper limb rehabilitation [7], and

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using tangible handles as haptic stimuli could improve patients' task performance and training results [8-10]. However, traditional VR controllers are not ideally suited for patients with various hand issues. The use of 3D printing to create cylindrical handles (modelled after conventional rehabilitation equipment) and the addition of VR sensor attachments have laid a foundation for developing specialized tangible handles that better meet the needs of these patients [11-14]. These tangible handles enable tactile stimulation at specific points on users' fingertips, enhancing the virtual interactive process and experience [15, 16]. In our research, partial tactile feedback is specifically defined as the activation of tactile stimuli solely in designated areas of the hand (e.g., fingertip or palm) instead of the entire hand. Considering the limited exploration of partial tactile feedback, particularly in the context of VR rehabilitation, this research utilizes it to enhance the interaction experience.

One essential factor of user perception in VR interactions is the sense of embodiment, and this concept enhances user experience by enabling more natural interactions and allowing users to own virtual bodies within the virtual world [17, 18]. The embodiment comprises four subcomponents: the subjective experience of owning (*body ownership*), controlling (*agency*), and being inside a virtual body (*self-location*) through multisensory information [19, 20], and haptic stimulation (*tactile sensation*) [21]. Enhanced embodiment may have a positive impact on kinematic movement training during rehabilitation if patients own the virtual hand to perform repetitive tasks, potentially improving upper limb function and cognitive abilities in patients [22-24]. Recent studies have highlighted the importance of haptic feedback in strengthening the embodiment within virtual environments (VEs), and they have also explored the use of tactile stimulation to investigate different embodiment dimensions in VR [3, 20, 25, 26]. It is now established that adding haptic feedback for users could influence their embodiment, but how partial tactile feedback from handles affects the embodiment in VR remains largely unexplored.

The research aims to investigate the effect of partial tactile feedback provided by tangible handle tools with different tactile stimulation on users' embodiment in virtual rehabilitation. We introduce an innovative design approach named *TouchMark*, which integrates partial tactile feedback to bridge the virtual and physical worlds. This integration is realized through the red mark that serves as both tactile and visual cues. This red mark is implemented as a tactile cue on real-world objects, providing a consistent and tangible point of reference. Correspondingly, the visual cue in the form of a red mark is displayed on virtual tools for easy identification. The design of *TouchMark* on tangible handles brings the raised tactile stimulator into contact with the user's thumb pad area (a region of high sensitivity), thereby ensuring rapid convergence between the user's virtual and physical interactions.

This research includes three experiments in non-VR (Study 1) and VR (Study 2 and 3). In Study 1, we assessed users' tactile perceptions and comfort levels that participants experienced while grasping various tangible handles. Study 2 investigated how various handles with different partial tactile feedback impact the embodiment of healthy users to perform virtual cooking tasks within VR, and Study 3 continued this exploration but focused on patient groups. We used a self-reported embodiment questionnaire to assess the degree of users' embodiment, and recorded objective data on eye tracking to help us understand users' behaviors.

The main contributions of this article are threefold: Our comprehensive research explores how the partial tactile feedback of tangible handles improves users' embodiment in VR-based upper limb exercise rehabilitation. Additionally, we introduce *TouchMark*, an innovative design that employs a red mark as both a tactile feature and a visual cue in VEs on real-world objects to bridge virtual and physical interactions. The design of *TouchMark* is cost-effective, enhancing its usability in VR rehabilitation and showing significant potential in further VR applications.

2 Related Work

2.1 Upper limb rehabilitation

Occupational therapy has been identified as a potential rehabilitation method to allow patients with upper limb disabilities to restore their ability to conduct ADLs [4, 5]. ADLs encompass activities that enable individuals to live independently without assistance, including food preparation. Research has indicated that task-oriented approaches, which emphasized the achievement of specific goals, could enhance performance for ADLs [4, 27]. Traditional task-oriented therapy necessitates patients performing tedious tasks in a controlled environment repeatedly. While these processes are important for effective rehabilitation, they can also be demanding, potentially reducing training efficiency.

VR rehabilitation complements traditional methods and enhances the effectiveness of training according to current research [5, 28, 29]. Several tasks are based on the repetition of ADLs, promoting patients' motor learning through increased intensity during task-oriented training [4]. A significant advantage of a VR rehabilitation system is the ability to customize training tasks through computer programming to meet users' specific needs. It also offers a secure environment for rehabilitation, minimizing any potential risks to physical safety [29, 30]. Importantly, patients with stroke need exercises that specifically focus on their hand movements to perform ADLs, and previous rehabilitation practices relied on using devices like computer mice or VR controllers. However, these traditional devices do not adequately train the fine motor skills (e.g., grasping handles) essential for them. Hence, the integration of tangible handles with VR tracking technology could be a valuable approach to developing specialized virtual rehabilitation tools.

2.2 Partial tactile feedback in VR

The tactile cues, besides visual stimuli, are also one of the driving factors for inducing user perceptions, and the presence of haptic feedback could provide users with more realistic interacting experiences in multiple backgrounds [31]. It has been reported that strong haptic stimuli are perceived by users' hands when they are wearing a whole tactile glove in VR [32, 33]. However, recent work highlighted that partial tactile stimulation has the potential to be one category of whole haptic feedback for users to improve their virtual interactive experience [34, 35]. Partial tactile feedback refers to the delivery of tactile stimuli specifically to localized areas on the hand, and several studies have focused on the feedback on partial hand fingertips [26, 34, 36-38] and hand palms [20, 36, 39]. Moreover, for patients with upper limb motor impairments and reduced tactile sensitivity, these partial tactile stimuli could provide precise sensory input, which assists them in more effectively recognizing and processing tactile information.

Tangible handles are used to convey the haptic sensation of touching virtual objects. It has been proposed to integrate tangible handles into the virtual world by attaching the tracking sensor to physical objects [11-14], and tangible proxies' three-dimensional shape feature is one of significant cues for recognizing objects by users' hands [40]. Research also indicates incorporating tactile feedback from tangible handles into VEs can heighten user perceptions, including immersion [38, 41] and presence [11, 13, 41].

2.3 The sense of embodiment in VR

One important factor of user perceptions in VR is the embodiment, and the subcomponents of embodiment (i.e., body ownership, agency, self-location, and tactile sensation) refer to users owning virtual hands or avatars as one part of their bodies to interact within VEs [19, 20, 42]. Previous research related to the sense of embodiment and haptic feedback has employed the standard questionnaire for measuring subjective data [25, 26]. Additionally, recent research suggests physiological monitoring (i.e., eye tracking) to obtain objective data in VR by complementing subjective assessments. It enables the tracking of how users' attention is drawn to specific visual cues in VEs, including the red marker correlated with *TouchMark* in this work.

Recent advancements in VR have highlighted enhancing user perceptions through tactile feedback. Studies have applied tactile feedback as external stimuli to humans in VR scenarios to explore how people perceive their virtual bodies in correlation with the dimensions of embodiment [25, 26]. Research has shown that the addition of vibrotactile stimulation provides a more realistic virtual interaction, becoming a key element in reinforcing the embodiment of VEs [20, 25, 26]. Furthermore, participants can use their fingers to identify partial tactile feedback, including textures and convex shapes [34, 36]. One study illustrated how basic geometric objects could be transformed into distinctive haptic feedback, exemplified by a small cuboid connected to a cylinder that mimics the form of a pistol with a trigger [33].

Overall, a deeper insight into how tangible haptic feedback influences users' embodiment (including healthy people and patients with upper limb motor function) during interactive experiences is important to improve both user experience and behavior within VR [43]. The embodiment can be characterized as a beneficial psychological state where patients perceive virtual bodies as their own, which is significant for enhancing upper limb function through kinematic movements [22]. While specialized tangible handles providing haptic feedback have shown a potential to significantly improve patient engagement and the effectiveness of upper limb rehabilitation [8], most previous studies have focused on reducing inconsistencies in physical interactions to match the visual richness of VEs, thereby enhancing user experience [36, 39]. However, the specific influence of partial tactile stimuli on users' embodiment remains underexplored in VR [13, 44]. This lack of detailed understanding represents an important gap in current research, particularly concerning how such partial tactile feedback affects the sense of embodiment and its applications in medical settings.

3 METHODOLOGY

These experiments were designed to evaluate the influence of various partial haptic feedback on user perceptions of upper limb rehabilitation in VR. There were three user studies as continuous explorations (see Fig. 2). The university ethics committee approved experimental studies with healthy participants, and Kunshan Rehabilitation Hospital's ethics committee approved this experiment with patients. All healthy participants and patients provided informed consent.

3.1 User Study 1: Haptic prediction without visual information in non-VR

The aim of conducting the non-VR tactile experiment is to allow participants to discern partial haptic feedback (i.e., shapes, size, and form) of tangible handles through their hand-based tactile stimulation (explicitly using the thumb) for users by grasping the tangible handle, and evaluate the tactile perception and comfort level. Drawing on previous studies about haptic perceptions of volume and surface area of 3D objects through users' hands and fingers, our experimental setup was designed to incorporate these tactile stimuli [40, 45, 46]. The setup of this study focused on the three-dimensional aspects of shape, size, and form as the partial haptic sensation. Our study explored the descriptors of tactile and comfort factors associated with grasping tangible handles, utilizing questionnaires designed for hand tools to gather subjective measurements related to tactility and comfort tactility (see Table I of Appendix) [47-49].

Design and Setup. The task was designed to simulate real-life scenarios where touch is critical for daily instrumental activities. Before the experiment, researchers thoroughly briefed participants on the correct way to grasp the tangible handle. The user's right hand was asked to grasp the tangible handle naturally and then placed the thumb pad on the area of partial tactile stimulation (see Fig. 1C). Based on prior literature on cylindrical grasping [33, 50] and aiming to enhance hand functionality for rehabilitation [51], this experiment used a cylindrical prototype as the tangible handle, measuring 3 cm in diameter and 15 cm in height (see Fig. 1C). The tangible handle was designed with two components: a cylinder 3D-printed from polylactic acid plastic and an HTC Vive tracker installed on top.

These objects provided partial tactile stimulus, necessitating the participants to focus on their hands' tactile perceptions. The independent variables in this research were defined by partial tactile **shapes** (cube and sphere), **sizes** (volume with 0.2, 0.4, and 0.6 cm^3), and **forms** (point, line, and ring), using a $2{\times}3{\times}3$ factorial design to explore their interactions. This design matrix resulted in 18 distinct types of handles (see Fig. 2 left), each representing a unique combination of shape, size, and form. These combinations were systematically designed to explore the interaction effects among these three variables on tactile perception. For instance, one tangible handle included a sphere shape with a volume of 0.4 cm^3 (i.e., approximately 1 cm in diameter) and a ring form (see Fig. 2 left for a detailed 3D model) as the *Touchmark*, which is located on the cylindrical handle's upper part and allowed users to touch this tactile stimulus with their right thumb pads.

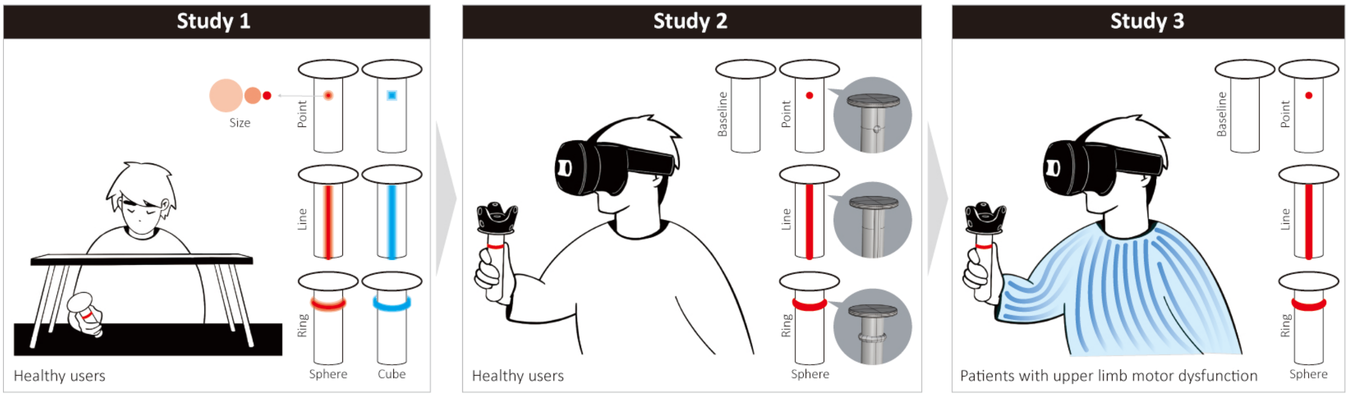

Fig. 2. Study 1: User tactile and comfort ratings were evaluated by grasping tangible handles in a non-VR environment. Study 2: Four tangible handles with various *TouchMark* were assessed in VR by healthy users. Study 3: Clinical trials with patients using four tangible handles with *TouchMark*.

All variables were within the subject, and each participant was asked to grasp all 18 tangible handles for perceptual experience. To ensure they rely solely on their sense of touch, we cover the partition board to prevent them from directly seeing the tangible handle. During the experiment, the various combinations of partial tactile stimulation (shapes, sizes, and forms) on tangible handles were changed within a range invisible to the participants (i.e., under the board). 32 adult participants (22 males and 10 females) aged 19 to 32 years (M (Mean) and SD (standard deviation): 23.31 ± 3.11) with healthy upper limb motor function and touch perception were recruited.

Procedure. The participants were instructed on grasping the tangible handle with a uniform posture, ensuring their thumbs adequately interacted with the handheld tangible tools' part. They are required to reach their hands into the board to grasp within the defined area and sense the partial tactile feedback while holding the tangible handle (see Fig. 2 left). They were not allowed to look at tangible handles in the whole process, and the experimenter could change the handle in and out below the partition. In each trial, one tangible handle from 18 objects was randomly chosen by the experimenter, and one participant needed to perceive all tactile stimuli situations randomly. After completing these tactile sensing tasks, they responded to questionnaire items related to the comfortable feeling and the sense of partial tactile stimuli. Participants were given a tablet that was placed on the table to fill out questionnaires using their left hand. To ensure they could still recall the tactile feeling accurately while responding, participants were allowed to hold the tangible handles with their right hand under the table. These questions of Study 1 that shown in Table I of the Appendix were slightly modified to align with the previous research [47-49], and the total time of the study was about 1 hour based on these 18 conditions.

3.2 User Study 2: Tangible handles for users in VR

This experiment was designed to evaluate the impact of various partial haptic feedback on the sense of embodiment for upper limb rehabilitation in VR. The experiment was conducted in a simulated VR kitchen environment, where participants were tasked to prepare a soup. This task choice is based on prior research on ADL in rehabilitation, which identified cooking as one of the daily activities involving a range of upper limb movements and hand postures, precisely cylindrical grasping.

Design and Setup. The HTC Vive Pro Eye Headset and a Windows-based computer (Intel(R) Core (TM) i7-9800X CPU) were used in the experiment, and participants could observe the virtual environment (i.e., a virtual kitchen scene) made with Unity (2019.4.16). Participants were asked to grasp a tangible handle without partial tactile stimuli and three tangible handles with stimuli (i.e., point, line, and ring with a sphere shape) based on the user perceived results of Study 1 in their right hand randomly. The HTC Vive Tracker was used to attach to the top of the tangible device to reflect the positions of these tangible designs concerning virtual objects. Participants could see a virtual kitchen, including a cooktop, a cupboard, a sink, and a variety of utensils. The tangible handle grasped in the participants' right hand in the physical world corresponded to various virtual kitchenware in this study, such as virtual knives, cups, spice jars and stirring rods. In addition to displaying virtual tools corresponding to these tangible handles, virtual translucent hands also appeared in the virtual environment while grasping tangible handles. The within-subject experiment followed four sessions (see Fig. 1B). Except for these three tangible handles, the absence of partial tactile stimuli was measured as the baseline to compare results.

These three designs of tangible handles with partial tactile stimuli (i.e., point form, line form, and ring form with sphere shape) were chosen in Study 2, which was based on the user perceived results of Study 1. 32 healthy right-handed participants with no or limited VR experience (16 males and 16 females) from the university who had regular or corrected-to-normal visions were invited, aged 20 to 41 years (M=25.44, SD=3.65).

Procedure. *(1) Pre-experiment.* Participants signed informed consent first. Before wearing the VR headset, the experimenter showed participants these four tangible handles they would use later and instructed them to grasp objects in the correct position (i.e., thumb pad of right hand touching partial tactile stimuli). Participants can pick up these four objects directly to familiarize themselves. Then, they were asked to complete the eye calibration before the VR experiment, using the researcher's guidance. The researcher orally explained the purpose and precautions of Study 2, and reminded them to pay attention to the visual and tactile stimulation of objects. Participants would enter this tutorial using a VR controller, which allowed them to familiarize themselves with virtual scenarios and subsequent soup preparation tasks.

(2) Experimental task. The experiment aimed to complete the soup preparation task in the VR game includes four key steps: chopping vegetables by grasping a virtual knife, adding water by grasping a virtual cup, adding seasoning by grasping a virtual spice jar, and stirring the soup by grasping a virtual stirring rod (see Fig. 1B). These steps correspond to the three spatial movements typically involved in cylindrical object grasping—upward and downward movements, flipping, and planar rotation. Participants are asked to grasp a tangible handle with various partial haptic feedback in the physical world. The cylinder's position is tracked using an HTC Vive tracker, making it a functional utensil in VR. In the game, a tangible handle morphs into a knife, a cup, a spice jar, and a stirring rod at different stages of the task, creating an immersive experience. The participants were able to observe their virtual hand grasping kitchenware and engaging with multiple objects within VEs. Each session of the soup preparation task lasts approximately 3 minutes, and it could take about 2 minutes to complete the embodiment questionnaire in VR. For every gap between the two sessions, participants were allowed to take a break of approximately 1 minute. Participants randomly performed these experimental tasks in all sessions according to Latin scales.

Data. The whole experiment took approximately 40 minutes to complete. The primary outcomes of interest are the participants' perceptions of the partial haptic stimuli and how these stimuli impact their perceptions of the task and overall VR experience. These outcomes are analyzed using an embodiment questionnaire, post-interview responses, task performance and eye tracking data.

(1) VR Questionnaire of the embodiment. The participants were instructed to use a commonly used questionnaire to evaluate the embodiment in VR, defined as the psychological sensation of feeling the virtual hand, to perform the experimental tasks, as they observed their hands grasping these tangible handles with partial tactile stimulus [21]. The VR questionnaire application enables participants to respond directly in VEs, thereby mitigating the potential influence of repetitive actions (donning and removing the VR headset) on the experimental data [52]. After each session, they were presented with a questionnaire featuring a 7-point Likert scale (ranging from -3 "Strongly disagree" to +3 "Strongly agree") to assess their embodiment scores, accompanied by seven numbered buttons for responses [21]. The participants needed to answer these embodiment questions, available in both English and Chinese, using the VR controller in their left hand, and the details of the questionnaire are provided in Table II of the Appendix.

(2) Eye tracking data and post-interview. Objective data of eye tracking movements in each session were recorded during the task for later analysis of user perceptions. These eye tracking data include eye behaviors under all sessions, including fixation count and fixation length. The fixation count shows the entire number of

eye fixations recorded on these tactile representations for virtual kitchenware (i.e., virtual hand tools and their partial tactile stimuli), and the fixation length refers to the amount of time each fixation lasted. For instance, when participants started the tasks, the number of fixations about what they viewed as tactile representations, virtual kitchenware or other places during the specified time was recorded in each task. After participants answered the question in VR for all sessions, they were instructed to take off the VR headset. Then, they participated in interviews to provide qualitative insights into their interactive experience.

3.3 User Study 3: Tangible handles for patients in VR

Mirroring Study 2's methodology, this user study aimed to assess how partial haptic feedback affects patients' perceptions during virtual upper limb rehabilitation exercises (see Fig. 1A). This VR-simulated kitchen activity was chosen for its incorporation of various upper limb motions under the ADL.

Design and Setup. The experimental design and system used in this research were mainly in line with those outlined in Study 2, with four modifications to better suit the specific needs of these patients. (1) The virtual scene's height was adjusted to ensure that patients who use wheelchairs could effectively engage in the tasks. (2) Trials were adjusted based on the general health status of all patients, which led to a reduced number of trials. (3) The VR questionnaire was adapted to the paper format, focusing on four subcomponents of the standard embodiment questionnaire and retaining all positive questions from each subset (see Table III of Appendix). (4) We did not record data on task performance and eye tracking due to concerns regarding patients' age and condition. The generally short duration of the experiment sessions also further supported the decision to exclude eye tracking, aiming to simplify the process and minimize potential stress for them.

25 patients (11 with hand trauma, 12 with stroke, and 1 with quadriplegia; 9 females and 16 males) without prior VR experience were invited to participate in this clinical VR study from the rehabilitation hospital. Their ages ranged from 13 to 78 years old (M=47, SD=15), and the majority were middle-aged and elderly individuals. All patients were required to use their affected limb (i.e., right hand) for rehabilitative exercises, and they had undergone assessments using hand function scales at the hospital.

Procedure. *(1) Pre-experiment.* After signing an informed consent form, the researchers verbally assured patients that this experiment posed no health risks and that the difficulty level would be adjusted according to each patient's health condition. All the tangible handles were presented directly to the patients to experience, and they touched the red mark while listening to the researcher's oral explanations. Then, they wore the VR headset and performed eye calibration with the researcher's guidance to ensure that the visual display was clear and not blurred. *(2) Experimental task.* The procedure was the same as Study 2, and four types of tangible handles (including a baseline with no tactile feedback and three with partial haptic feedback) were conducted in random order. However, we observed that adding the seasoning step required a complete arm inversion, making the movement quite challenging for patients with stroke, and then deleting this step. Each soup preparation task lasted approximately 2 minutes, after which patients removed the VR headset to complete a paper-based questionnaire (see Table III of Appendix). Upon completion of the tasks, researchers conducted interviews to obtain qualitative insights into patients' interactive experience and their preferences regarding the tangible handles used.

4 Results

All the results were reported in this section, and the raw question data from three studies were summarized using Excel from *Tencent* questionnaire software. Additionally, objective task-related data (i.e., task performance and eye tracking) in Study 2 were recorded within the task system. The IBM SPSS statistical analysis software was used to perform all data.

4.1 User Study 1: Haptic perceptions without visual information

The comfort description questionnaire and an overall comfort question evaluated the total comfortable grasping scores. Based on *Shapiro-Wilk tests* ($p<0.05$), the distributions of the tactile perception and total comfortable grasping values were not normal. For nonparametric data testing, we applied an aligned rank transform (ART) analysis of variance (ANOVA) [52]. These self-reported results were therefore analyzed by three-way repeated measures ANOVAs with ART, including three variables (sizes, forms, and shapes) as within-subjects factors.

4.1.1 Tactile perception of grasping tangible handles

Whole tangible handles. The main effect of **form** was significant, $F(2, 558)=9.194$, $p=0.000$. Tactile perception of grasping whole tangible handles was shown significantly higher values for line (M=5.52, SD=0.86) to point (M=4.74, SD=1.17), and ring (M=5.51, SD=0.92) to point ($p<0.05$) by the *post-hoc* analysis. The main effects of size and shape were not significant, but these tangible handles with the cube shape were rated with a lower tactile perception compared to the sphere shape. Participants were asked to perform three movements (i.e., cut, pour, and stir) to assess their overall grasp perceptions of these tangible handles. For the cutting and pouring motion, there were statistically significant differences in the **form** ($p<0.05$). *Post-hoc tests* showed significant differences among each set of forms, such as a line to point, and ring to point. However, no statistically significant differences existed in the pouring motion—partial **tactile stimuli.** There was a statistically significant difference in the **form** for perceiving a better feeling about users' thumb, $F(2, 558)=14.688$, $p=0.000$. The forms with line (M=5.05, SD=1.23) and ring (M=4.90, SD=1.34) significantly revealed a higher mean value about the better perception of grasping tangible handles with partial stimuli to the point from (M=3.88, SD=1.58). The main effect of the **form** ($F(2, 558)=4.050$, $p=0.018$) was revealed for a clear sensation of partial stimuli on the thumb pad. The form with point (M=6.05, SD=1.12) showed the highest mean value over the line form (M=5.66, SD=1.19) and ring (M=5.76, SD=1.26). Besides, it was found that the mean **form** × **shape** interactions for believing that this partial stimulation was necessary for the thumb's tactile perception, $F(2, 558)=3.324$, $p=0.037$. For the tangible handle with point and ring forms, the sphere shape was rated significantly higher than the cube.

4.1.2 Subjective comfortable grasping ratings

The main effect of size and shape was not significant. However, the main impact of **form** was significant, $F(2, 558)=6.767$, $p=0.001$. *Post-hoc (Bonferroni-corrected t-tests) tests* revealed significantly higher comfortable grasping ratings for line (M=4.92, SD=1.08) compared to point (M=4.10, SD=1.21), and ring (M=5.00, SD=1.13) compared to point ($p<0.05$). Moreover, a tangible handle with a small size, ring form, and sphere shape was rated as the highest comfortable grasping perception value (M=5.24, SD=1.03).

4.2 User Study 2: Partial tactile forms for users in VR

4.2.1 Self-reported embodiment ratings

A total of 32 data sets were analyzed using the commonly used avatar embodiment questionnaire in Table II of Appendix [21], which evaluates embodiment scores during the interactive process of virtual hand based on its subcomponents, such as the tactile sensations, body ownership, agency, and self-location. Given the data collected under these four conditions, pairwise comparisons between each condition were planned to investigate significant differences. To ensure the validity of the *paired t-tests*, a *Shapiro-Wilk test* ($p>0.05$) was first applied to the differences in scores between each pair of conditions to assess normality. With this confirmation of normal distribution, the statistical analysis was conducted using *paired t-tests* to compare the impact of four independent variables (no tactile stimulation, and three tactile forms including the point, line, and ring) on the embodiment. The results indicated varying levels of significance, which were detailed below in Fig. 3.

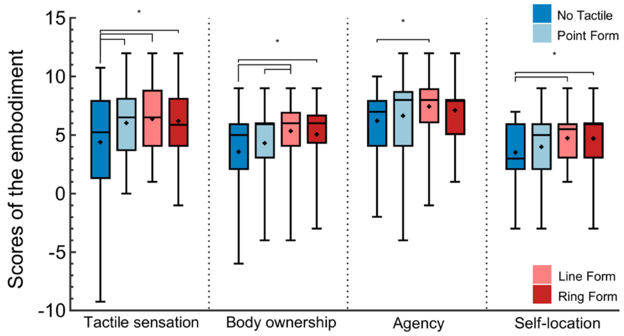

Fig. 3. The embodiment results about four subcomponents in Study 2.

Tactile sensations. The *t-test* revealed a significant difference in the effect on the users' tactile sensations, with no tactile stimulation session (M=4.398, SD=4.68) showing a significantly lower value than other three partial tactile sessions ($p<0.05$), such as partial point session (M=6.039, SD=3.02; $t(31)=-2.365$), partial line session (M=6.391, SD=2.85; $t(31)=-2.267$), and partial ring session (M=6.188, SD=2.99; $t(31)=-2.502$). **Body ownership.** These significant differences were observed in the body ownership when comparing no tactile stimulation session (M=3.563, SD=3.72) and partial line session (M=5.344, SD=2.95) and no tactile stimulation session and partial ring session (M=5.063, SD=3.03), where no tactile stimulation session demonstrated a significantly lower value than these two the forms (line: $t(31)=-2.434$; ring $t(31)=-2.436$; $p<0.05$). Moreover, the partial line session also reported a significantly higher value than the point form (M=4.313, SD=3.23; $t(31)=-2.442$; $p<0.05$). **Agency.** Statistical analysis revealed a significant difference between the effects of different partial tactile stimulation sessions (no tactile stimulation and the partial line form) on the agency. The mean value associated with no tactile stimulation session (M=6.219, SD=3.04) was significantly less than that of line form (M=7.438, SD=2.95; $t(31)=-2.115$, $p<0.05$), pointing to a distinct disparity in their effects. **Self-location.** Comparing the impact of no tactile stimulation session and other partial tactile stimulation sessions on the sense of self-location, the results of the *t-test* were significant on the line form (M=4.750, SD=1.98; $t(31)=-2.865$, $p<0.05$) and ring form (M=4.719, SD=2.65; $t(31)=-3.065$, $p<0.05$). No tactile session (M=3.531, SD=2.76) was associated with substantially lower mean values than others, indicating significant differential effects. **Total embodiment** Analysis using the *t-test* revealed statistically significant differences in the influence of no tactile stimulation session compared to partial tactile line stimulation (M=1.721, SD=0.64; $t(31)=-2.886$) and ring form (M=1.662, SD=0.70; $t(31)=-2.976$) on the embodiment. Results showed that the mean effect of no tactile stimulation session (M=1.277, SD=0.89) was significantly lower than others ($p<0.05$). In the paired comparison between partial tactile point stimulation (M=1.483, SD=0.83) and line form, the analysis revealed a significant difference ($t(31)=-2.578$, $p<0.05$), and the higher mean value was shown in the line form between them.

4.2.2 Task performance

Regarding the data on task performance, the time participants spent completing each task was recorded. The experimenter started the timer by operating the VR controller, and the timer stopped after the participant completed the final stirring action with the spoon. Participants only held a tangible handle in their right hand, and when they were ready, they verbally told the experimenter the signal to start. Then, the experiment begins, and the background time data is recorded. The *t-test* was conducted to compare the effect of tangible handles with different partial tactile stimuli on the time taken to complete a specific task as a measure of users' task performance. There was a significant difference in the scores for using a tangible handle without partial tactile stimuli (M=79.75 seconds, SD=19.45) and a tangible handle with partial tactile ring form (M=91.72 seconds, SD=25.98; $t(31)=-2.579$; $p<0.05$). This significant result indicates that tasks performed using no tactile stimuli's object took shorter on average than those performed under objects with partial ring stimuli. No significant differences were found when comparing these other partial tactile stimuli on users' performance, as evidenced by a *t-test* ($p>0.05$). The results also showed that the mean completion time for tasks in a condition without no tactile stimuli was lower than that of the other conditions. Partial line stimuli were used (M=91.72 seconds, SD=25.98). Conditions with partial point and ring stimuli had similar mean completion times (M=90.16 seconds, SD=27.29 for point stimuli).

4.2.3 Eye tracking results

To analyze user perceptions in all sessions, the objective data of eye tracking behavior data (i.e., fixation count and fixation length) was recorded during the task. The eye tracking data for the whole virtual kitchenware including both comprehensive visual attention and partial *TouchMark* can be analyzed in Fig. 4. It is important to note that the baseline condition lacks partial tactile feedback, thereby focusing solely on comprehensive visual attention. In this study, 32 participants were initially recruited. Upholding strict scientific standards, several datasets were excluded from the final analysis. For example, there were calibration issues in datasets from 3 participants and incomplete datasets from another 3, which lacked recordings for certain experimental conditions. The final analysis of data from the remaining 26 participants is reliable, in accordance with established practices emphasizing data accuracy in research.

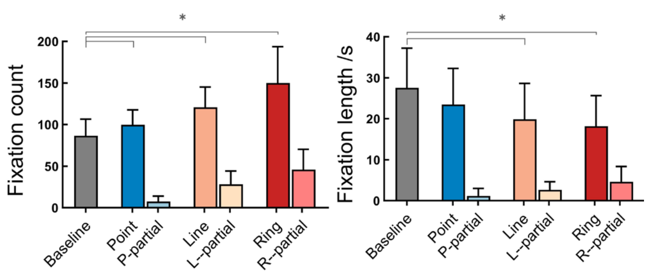

Fig. 4. The bar charts about users' eye tracking behavior data.

Fixation count. The fixation count refers to the entire number of eye fixations recorded on these virtual partial tactile representations of kitchenware or whole kitchenware. The *t-tests* revealed significant differences in the number of fixations on tangible handles (including both global and partial stimuli) across the four conditions. Specifically, the condition featuring a handle without *TouchMark* yielded a significantly lower fixation count compared to the other three conditions (M=86.66, SD=20.05; $p<0.05$), such as in point form (M=99.846, SD=17.97), line form (M=120.77, SD=24.32), and ring form (M=149.96, SD=43.63). **Fixation length.** The amount of time each fixation lasted for the partial tactile representation or whole kitchenware is explained as the fixation length. Analysis of fixation duration yielded significant differences when participants interacted with tangible handles during the experience, considering both global and partial stimuli across four conditions. It was observed that the condition featuring the handle with no *TouchMark* (M=27.58, SD=9.65; $p<0.05$) resulted in significantly longer durations of fixations compared to the two conditions that provided partial tactile feedback through line from (M=19.87, SD=8.77) and ring from (M=18.19, SD=7.50).

4.2.4 User preference ranking in the interview

The post-experiment preference rankings shed light on users' attitudes towards the four tangible handles investigated. Using the object with partial tactile line stimuli emerged as the most favored overall. It garnered the highest percentage (21.9%) of top rankings and was rated second by a considerable 34.4% of participants. The longitudinal tactile cue appeared to resonate well with users' expectations for grasping elongated tools like knives or utensils. While 25% ranked the point as their prime preference, an equal 25% gave it the lowest rating. The ring form yielded a more evenly distributed set of rankings, with 21.9% scoring it highest and the same percentage ranking it last. Lastly, the object without *TouchMark* drew the most criticism, with 43.8% of participants deeming it least preferable.

4.3 User Study 3: Partial tactile feedback for patients

A clinical study was conducted with 25 patients to explore their perceptions of these tangible handles performing these upper limb tasks in VR. Two patients could not accurately understand our questionnaire questions due to their older age, and their subjective questionnaire data of embodiment were excluded from this analysis. Notably, several patients suffering from cerebral damage exhibited symptoms including impaired speech clarity, which often led to confusion when responding to the quantitative questions in the questionnaires. Consequently, we also conducted oral interviews to inquire about the patients' authentic experiences while engaging in the virtual tasks. The findings are analyzed through a combination of questionnaires and interviews.

4.3.1 Self-reported embodiment ratings

Data gathered under four conditions were analyzed through pairwise comparisons to detect any significant disparities. The *Shapiro-Wilk test* ($p>0.05$) was used to determine the score differences among each condition pair to confirm normal distribution. Following this verification, the data analysis proceeded with *paired t-tests*. **Tactile sensations.** The *t-test* revealed a significant difference in the effect on the users' tactile sensations, with no tactile stimulation session (M=1.848, SD=0.82) showing a significantly lower value than another partial tactile session with line form (M=2.098, SD=0.90; $t(22)=-2.296$; $p<0.05$). The results indicated that there were statistically significant lower tactile sensations between partial tactile sessions with point form (M=1.652, SD=1.08; $p<0.05$) and the other two forms for line (M=2.098, SD=0.90; $t(31)=-2.925$) and ring (M=1.924, SD=0.98; $t(31)=-2.253$). **Body ownership.** Statistical analysis revealed significant differences in body ownership across the different tactile stimulation conditions. Paired comparisons indicated that the partial line condition (M=1.826, SD=1.61; $p<0.05$) significantly differed from both no tactile stimulation (M=1.391, SD=1.53; $t(31)=-2.206$) and partial point conditions (M=1.261, SD=1.60; $t(31)=-4.092$). **Agency.** These significant differences were observed in the sense of agency when comparing partial line session (M=1.957, SD=1.58; $p<0.05$) and other two conditions, including no tactile stimulation session (M=1.609, SD=1.56; $t(31)=-2.152$) and partial point session (M=1.304, SD=1.96; $t(31)=-2.182$). **Self-location.** For the sense of self-location, it showed a significant result by comparing the influence of no tactile stimulation session (M=1.609, SD=1.23) and partial tactile stimulation session with line form (M=1.913, SD=1.24; $t(31)=-2.077$; $p<0.05$). **Total embodiment.** The *t-test* indicated statistically significant differences in the impact of partial tactile line stimulation (M=3.372, SD=2.35) compared to no tactile stimulation session (M=2.766, SD=2.24; $t(31)=-2.390$; $p<0.05$) on the embodiment.

4.3.2 User preference ranking in the interview

This ranking revealed the preferences of patients with upper limb disabilities regarding the four tangible handles. 18 participants ranked the object with *TouchMark* featuring partial ring and line stimuli as their top choice, with ring form and line favoured by 10 (40% of participants) and 8, respectively. The scenario without any partial tactile stimuli was consistently ranked last.

5 Discussion

5.1 The theoretical implication of *TouchMark*

Three experiments of this research investigated the effects of different tangible handles with various partial tactile stimuli on users' experience when grasping them. The results of Study 1 provided insights into the haptic perception and grasp comfort in a non-VR setting. Users' ability to discern partial haptic feedback of tangible handles through hand-based tactile stimulation was evaluated. The findings revealed that cube-shaped objects were rated lower in terms of tactile perception compared to objects sphere-shaped. The results in a non-VR environment inform subsequent VR experiments by showing that users' comfort and tactile perception are influenced by the form and shape of objects, with **line form** and **sphere shapes** preferred for partial haptic feedback. Moreover, different forms of tangible handles (point, line and ring) influenced their perceived comfort during grasping. Objects with line form were rated as more comfortable than point form and ring form, and line and ring stimuli were associated with better perceived grasping sensations over the point form. It aligns with ergonomic design principles, suggesting that objects conforming to the hand's curvature improve comfort [47].

The findings of Study 2 related to the impact of *TouchMark* as partial haptic feedback on user perceptions during virtual interaction in VR were discussed. In addition to collecting subjective questionnaire data on the embodiment and post-interview, this experiment also gathered and analyzed objective measures of task performance and eye-tracking data. The experiment demonstrated that the inclusion of *TouchMark* on tangible handles had a significant effect on the total embodiment based on the embodiment questionnaire results. The results indicated that the presence of partial tactile stimulation significantly enhanced users' tactile sensations compared to the absence of *TouchMark*, which is consistent with existing studies that suggest tactile feedback enhances the authenticity of interactions within VEs [25, 26]. The study also revealed that the sense of ownership was influenced by the *TouchMark* of objects, and users reported a stronger feeling of owning the virtual hand during engaging with tangible handles that provided tactile stimulation. Previous studies have shown that congruent multi-sensory feedback can enhance the ownership over a virtual body [17, 18]. The line form's higher ownership scores over the point form could be due to the more continuous tactile feedback it provides, which may better mimic the natural sensations one expects when interacting with tangible tools. *TouchMark* also had impacts on the sense of agency and self-location, and the findings contribute to the growing evidence that tactile feedback could enhance them [25, 26]. Individuals may experience an improved sense of control and spatial presence, as tactile cues provide users with a more definitive positional anchoring within the interaction. The total embodiment scores were significantly higher with partial tactile line and ring forms compared to those without *TouchMark*, indicating that the design of tactile stimuli plays an important role in inducing a comprehensive embodiment for users.

The presence of both tactile and visual stimuli extends the time participants engage in the task, compared to when these stimuli are absent. This increase in task time may be primarily attributed to participants spending additional time observing the *Touchmark*, which serves as visual cues drawing their attention. This behavior suggests that the visual and tactile components of the stimuli play significant roles in how participants interact with the task environment in VR. Besides, when interpreting the eye tracking data from Study 2, several significant findings merit a detailed examination. The objective measures of fixation count and fixation length served as indicators of user attention and interaction with virtual kitchenware under different conditions. The lower fixation count for the handle without *TouchMark* suggests that tactile stimuli may play a role in attracting visual attention. The significant increase in fixations with the introduction of *TouchMark*, particularly in the ring form, could indicate that participants were more engaged or required more cognitive processing to integrate the tactile feedback with visual information. The potential explanation for this phenomenon could be that multisensory integration may enhance the salience of objects in perceptual tasks, potentially leading to more frequent fixations. Regarding fixation length, longer durations observed without *TouchMark* are reported, while the fixation count is given lower. One possibility is that the absence of tactile feedback led participants to rely more heavily on visual information to understand the object, resulting in longer fixations. Within the *TouchMark* conditions, the point form's significantly shorter fixation durations suggest that this stimulus was the least cognitively demanding, allowing for quicker visual processing and understanding of the object. As the complexity of the tactile stimulus increased (from point to line to ring), so did the duration of fixations. This pattern could be indicative of the cognitive effort required to integrate multiple sensory inputs, with the ring form demanding the most attention and processing time.

Study 3 provided data on the perceptions of patients performing upper limb tasks in a VR setting. The subjective embodiment ratings and a post-interview highlighted the importance of tactile feedback in enhancing the interactive experience for individuals with sensorimotor impairments. The significant difference in tactile sensations, particularly in sessions with line-form tactile stimulation, suggests that this form of tactile feedback is more effective at eliciting a sense of touch compared to no tactile or point-form stimulation. This finding is consistent with literature suggesting that more continuous and extensive tactile stimuli may enhance the sensory feedback necessary for embodying virtual limbs [25, 26]. Similarly, the sense of agency and self-location benefited from the tactile line form. The total embodiment was significantly higher in the *TouchMark* with line condition compared to the absence of tactile stimulation, highlighting the effect of tactile feedback on the integration of virtual limbs during upper limb exercises.

5.2 The practical implication of *TouchMark* in further virtual rehabilitation

The integration of partial tactile feedback designs with VR technology is influencing upper limb rehabilitation, and this work elucidates how the design concept of partial tactile feedback (i.e., *TouchMark*) can impact user perceptions and performance in VR. Based on non-VR research of Study 1, two subsequent VR studies demonstrate that *TouchMark* (i.e., users touch the physical partial tactile stimuli with point, line, and ring form) could increase the embodiment in virtual cooking tasks. The clinical experiment with patients confirms the practicality of *TouchMark* in VR training.

5.2.1 Design considerations of partial tactile feedback

These studies reported that the embodiment is heightened by *TouchMark*, and the sense of embodiment serves as an extension of user's hands from a tangible handle to a virtual representation, thereby increasing their interactive experience within VEs. Drawing from users' positive perceptions, several design guidelines are proposed.

Impact of partial haptic designs based on user fingertip sensitivity on virtual interaction. The tactile dimension within VR is also a critical factor for immersive interactive experiences, while visual stimuli have been paid more attention in research due to technological constraints about haptic feedback. Moreover, tactile feedback becomes essential for interpreting the virtual world with the user's vision occluded by the VR head-mounted display. It has been shown that user experience feedback improves significantly when physical haptic feedback mirrors that of the virtual world. However, high-fidelity touch replication remains a challenge due to cost and technology barriers. An opportunity lies in addressing the user's reduced sensitivity to haptic cues in the visually dominant virtual world. By targeting specific hand and finger movements, partial design changes could enhance user interaction, particularly as users typically perform delicate movements with these extremities. Recognizing the varying sensitivity across different fingertips (higher sensitivity of the thumb and index finger) could lead to meaningful design enhancements. These sensitive areas can be targeted for amplified partial tactile feedback, which can improve interaction quality without a proportionate increase in cost. This user-centric design method leverages the physiological characteristics of users to unlock new possibilities for interaction within VEs.

Low-cost design recommendations for broad applicability with a simple approach during virtual interaction. The quest for realistic haptic feedback in VR is ongoing, with the aim of mimicking real-world interactions to boost user experience. The complexity and cost of accurate, real-time haptic systems limit the widespread applications, especially in settings with diverse needs (e.g., patients performing rehabilitation in VEs). The pursuit of low-cost tactile feedback solutions for virtual interaction is crucial. Based on the related research about the high sensitivity of the finger, small-scale haptic stimuli in these areas of the thumb and index fingers may be effective. Research indicates that users can discern features of objects through touch, including curves and textures [34, 36]. Integrating partial tactile enhancements that simulate different shapes and textures could lead to cost-effective haptic design concepts with broad applicability. The small area of the hand (i.e., fingertip) and a small range of tactile stimulation are the basis for this low-cost design, which can be quickly added and applied to the *TouchMark* in other prototypes. These partial design interventions in small areas are unlikely to have significant negative impacts on other larger and more complex virtual models, and incorporating the *TouchMark* is relatively straightforward to the complex models with this low-cost approach.

Recommendations for multimodal feedback designs from post-interviews. A preferred interaction mode for the *TouchMark* was evident among participants during the interview, who appreciated the realistic partial tactile feedback provided by the raised line and ring features. These modes were seen as superior in simulating the contours of real-world objects and facilitating natural interaction, with linear protrusion resembling a knife's handle for precise control. The ring form also facilitates enhanced interaction while receiving criticism for potentially restricting hand movement and imparting an unnatural feel. The absence of

TouchMark led to a diminished embodiment, while the point form was considered too tactilely stimulating and visually inconspicuous, resulting in poor effectiveness. Partial tactile feedback with *TouchMark* highlighted the necessity for a balance between realistic tactile cues and freedom of movement to enhance users' naturalness in VR. Participant feedback yielded several recommendations to improve the interactive design of tangible handles. The location of the partial form is needed to ensure comfortable grasping without restricting movement. The tactile elements match the specific form and function of various virtual objects, such as longitudinal textures for tools like knives and lateral ones for objects like cups. A multimodal approach that integrates haptic and visual feedback is essential for an immersive experience that mirrors the nuances of the real world.

5.2.2 Potential rehabilitation applications of *TouchMark*

They are enhancing the rehabilitation experience through *TouchMark*. The upper extremity function stands as a pivotal objective for patients with upper limb movement disorders due to its influence on ADLs. These patients often experience unilateral muscular weakness. For those recovering from hand injuries, regaining strength and control involves a complex rehabilitation process. Traditional rehabilitation therapies, despite their foundational role, frequently fall short of sustaining patient positive engagement. This highlights the need for innovative approaches to enhance traditional virtual rehabilitation techniques, aiming to optimize patient outcomes. However, the efficacy of VR rehabilitation is sometimes compromised due to a lack of personalized haptic feedback. Many patients have limited VR experience and initial discomfort with the technology, mainly when manipulating virtual limbs. The integration of partial tactile feedback via *TouchMark* has shown potential in helping patients' rapid acclimatization to their virtual avatars, thus fostering the sense of embodiment within VEs. This method of tactile guidance integrates physical tactile stimuli with corresponding virtual objects, facilitating the successful execution of tasks in VR rehabilitation.

Customized and cost-effective rehabilitation solutions. Our research emphasizes the innovative design of tangible handles using *TouchMark* to enhance VR rehabilitation. By leveraging 3D printing and VR tracking technologies, we achieve precise motion tracking for patients within these virtual rehabilitative exercises. The integration of partial haptic feedback with visual stimuli from tangible handles using *TouchMark* facilitates patient control of the virtual hand during training tasks. These design principles could enhance the embodiment experienced during rehabilitation. This therapeutic approach addresses the diverse and individualized needs of patients, thereby allowing the rapid and cost-effective implementation of VR technology across various rehabilitations. The objective of integrating visuo-tactile feedback with *TouchMark* is to accelerate adaptation among novices in the VR domain, fostering precise and repetitive hand movements.

Application of *TouchMark* in VR rehabilitation frameworks. The targeted application of *TouchMark* in VR-based rehabilitation represents an innovative approach to improving patient treatment protocols. The use of partial tactile feedback, with an emphasis on linear forms, could enhance therapeutic motivation by promoting heightened embodiment. Users' embodiment in VR is relevant for their upper limb rehabilitation, where reconstructing the ownership of virtual hands influences the rehabilitation outcome. Our research suggests that tactile feedback enhances the sense of embodiment, it might also subtly affect the user's perception of time within VEs. The goal is to ensure that the addition of *TouchMark*, this low-cost and easy method, improves the rehabilitation interaction and its experience. The interaction could potentially extend users' perceived duration of tasks, immersing them more deeply in the activities to enhance the effectiveness of the training. Besides, the integration of tactile stimuli and virtual interaction should strive to strike a balance between intensifying users' positive experiences and preventing cognitive overload.

5.3 Limitations and Future Work

Our exploration into the effects of *TouchMark* on users' perceptions of virtual rehabilitation has yielded important insights, yet several limitations warrant consideration. The study's reliance on subjective measures for patients may undermine the generalizability and robustness of our findings. In Study 2, technical issues related to eye tracking in VR led to the exclusion of data from 6 participants, potentially impacting the study's outcomes. Additionally, the inability to collect usable data from 2 older patients due to the complexity of the questionnaire raises concerns about the accessibility of our assessment tools in Study 3. This issue was further compounded by difficulties encountered by patients with cerebral damage in understanding the questionnaire, suggesting a need for multiple, adaptable methods of data collection (e.g., the inclusion of physiological data) to ensure the experiences of all patients are accurately captured.

Future research could prioritize expanding the sample size for patients and utilizing objective measures alongside subjective reports to validate and extend our findings. Research should also consider the design of object form on comfort and tactile perception, and the ergonomic implications for VR device designs. Optimizing tangible handles with *TouchMark* for rehabilitation presents a promising area for further applications, especially in tailoring interventions to meet the varied needs of users.

6 Conclusion

The research aims to investigate the effects of different tangible handles with partial tactile feedback on users' embodiment when grasping them during virtual interaction. The results of three experiments have demonstrated the significant potential of tangible handles with *TouchMark* in enhancing the embodiment, particularly benefiting patients who need upper limb rehabilitation. Our findings indicate that integrating partial tactile cues into tangible handle designs can significantly improve user interaction within VEs by strengthening the connection between physical touch and virtual perception. This work's innovative approach of incorporating *TouchMark* with its distinctive tactile and visual cues has shown to be effective in inducing higher embodiment and in offering a cost-effective solution conducive to further virtual rehabilitation settings. Moreover, the design concept is promising to enhance the interactive experience for users with limited VR exposure. Overall, this research lays the groundwork for future research to refine tangible handles with *TouchMark* for rehabilitation and to expand the application of VR technologies to facilitate patient recovery.

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