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RESEARCH ARTICLE

Effects of Gamification and Communication in Virtual Reality Frozen Shoulder Rehabilitation for Enhanced Rehabilitation Continuity

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ABSTRACT The monotony of movements makes frozen shoulder rehabilitation an boring task for certain patients. This study posits that gamification and the presence of others can effectively address this issue. Accordingly, we developed a virtual reality (VR) application for frozen shoulder rehabilitation exercises and empirically examined the effects of gamification and the presence of others on rehabilitation duration. A user study on 32 subjects revealed that the integration of game elements into a VR rehabilitation program significantly prolonged the rehabilitation duration ($p < 0.001, d = 0.983$). Additionally, the rehabilitation duration was considerably longer when participants performed the rehabilitation program with others ($p < 0.05, d = 0.455$).

INDEX TERMS Communication, gamification, rehabilitation, virtual reality.

I. INTRODUCTION

Continuous rehabilitation is indispensable to restore motor functions impaired by illnesses and lead an unhindered life. If participants fail to sustain rehabilitation programs, their physical capabilities will not fully recover despite access to a therapeutic environment. Therefore, motivating patients to sustain their rehabilitation is crucial to successful rehabilitation [1].

Despite the importance of rehabilitation in restoring physical function, patients often find the process monotonous because it entails performing repetitive movements over a long duration [2]. Consequently, it is difficult for certain patients to complete rehabilitation programs.

For example, the rehabilitation of frozen shoulder, which is accompanied by shoulder pain owing to the joint capsule stiffness, is relatively monotonous and requires several months of continuous rehabilitation [3]. With a worldwide incidence of 2% to 5% [4], [5], [6], frozen shoulder is highly prevalent. Most patients experience its onset between 40 and 60 years [7]. Given the aging population in many countries, the incidence of frozen shoulder is expected to increase [8]. Therefore, it is necessary to determine the factors of the rehabilitation environment that enable patients with frozen shoulder to sustain their rehabilitation.

Gamification [9], [10] and the presence of others [11] are recognized as effective strategies for promoting task adherence. We postulate that applying these techniques to frozen shoulder rehabilitation can improve patients' motivation to continue rehabilitation. Virtual reality (VR) technology has recently gained popularity, and various VR-based rehabilitation methods have been proposed and implemented [12], [13], [14]. There are three reasons for using VR in our study. First, immersive VR rehabilitation is more effective in restoring motor function than rehabilitation using conventional displays [15]. Second, because VR rehabilitation creates a stronger sense of the presence of others [16], involving other patients through the multiplayer mode in VR rehabilitation can significantly impact the continuation of rehabilitation. Finally, VR technology offers patients a time-compression effect that allows patients to complete tedious or painful treatments in a shorter perceived time [17], [18].

However, previous studies applying gamification to frozen shoulder rehabilitation [19], [20] have not reported

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rehabilitation continuation quantitatively, leaving the extent to which gamification mitigates boredom during rehabilitation unclear. Additionally, no previous studies have explored the impact of the presence of others during rehabilitation.

Therefore, this study investigated the effects of incorporating game and multiplayer elements into a VR rehabilitation system for frozen shoulders. We used healthy participants as test subjects before experimenting on frozen shoulder patients.

II. RELATED WORK

A. FROZEN SHOULDER

Frozen shoulders are divided into four consecutive stages based on the symptoms [21]. During Stage 1, patients may experience mild shoulder pain. In Stage 2, or the freezing stage, patients experience severe shoulder pain and limited range of motion. In Stage 3, or the frozen stage, shoulder pain is somewhat alleviated, but the range of motion remains restricted. Finally, in Stage 4, or the thawing stage, shoulder pain almost subsides, and the range of motion is almost entirely recovered. Patients with frozen shoulders must receive appropriate treatment at each stage. In Stage 2, exercise therapy is not recommended owing to severe shoulder pain. Instead, treatment primarily involves compression and analgesics. Exercise therapy is introduced at Stages 3 and 4.

This study focused on one of the rehabilitation exercises called the "table-reach exercise," adopted in treating Stages 3 and 4. The exercise involves placing both hands on a towel laid on a table and moving them back and forth in a straight posture to increase the range of motion (Fig. 1). The patient repeats pushing both hands forward slowly, as long as it does not cause pain in the shoulder. However, the monotonous nature of the exercise makes it difficult for some patients to maintain their motivation. In the following sections, we discuss the methods applied in this study to sustain motivation during rehabilitation.

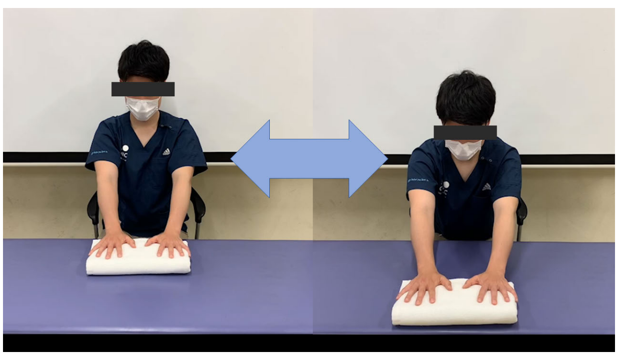

FIGURE 1. Table-reach exercise.

B. EFFECT OF GAMIFICATION ON TASK CONTINUATION

Gamification is a method that integrates game mechanics and game dynamics to non-game platform [22]. This method can attract users' interest and motivate users to continue monotonous activities. Gamification has been employed across various domains, including business [23], [24], [25], education [10], [26], [27], and healthcare [28], [29], [30]. Numerous studies have explored using gamification in rehabilitation, including stroke rehabilitation systems implemented as smartphone applications [31] and rehabilitation systems designed for patients with hand disabilities [32]. Even within the narrow domain of frozen shoulder rehabilitation, several gamification-based methods have been proposed, such as a tracking system to facilitate frozen shoulder rehabilitation [19] and a rehabilitation system using Microsoft Kinect [20]. However, the extent to which gamification mitigates boredom when performing rehabilitation activities and its impact on the duration of rehabilitation remains unclear.

C. EFFECTS OF THE PRESENCE OF OTHERS ON TASK CONTINUATION

The presence of others effectively sustains user engagement in monotonous tasks [11], and there have been various related investigations. A study involving infants validated that the learning outcomes of video materials were augmented when learning alongside peers [33]. Similarly, an examination involving adults verified that the presence of peers amplified the learning achievements from video materials [34]. Another study ascertained that participation frequency in recycling activities increases when participants recognize the involvement of others in the activities [35]. Imada et al. suggested that the presence of others affects task endurance in virtual environments and substantiated that the duration of English vocabulary learning and knowledge acquisition was enriched in a virtual environment where others' efforts are visualized [36]. We hypothesized that the utilization of the presence of others for monotonous rehabilitation movements would improve their duration. Previous studies have not investigated the effects of the presence of others on the duration of rehabilitation exercises. Therefore, we tested our hypotheses experimentally.

III. USER STUDY

A. EXPERIMENT OVERVIEW

This study aimed to verify the effects of gamification and the presence of others on frozen shoulder rehabilitation. In this experiment, the participants performed the table-reach rehabilitation exercise using three VR rehabilitation contents. The participants were instructed to sustain the rehabilitation using each VR rehabilitation content until they became bored. Subsequently, the rehabilitation duration for each condition was compared. This study was approved by the Ethics Committee in our institution (Approval No.: 22-59, Office of Environmental Safety Management, School of Engineering and Information Science and Technology, University of Tokyo).

B. EXPERIMENT SETUP

Fig. 2 illustrates the experimental environment. A platform for the frozen shoulder rehabilitation experiment, which consists of an aluminium frame and a plastic board, is fixed to a table. The participant sits in front of the platform wearing a head-mounted display (HMD). Then, the participant performs the table-reach exercise by sliding the plastic board back and forth. The trackers (Vive Tracker 3.0) are attached to the frame and plastic board.The frame and plastic board are attached to the trackers. The distance between the trackers measures the extent to which the participants could stretch their shoulder blades. The avatar's arms in the VR rehabilitation content movemoved according to real participants' movements, and the first-person perspective of the avatar is projected onto the HMD (HTC Vive Pro Eye) with a 1440 × 1600 pixel resolution per eye, 615 PPI, and a 110° diagonal field of view at a refresh rate of 90Hz.

Hand redirection, a non-isomorphic mapping from the hand position in real space to that in VR space [37], is employed to realize the illusion of full- arm movement for patients with limited mobility due to a frozen shoulder. Specifically, let d be the maximum distance that the participant can reach from the initial position in real space, D be the maximum length to which the plastic board can be moved on the platform, and x_{real} be the distance from the initial position in real space to the position where the participant's hand is located. Then, x_{vir}, the distance from the initial position to the avatar's hand in virtual space, is calculated as follows:

$$x_{vir} = \begin{cases} \frac{x_{real}}{d} D & (x_{real} \leq d) \\ D & (x_{real} > \mathrm{d}) \end{cases} \tag{1}$$

The avatars were implemented in the Microsoft Rocketbox Avatar Library.[1] This selection is based on the notion that realistic-looking avatars improve co-presence in cooperative contexts [38], whereas avatars' appearance does not significantly a ffect co-presence in competitive contexts [39]. Thus, using a realistic-looking avatar is not expected to have at least a negative effect on coCo-presence, regardless of whether the partner is interpreted as a competitor or collaborator in the COMMUNICATION condition described in Section III-D3.

C. EXPERIMENT CONDITION

We recruited 32 healthy participants (22 males and 10 females) with a mean age of 24.8 (SD:5.2) through Twitter and jikken-baito.com,[2] a website for recruiting experimental participants. The experimental design was a within-subject experiment comparing the rehabilitation duration across three different VR rehabilitation conditions: SIMPLE condition with simple VR rehabilitation content, GAMIFICATION condition with added game elements, and COMMUNICATION condition with multiplayer elements added. To counteract any potential order effects, the order in which the participants experienced the three rehabilitation conditions was counterbalanced (see Appendix Table 4). The participants were instructed to perform rehabilitation exercises until they felt bored. If the participants did not finish the rehabilitation after 15 minutes (900 seconds), the experimenter requested them to finish the rehabilitation exercise. The participants were not informed that the upper time limit was 15 minutes before the commencement of the experiment.

[1] https://github.com/microsoft/Microsoft-Rocketbox

[2] https://www.jikken-baito.com

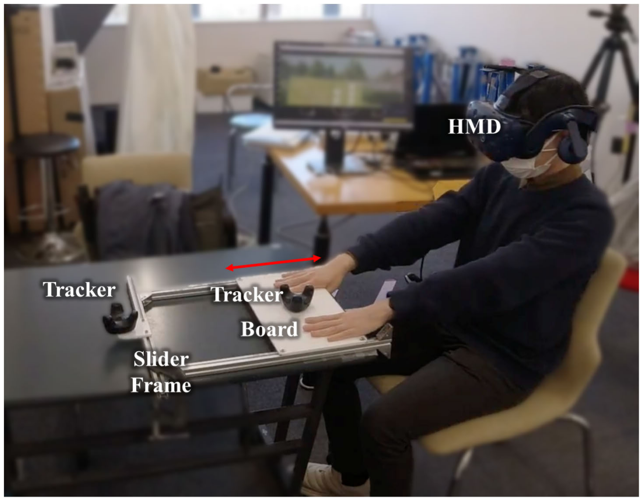

FIGURE 2. Experimental environment. Participants perform rehabilitation movements by moving the board on the slider back and forth. The board's moving distance is calculated from the trackers mounted on the board and frame.

D. VR REHABILITATION CONTENT

1) SIMPLE CONDITION

In the SIMPLE condition, the participants engaged in rehabilitation actions in a basic VR environment. Fig. 3(a) shows a VR view of the rehabilitation content under the SIMPLE condition. This virtual environment evoked a tranquil town. During the rehabilitation exercise, the hands of the avatar in the virtual environment moved back and forth, following the movements of the participant's hands. Since the SIMPLE condition serves as a control condition, the content of this condition does not include any additional features.

2) GAMIFICATION CONDITION

In the GAMIFICATION condition, game elements were incorporated into the VR rehabilitation content of the SIMPLE condition. The game story is that game players come to a town under urban development and enrich themselves and their surroundings by performing knife-sharpening jobs. Fig. 3(b) shows a third-person viewpoint image of the rehabilitation content in the GAMIFICATION condition. The game user interface (UI) is displayed in front of the user. The upper part of Fig. 3(b) presents an enlarged view of the game's UI. The total number of sharpened knives, shown in the upper left of the game UI, increases when performing more rehabilitation exercises. The log displaying the progress of the game is shown in the lower left of the game UI. The released production facilities are shown in the right of the game UI. The production facility acceleratesaccelerated the increase in the total number of sharpened knives. More production facilities are

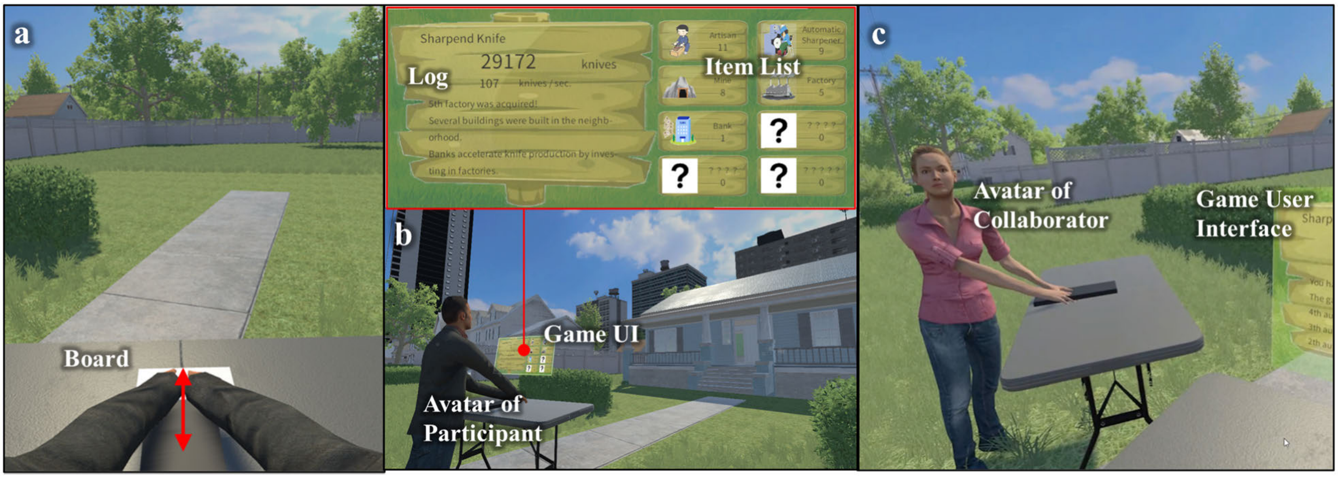

FIGURE 3. VR rehabilitation environment in each condition. (a) VR view of rehabilitation content in the SIMPLE condition, (b) third-person view when executing rehabilitation content in the GAMIFICATION condition, (c) partner's avatar in the COMMUNICATION condition.

released in this game as more rehabilitation actions are performed. Consequently, the total number of sharpened knives increases at an accelerated rate. In addition, the surrounding VR environment changes as the total number of sharpened knives increases. Specifically, a gimmick is where trees grow larger, houses are built on the site, houses become luxurious, houses are built around the site, buildings are built around the site, skyscrapers are built around the site, and the expansion continues. These gimmicks correspond to the story in which the game player emigrates to a town under urban development and enriches it through knife sharpening. The rehabilitation content of this condition was implemented based on review papers on gamification in musculoskeletal rehabilitation [40] and includes the following common features: points (display of the total number of sharpened knives), tasks (the knife-sharpening job), avatars (avatars of Microsoft Rocketbox), messages or information (logs showing game progress), achievements (the surrounding VR environment that changes according to the total number of sharpened knives), unlocking content (unlocking production facilities).

3) COMMUNICATION CONDITION

The VR rehabilitation content in the COMMUNICATION condition involves a multiplayer element added to the rehabilitation content in the GAMIFICATION condition. Specifically, as depicted in Fig. 3(c), the COMMUNICATION condition featured the partner's avatar positioned beside the participant. The partner's avatar also reflects the partner's behavior in another room. Furthermore, the total number of sharpened knives of the partner is displayed sequentially in the game UI log. The paired experimental participants were asked to introduce themselves to each other for approximately 30 seconds orally only prior to the commencement of rehabilitation to make them aware of their partner's presence.

E. EXPERIMENT PROCEDURE

Before initiating the experiment, participants were fully informed about the process and completed a participant consent form. Subsequently, the participants completed a general questionnaire (including sex, age, height, and other visual impairments) and a simulator sickness questionnaire (SSQ) [41], quantifying the degree of simulator sickness. Subsequently, the participants practiced the rehabilitation exercises using the VR rehabilitation contents of the SIMPLE condition. After practice, the participants were instructed to perform the rehabilitation task for three trials (one trial for each of the three conditions), in accordance with the following procedures.

1) The participant wore an HMD and sat on a chair in front of the platform.
2) The experimenter launched the VR rehabilitation system.
3) The participant calibrated the maximum distance the participant could comfortably reach from the initial position in the real space.
4) The participant started the rehabilitation exercise using the platform.
5) The participant was instructed to report the end of the rehabilitation when they felt bored with the rehabilitation. If the participant did not report the end of rehabilitation within 15 minutes, the experimenter asked the participant to finish the rehabilitation.
6) The participant was requested to complete the SSQ, the igroup presence questionnaire (IPQ) [42], and the NASA TASK LOAD INDEX (NASA-TLX) [43], [44]. The IPQ is an instrument for quantifying the level of user's presence in the virtual environment; NASA-TLX is a measure for assessing the subjective workload of a given task.
7) The experimenter ensured that the participant exhibited no signs of physiological irregularities before proceeding to subsequent rehabilitation trials.

After completing the rehabilitation task under all three conditions, the participants answered questions Q1–Q3 orally.

Q1 Which do you think is better in terms of fostering motivation to continue rehabilitation, SIMPLE or GAMIFICATION?
Q2 In the COMMUNICATION condition, did the partner feel like a collaborator or a competitor?
Q3 If you have any comments about the experiment, please let me know.

Finally, participants received an Amazon gift card worth approximately 20 USD as a reward.

IV. RESULT

A. ABSOLUTE REHABILITATION DURATION

The time from the start to the end of rehabilitation in each trial was defined as "the absolute rehabilitation duration" of the trial. Fig. 4 depicts a boxplot of the absolute rehabilitation duration for all participants in each condition. The vertical axis represents the rehabilitation duration measured in seconds. The minimum, first quartile, median, third quartile, and maximum values of absolute rehabilitation duration for each condition are illustrated. The data indicated by dots are those with values greater than $(3rd\ quartile) + 1.5 \times (interquartile\ range)$. In the following analyses, these data are also included in the test without being excluded as outliers.

First, the Shapiro-Wilk normality test was performed for each condition group. The results showed normality for all three conditions: SIMPLE ($p < 0.001, W = 0.642$), GAMIFICATION ($p < 0.001, W = 0.867$), and COMMUNICATION ($p < 0.05, W = 0.871$). Next, Bartlett's test revealed no homoscedasticity among the condition groups ($p = 0.301, T = 2.40$). Since the data showed normality but not homoscedasticity, a Bonferroni-corrected paired-samples t-test was performed. The results showed that the absolute rehabilitation duration was significantly longer in the GAMIFICATION condition than in the SIMPLE condition ($p_{adj} < 0.001, d = 0.983$), significantly longer in the COMMUNICATION condition than in the SIMPLE condition ($p_{adj} < 0.001, d = 1.39$), and significantly longer in COMMUNICATION condition than in the GAMIFICATION condition ($p_{adj} < 0.05, d = 0.455$). The effect size d in the paired-samples t-test is Cohens's d [45].

B. RELATIVE REHABILITATION DURATION

To evaluate the rate of increase in rehabilitation duration owing to the introduction of game and multiplayer elements, we calculated the ratio of the absolute rehabilitation duration in the GAMIFICATION and COMMUNICATION conditions to that in the SIMPLE condition. This value was defined as "the relative rehabilitation duration." Fig. 5 presents a boxplot of the relative rehabilitation duration for each condition for all experimental participants. The vertical axis represents the rehabilitation duration; the unit is dimensionless because the measure is a ratio. The minimum, first quartile, median, third quartile, and maximum values of the relative rehabilitation duration for each condition are illustrated. The data indicated by dots are those with values greater than

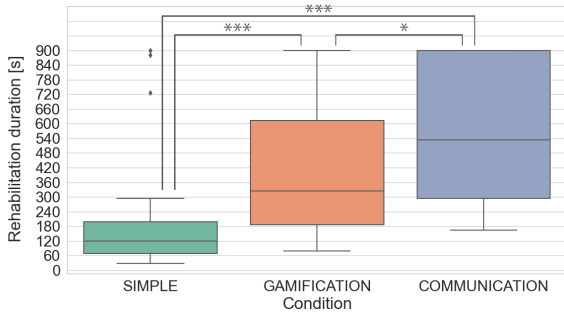

FIGURE 4. Boxplot of absolute rehabilitation duration. Symbols indicating significant difference are following: $p : *** < 0.001 < ** < 0.01 < * < 0.05 < \dagger < 0.1$.

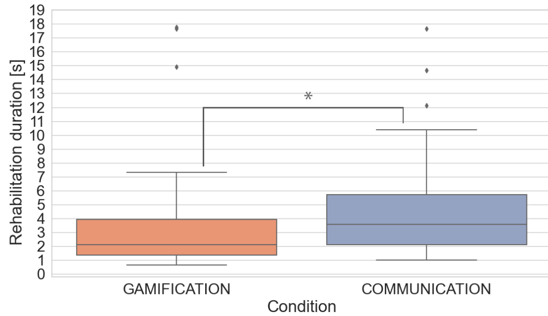

FIGURE 5. Boxplot of relative rehabilitation duration. Symbols indicating significant difference are following: $p : *** < 0.001 < ** < 0.01 < * < 0.05 < \dagger < 0.1$.

$(3rd\ quartile) + 1.5 \times (interquartile\ range)$. These data were also included in the test analysis without being excluded as outliers.

First, the Shapiro-Wilk normality test for each condition group revealed normality for the GAMIFICATION ($p < 0.001, W = 0.645$) and COMMUNICATION ($p < 0.001, W = 0.812$) condition groups. Next, the paired-samples t-test showed that the relative rehabilitation duration was significantly longer in the COMMUNICATION condition than in the GAMIFICATION condition ($p < 0.05$, $d = 0.381$).

C. SSQ

Fig. 6 illustrates a bar chart of the SSQ results for all participants, grouped by scale. The vertical axis represents the SSQ score; the results for each scale are aligned horizontally. Error bars indicate standard deviation.

D. IPQ

Fig. 7 illustrates a bar chart of the IPQ results for all participants in the experiment, grouped by scale. The vertical axis represents the IPQ score, and the results for each scale are aligned horizontally. Error bars indicate standard deviation.

For the general presence, we examined for differences between the condition groups using the Bonferroni-corrected paired-samples t-test. We found marginally significant differences between the SIMPLE and GAMIFICATION condition

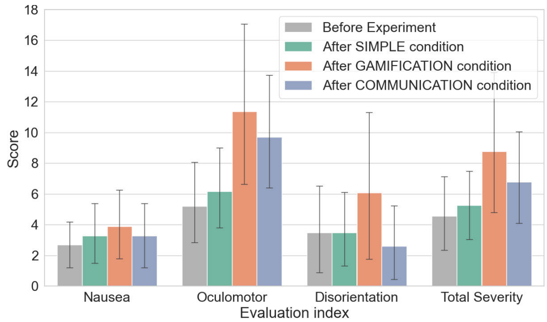

FIGURE 6. Barchart of the SSQ results.

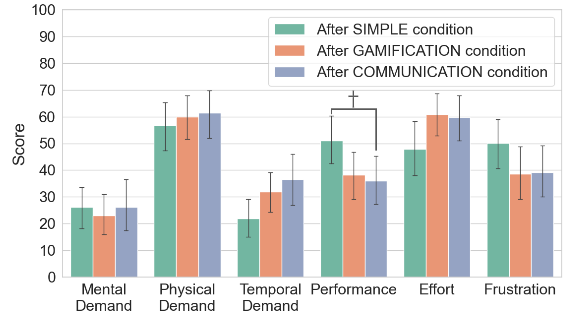

FIGURE 8. Rating of NASA-TLX. Symbols indicating significant difference are following: p : ∗∗∗ < 0.001 < ∗∗ < 0.01 < ∗ < 0.05 < † < 0.1.

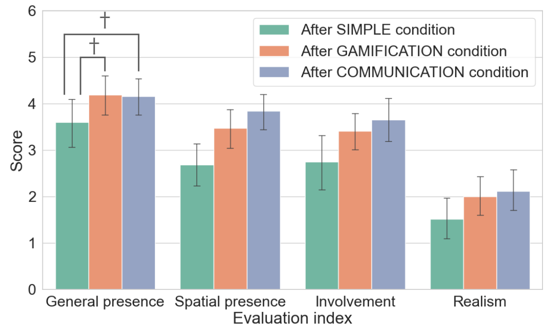

FIGURE 7. Barchart of the IPQ results. Symbols indicating significant difference are following:
p : ∗∗∗ < 0.001 < ∗∗ < 0.01 < ∗ < 0.05 < † < 0.1.

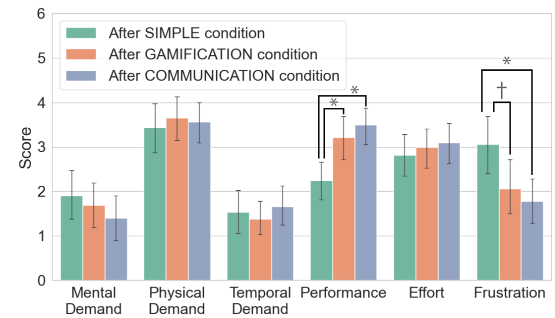

FIGURE 9. Weight of NASA-TLX. Symbols indicating significant difference are following: p : ∗∗∗ < 0.001 < ∗∗ < 0.01 < ∗ < 0.05 < † < 0.1.

groups ($p_{adj} < 0.1$) and between the SIMPLE and COMMUNICATION condition groups ($p_{adj} < 0.1$).

E. NASA-TLX

Fig. 8 describes the results of the Rating of NASA-TLX for all participants grouped by scale. The vertical axis represents the NASA-TLX score, and the results for each scale are aligned horizontally. Error bars indicate standard deviation.

The Steel-Dwass test examined for differences between the condition groups for all scales. The results showed a marginally significant difference between the SIMPLE and COMMUNICATION conditions in terms of performance ($p < 0.1$).

Fig. 9 describes the results of the weight of the NASA-TLX for all participants, grouped by scale.

The Steel-Dwass test examined for differences between the condition groups for all scales. The results showed a significant or marginally significant difference between the SIMPLE and GAMIFICATION condition groups for performance ($p < 0.05$) and frustration ($p < 0.1$), and between the SIMPLE and COMMUNICATION condition groups for performance ($p < 0.05$) and frustration ($p < 0.05$).

Fig. 10 indicates the results of the weighted rating of the NASA-TLX for all participants, grouped by scale.

The Steel-Dwass test found no significant differences in the weighted ratings among the condition groups.

F. PAIR ANALYSIS

To analyze the influence of partners on each participant in the COMMUNICATION condition, we classified 16 pairs. For example, when participants who can and cannot continue a monotonous task for a long time collaborate, the latter participant may continue the task longer because of the partner's presence.

First, we classified all the participants into three categories based on their absolute rehabilitation duration in the GAMIFICATION condition: LONG (top 33%), MEDIUM (middle 33%), and SHORT (remaining participants). The pairs were grouped based on the categories of the two participants in each pair. The grouping results revealed five LONG and MEDIUM pairs, four MEDIUM and SHORT pairs, three LONG and SHORT pairs, two SHORT and SHORT pairs, one LONG and LONG pair, and one MEDIUM and MEDIUM pair.

Subsequently, we analyzed combinations of LONG and MEDIUM, MEDIUM and SHORT, and LONG and SHORT groups, which had a relatively large number of pairs. Tables 1, 2,and 3 display the absolute rehabilitation durations for the LONG and MEDIUM, MEDIUM and SHORT, and LONG and SHORT pair groups, respectively. In the table, the GAMIFICATION and COMMUNICATION conditions are denoted as G and C, respectively. The cells are colored red when the duration of rehabilitation in the COMMUNICATION condition is longer than that in the GAMIFICATION condition.

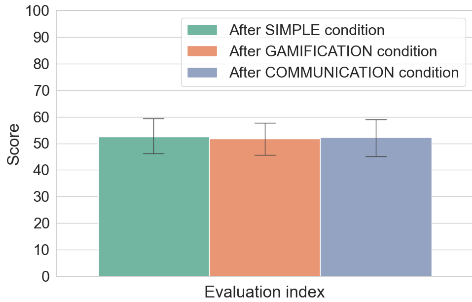

FIGURE 10. Weighted rating of NASA-TLX. Symbols indicating significant difference are following:
p : $*** < 0.001 < ** < 0.01 < * < 0.05 < \dagger < 0.1$.

TABLE 1. Rehabilitation duration for LONG and MEDIUM pair group [s].

Pair	LONG		MEDIUM	
	G	C	G	C
P1 + P2	900	900	293	483
P13 + P14	578	452	535	584
P15 + P16	900	900	536	528
P21 + P22	569	900	284	680
P31 + P32	900	900	233	900

G: GAMIFICATION, C: COMMUNICATION.

TABLE 2. Rehabilitation duration for MEDIUM and SHORT pair group [s].

Pair	MEDIUM		SHORT	
	G	C	G	C
P9 + P10	355	589	186	276
P23 + P24	515	352	208	299
P25 + P26	534	663	95	164
P29 + P30	264	276	133	192

G: GAMIFICATION, C: COMMUNICATION.

TABLE 3. Rehabilitation duration for LONG and SHORT pair group [s].

Pair	LONG		SHORT	
	G	C	G	C
P7 + P8	721	608	97	540
P17 + P18	833	593	201	203
P27 + P28	900	900	152	900

G: GAMIFICATION, C: COMMUNICATION.

G. QUESTTIONNAIRE

In response to Q1 (Which do you think is better in terms of motivation to continue rehabilitation, SIMPLE or GAMIFICATION?), 29 answered GAMIFICATION and 3 answered SIMPLE.

In response to Q2 (Did the partner in the COMMUNICATION condition feel like a collaborator or a competitor?), 13 participants answered "collaborators," 17 answered "competitors," and 2 answered "neither."

V. DISCUSSION

In the absolute rehabilitation duration analysis, significant differences were observed between SIMPLE and GAMIFICATION conditions and between GAMIFICATION and COMMUNICATION conditions. This indicates that gamification and the presence of others increased rehabilitation duration. In the SIMPLE condition, all experimental participants finished the rehabilitation exercise within 300 seconds except for three. The standard required time to perform one set of the most common frozen shoulder rehabilitation exercises [1] is approximately 5 minutes (300 seconds). In the SIMPLE condition, the participants gave up before the 5 minutes. In contrast, the median rehabilitation duration in the GAMIFICATION condition and the third quartile of duration in the COMMUNICATION condition were longer than 300 seconds. In other words, while most participants in the SIMPLE condition felt bored during the standard duration of rehabilitation, more than half of the participants in the COMMUNICATION condition performed rehabilitation without being bored during the standard required time to perform one set of rehabilitation.

In addition, significant differences were found between the SIMPLE and GAMIFICATION conditions and between the SIMPLE and COMMUNICATION conditions when analyzing the relative rehabilitation duration. The increased rehabilitation duration for each participant confirmed the effects of adding gamification and multiplayer elements to VR rehabilitation.

In the SSQ analysis, only a few participants had total severity scores exceeding 20 (one before the start of the experiment, one immediately after the SIMPLE condition, four immediately after the GAMIFICATION condition, and two immediately after the COMMUNICATION condition). Therefore, the number of participants who experienced serious VR sickness using this system was small [46]. Furthermore, when we checked specifically when the Total Severity exceeded 20, there was one participant whose score exceeded 20 immediately after the second and third trials and five participants whose score exceeded 20 immediately after only the third trial. As none of the participants had a total severity score of 20 or higher immediately after the first trial, there are no concerns about VR sickness as long as the participants used this system for the standard duration of one rehabilitation exercise.

Regarding the IPQ analysis, marginally significant differences in general presence were found between the SIMPLE and GAMIFICATION conditions and between the SIMPLE and COMMUNICATION conditions, suggesting that there may have been a difference in presence. Considering the possibility that presence in VR may affect time perception [47], it is also possible that differences in presence may have affected time perception. Consequently, the difference in time perception may have affected the rehabilitation duration. However, it would be premature to deduce that the difference in presence changed the time perception for two primary reasons: first, the test result showed only marginally significant differences; second, in light of Vierordt's law [48], which suggests that longer intervals of time are perceived as shorter retrospectively and vice versa, it is plausible that the difference in VR experience duration across the conditions impacted the time perception.

In the NASA-TLX Rating analysis, a marginally significant difference in performance was found between the

SIMPLE and COMMUNICATION conditions, suggesting that the participants' subjective sense of task accomplishment was higher in the COMMUNICATION condition (the lower the performance score in NASA-TLX, the greater the sense of task accomplishment). Furthermore, the analysis of the weight of NASA-TLX revealed a significant difference in frustration. This can be interpreted as the participants perceiving that adding the game and multiplayer elements decreased enduring boredom when performing rehabilitation movements.

Regarding the pair analysis, Tables 1, 2, and 3 present the rehabilitation durations of the paired groups LONG and MEDIUM, MEDIUM and SHORT, and LONG and SHORT, respectively. These tables indicate that the participant with the shorter duration of GAMIFICATION between pairs increased the duration by being paired with a partner in four out of five pairs in the LONG and MEDIUM pair group, in all four pairs in the MEDIUM and SHORT pair group, and in all three pairs in the LONG and SHORT pair group. The duration of GAMIFICATION increases when the participant with a shorter duration of GAMIFICATION is paired. This suggests that the multiplayer element has the potential to increase the duration of rehabilitation for participants who originally had a short rehabilitation duration.

Finally, in the questionnaire analysis, 29 out of 32 participants responded that GAMIFICATION offered better motivation to continue rehabilitation. This confirms the effectiveness of GAMIFICATION as a subjective evaluation tool. In Q2, 13 of the 32 participants answered "cooperators," and 17 answered "competitors." According to a previous study that compared competitive and cooperative rehabilitation content [49], competitive content is more effective at increasing motivation and exercise intensity, whereas cooperative content is reported to be less stressful. Based on this report, the reason why the duration of the experiment was significantly increased by adding multiplayer games is considered to be that participants who considered their partner as a collaborator were more motivated, while those who considered their partner as a competitor were less stressed on the simple task. With respect to Q3, we received various range of comments on the experiment. Notably, haptic feedback from the platform was mentioned by 4 of the 32 participants. For example, the tactile sensation and sound generated by the friction between the board and frame, which matched the knife-sharpening content. Considering the possibility that haptic feedback may intensify the sense of immersion in virtual reality [50], it is conceivable that the haptic feedback delivered by the platform also contributed to the prolonged rehabilitation duration in GAMIFICATION and COMMUNICATION conditions.

VI. LIMITATION AND FUTURE WORK

The main limitations of this study are that the participants were healthy subjects, there was a ceiling effect, and the interaction effect was not tested.

First, the experiment was conducted on healthy subjects. Although the present experiment showed that game and multiplayer elements in VR rehabilitation significantly increased the duration of VR rehabilitation in healthy subjects, it cannot be claimed that the results could be transferred to actual patients with frozen shoulder.

Second, there was a ceiling effect. In order to reduce the burden of the experiment on the participants, the experimental design limited the rehabilitation to 15 minutes. Therefore, we expect that there was a ceiling effect, particularly for the duration of the GAMIFICATION and COMMUNICATION conditions. However, the test in this experiment showed a significant difference between the GAMIFICATION and COMMUNICATION conditions. Moreover, the standard duration required for one rehabilitation exercise in the actual rehabilitation setting is approximately 5 min. Therefore, 15 min must be sufficient for performing rehabilitation.

Third, we could not examine the interaction effects between the game and multiplayer elements. To reduce the burden of the experiment on the participants, we conducted three trials in the SIMPLE, GAMIFICATION, and COMMUNICATION conditions; therefore, we did not include the condition with no game element and a multiplayer element in the experimental condition (the GAMIFICATION condition had an additional game element, and the GAMIFICATION condition had an additional game element, and the COMMUNICATION condition had both a game element and multiplayer elements). Therefore, the significant difference between the GAMIFICATION and COMMUNICATION conditions in this experiment was caused by the sum of the main effects of the multiplayer element and the interaction effect between the game and multiplayer elements. However, it is unlikely that the contents with multiplayer elements without game elements will be put to practical use, as it is not interesting. Therefore, it is considered sufficient to have found that content including both game and multiplayer elements is more effective for continuing rehabilitation than content with only game elements.

We have two future directions for our research. First, we plan to conduct a user study on patients with frozen shoulders. In actual patients, it is crucial to verify not only the duration of rehabilitation but also the effect of functional recovery. Therefore, we plan to follow the rehabilitation progress to investigate its effects on functional recovery. Second, we aim to implement our system as a stand-alone system on the Oculus Quest Pro. Our system is essentially configured only with an HMD and two tracking devices, which means it can be implemented as a stand-alone system (a system that operates without a PC) using an Oculus Quest Pro and two Oculus controllers. Given that stand-alone systems can be easily used at home, addressing this is an important future issue. Since the effectiveness of the system has been confirmed by our experiment, we have started to implement our proposed system as a stand-alone solution on the Oculus Quest Pro.

VII. CONCLUSION

This study hypothesized that gamification and the presence of others are effective for rehabilitation continuation and quantitatively investigated the effects of game and multiplayer elements in VR frozen shoulder rehabilitation on rehabilitation continuation. Our user study yielded evidence that adding game elements to VR rehabilitation significantly extended rehabilitation duration. Additionally, incorporating a multiplayer element in VR rehabilitation game content also significantly extended the rehabilitation duration. This study is a fundamental quantitative investigation into the efficacy of gamification and communication in mitigating tedium during rehabilitation. The findings of this study are anticipated to serve as a cornerstone for various studies aimed at reinforcing rehabilitation continuity.

APPENDIX

Table 4 presents the experimental conditions for each participant. This table describes the partners and the order of the three trial conditions for each participant. In the table, S, G, and C denote the SIMPLE, GAMIFICATION, and COMMUNICATION conditions, respectively.

TABLE 4. Experimental conditions for each participant.

Participant	Partner	Trial 1	Trial 2	Trial 3
P1	P2	S	G	C
P2	P1	S	G	C
P3	P4	G	S	C
P4	P3	G	S	C
P5	P6	S	G	C
P6	P5	G	S	C
P7	P8	C	S	G
P8	P7	C	S	G
P9	P10	C	G	S
P10	P9	C	G	S
P11	P12	C	S	G
P12	P11	C	G	S
P13	P14	S	C	G
P14	P13	S	C	G
P15	P16	G	C	S
P16	P15	G	C	S
P17	P18	S	C	G
P18	P17	G	C	S
P19	P20	G	S	C
P20	P19	S	G	C
P21	P22	C	G	S
P22	P21	C	S	G
P23	P24	G	C	S
P24	P23	S	C	G
P25	P26	S	G	C
P26	P25	S	G	C
P27	P28	C	S	G
P28	P27	C	S	G
P29	P30	G	C	S
P30	P29	S	C	G
P31	P32	S	G	C
P32	P31	G	S	C

REFERENCES

[1] K. Knopf, *Healthy Shoulder Handbook: 100 Exercises for Treating Common Injuries Ending Chronic Pain*, 2nd ed. Berkeley, CA, USA: Ulysses Press, 2021.

[2] J. Luker, E. Lynch, S. Bernhardsson, L. Bennett, and J. Bernhardt, ''Stroke survivors' experiences of physical rehabilitation: A systematic review of qualitative studies,'' *Arch. Phys. Med. Rehabil.*, vol. 96, no. 9, pp. 1698–1708.e10, Sep. 2015.

[3] V. Pandey and S. Madi, ''Clinical guidelines in the management of frozen shoulder: An update! *Indian J. orthopaedics*, vol. 55, no. 2, pp. 299–309, 2021.

[4] D. A. van der Windt, B. W. Koes, B. A. de Jong, and L. M. Bouter, ''Shoulder disorders in general practice: Incidence, patient characteristics, and management,'' *Ann. Rheumatic Diseases*, vol. 54, no. 12, pp. 959–964, Dec. 1995.

[5] C. Robinson, K. M. Seah, Y. Chee, P. Hindle, and I. Murray, ''Frozen shoulder,'' *J. Bone Joint Surg. Brit.*, vol. 94, no. 1, pp. 1–9, 2012.

[6] H. V. Le, S. J. Lee, A. Nazarian, and E. K. Rodriguez, ''Adhesive capsulitis of the shoulder: Review of pathophysiology and current clinical treatments,'' *Shoulder Elbow*, vol. 9, no. 2, pp. 75–84, Apr. 2017.

[7] K. L. Boyle-Walker, D. L. Gabard, E. Bietsch, D. M. Masek-VanArsdale, and B. L. Robinson, ''A profile of patients with adhesive capsulitis,'' *J. Hand Therapy*, vol. 10, no. 3, pp. 222–228, Jul. 1997.

[8] C.-H. Cho, T. W. Koo, N.-S. Cho, K.-J. Park, B. G. Lee, D. Shin, S. Choi, S.-H. Cho, M.-S. Kim, S.-H. Ko, C.-H. Kim, J.-Y. Park, and Y.-S. Yoo, ''Demographic and clinical characteristics of primary frozen shoulder in a Korean population: A retrospective analysis of 1,373 cases,'' *Clinics Shoulder Elbow*, vol. 18, no. 3, pp. 133–137, Sep. 2015.

[9] L. Zheng, G. Li, X. Wang, H. Yin, Y. Jia, M. Leng, H. Li, and L. Chen, ''Effect of exergames on physical outcomes in frail elderly: A systematic review,'' *Aging Clin. Experim. Res.*, vol. 32, no. 11, pp. 2187–2200, Nov. 2020.

[10] M. Nurtanto, N. Kholifah, E. Ahdhianto, A. Samsudin, and F. D. Isnantyo, ''A review of gamification impact on student behavioral and learning outcomes,'' *Int. J. Interact. Mobile Technol.*, vol. 15, no. 21, pp. 1–15, 2021.

[11] M. Gregory Walton, L. Geoffrey Cohen, D. Cwir, and S. J. Spencer, ''Mere belonging: The power of social connections,'' *J. Personality Social Psychol.*, vol. 102, no. 3, pp. 32–513, 2012.

[12] M. C. Howard, ''A meta-analysis and systematic literature review of virtual reality rehabilitation programs,'' *Comput. Hum. Behav.*, vol. 70, pp. 317–327, May 2017.

[13] H. Sveistrup, ''Motor rehabilitation using virtual reality,'' *J. Neuroeng. Rehabil.*, vol. 1, no. 1, pp. 1–8, 2004.

[14] T. D. Parsons, A. A. Rizzo, S. Rogers, and P. York, ''Virtual reality in paediatric rehabilitation: A review,'' *Develop. Neurorehabilitation*, vol. 12, no. 4, pp. 224–238, Jan. 2009.

[15] M. Matamala-Gomez, M. Slater, and M. V. Sanchez-Vives, ''Impact of virtual embodiment and exercises on functional ability and range of motion in orthopedic rehabilitation,'' *Sci. Rep.*, vol. 12, no. 1, p. 5046, Mar. 2022.

[16] A. Bayro, Y. Ghasemi, and H. Jeong, ''Subjective and objective analyses of collaboration and co-presence in a virtual reality remote environment,'' in *Proc. IEEE Conf. Virtual Reality 3D User Interfaces Abstr. Workshops (VRW)*, Mar. 2022, pp. 485–487.

[17] S. M. Schneider, C. K. Kisby, and E. P. Flint, ''Effect of virtual reality on time perception in patients receiving chemotherapy,'' *Supportive Care Cancer*, vol. 19, no. 4, pp. 555–564, Apr. 2011.

[18] J. I. Gold and N. E. Mahrer, ''Is virtual reality ready for prime time in the medical space? A randomized control trial of pediatric virtual reality for acute procedural pain management,'' *J. Pediatric Psychol.*, vol. 43, no. 3, pp. 266–275, Apr. 2018.

[19] M.-C. Huang, S.-H. Lee, S.-C. Yeh, R.-C. Chan, A. Rizzo, W. Xu, W. Han-Lin, and L. Shan-Hui, ''Intelligent frozen shoulder rehabilitation,'' *IEEE Intell. Syst.*, vol. 29, no. 3, pp. 22–28, May 2014.

[20] N. K. Mangal, S. Pal, and A. Khosla, ''Frozen shoulder rehabilitation using Microsoft Kinect,'' in *Proc. Int. Conf. Innov. Green Energy Healthcare Technol. (IGEHT)*, Mar. 2017, pp. 1–6.

[21] J. A. Hannafin and T. A. Chiaia, ''Adhesive capsulitis. A treatment approach,'' *Clin. Orthopaedics Rel. Research*, vol. 372, pp. 95–109, Mar. 2000.

[22] S. Deterding, R. Khaled, E. L. Nacke, and D. Dixon, ''Gamification: Toward a definition,'' in *Proc. CHI*, Jan. 2011.

[23] M. B. Armstrong and R. N. Landers, ''Gamification of employee training and development,'' *Int. J. Training Develop.*, vol. 22, no. 2, pp. 162–169, Jun. 2018.

[24] R. J. Baxter, D. K. Holderness, and D. A. Wood, "The effects of gamification on corporate compliance training: A partial replication and field study of true office anti-corruption training programs," *J. Forensic Accounting Res.*, vol. 2, no. 1, pp. A20–A30, Dec. 2017.

[25] M. T. Cardador, G. B. Northcraft, and J. Whicker, "A theory of work gamification: Something old, something new, something borrowed, something cool? *Human resource Manage. Rev.*, vol. 27, no. 2, pp. 353–365, 2017.

[26] R. Al-Azawi, F. Al-Faliti, and M. Al-Blushi, "Educational gamification vs. game based learning: Comparative study," *Int. J. Innov., Manage. Technol.*, vol. 7, no. 4, pp. 132–136, 2016.

[27] L. da Rocha Seixas, A. S. Gomes, and I. J. de Melo Filho, "Effectiveness of gamification in the engagement of students," *Comput. Hum. Behav.*, vol. 58, pp. 48–63, May 2016.

[28] J. A. Cafazzo, M. Casselman, N. Hamming, D. K. Katzman, and M. R. Palmert, "Design of an mHealth app for the self-management of adolescent type 1 diabetes: A pilot study," *J. Med. Internet Res.*, vol. 14, no. 3, p. e70, May 2012.

[29] J. Hamari and J. Koivisto, "'Working out for likes': An empirical study on social influence in exercise gamification," *Comput. Hum. Behav.*, vol. 50, pp. 333–347, Sep. 2015.

[30] J. Koivisto and J. Hamari, "Demographic differences in perceived benefits from gamification," *Comput. Hum. Behav.*, vol. 35, pp. 179–188, Jun. 2014.

[31] C. Ferreira, V. Guimarães, A. Santos, and I. Sousa, "Gamification of stroke rehabilitation exercises using a smartphone," in *Proc. 8th Int. Conf. Pervasive Comput. Technol. Healthcare*, 2014, pp. 282–285.

[32] I. Afyouni, F. U. Rehman, A. M. Qamar, S. Ghani, S. O. Hussain, B. Sadiq, M. A. Rahman, A. Murad, and S. Basalamah, "A therapy-driven gamification framework for hand rehabilitation," *User Model. User-Adapted Interact.*, vol. 27, no. 2, pp. 215–265, Jun. 2017.

[33] S. Lytle, A. Garcia-Sierra, and P. Kuhl, "Two are better than one: Infant language learning from video improves in the presence of peers," *Proc. Nat. Acad. Sci. USA*, vol. 115, Oct. 2018, Art. no. 201611621.

[34] Z. Pi, C. Liu, Q. Meng, and J. Yang, "Co-learner presence and praise alters the effects of learner-generated explanation on learning from video lectures," *Int. J. Educ. Technol. Higher Educ.*, vol. 19, no. 1, pp. 1–20, Dec. 2022.

[35] P. W. Schultz, "Changing behavior with normative feedback interventions: A field experiment on curbside recycling," *Basic Appl. Social Psychol.*, vol. 21, no. 1, pp. 25–36, Mar. 1999.

[36] S. Imada, N. Hayashida, H. Kuzuoka, K. Suzuki, and M. Oki, "Making others' efforts tangible:—How other learners affect climate fostering long-term self-paced learning in virtual environment," in *Proc. 22nd Int. Conf. (HCI)*. Copenhagen, Denmark: Springer, Jul. 2020, pp. 239–247.

[37] A. Zenner and A. Krüger, "Estimating detection thresholds for desktop-scale hand redirection in virtual reality," in *Proc. IEEE Conf. Virtual Reality 3D User Interfaces (VR)*, Mar. 2019, pp. 47–55.

[38] J. S. Casaneuva, "Presence and co-presence in collaborative virtual environments," M.S. thesis, Dept. Comput. Sci., Univ. Cape Town, Cape Town, South Africa, 2001.

[39] J. P. Freiwald, J. Schenke, N. Lehmann-Willenbrock, and F. Steinicke, "Effects of avatar appearance and locomotion on co-presence in virtual reality collaborations," in *Proc. Mensch Comput.*, 2021, pp. 393–401.

[40] B. Steiner, L. Elgert, B. Saalfeld, and K.-H. Wolf, "Gamification in rehabilitation of patients with musculoskeletal diseases of the shoulder: Scoping review," *JMIR Serious Games*, vol. 8, no. 3, Aug. 2020, Art. no. e19914.

[41] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, "Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness," *Int. J. Aviation Psychol.*, vol. 3, no. 3, pp. 203–220, Jul. 1993.

[42] (2001). *iGroup Presence Questionnaire (IPQ)*. [Online]. Available: https://igroup.org

[43] S. G. Hart and L. E. Staveland, "Development of NASA-TLX(task load index): Results of empirical and theoretical research," *Human Mental Workload*, vol. 1, no. 3, pp. 139–183, 1988.

[44] S. Haga and N. Mizukami, "Japanese version of NASA task load index: Sensitivity of its workload score to difficulty of three different laboratory tasks," *Jpn. J. Ergonom.*, vol. 32, no. 2, pp. 71–79, 1996.

[45] J. Cohen, *Statistical Power Analysis for the Behavioral Sciences*. Evanston, IL, USA: Routledge, 2013.

[46] K. M. Stanney, R. S. Kennedy, and J. M. Drexler, "Cybersickness is not simulator sickness," in *Proc. Hum. Factors Ergonom. Soc. Annu. Meeting*, vol. 41, no. 2. Los Angeles, CA, USA: SAGE, 1997, pp. 1138–1142, doi: 10.1177/107118139704100292.

[47] G. Mullen and N. Davidenko, "Time compression in virtual reality," *Timing Time Perception*, vol. 9, no. 4, pp. 377–392, May 2021.

[48] S. Glasauer and Z. Shi, "150 years of research on Vierordt's law-fechner's fault?" *PsyCh J.*, vol. 10, no. 5, May 2021.

[49] M. Goršič, I. Cikajlo, and D. Novak, "Competitive and cooperative arm rehabilitation games played by a patient and unimpaired person: Effects on motivation and exercise intensity," *J. NeuroEngineering Rehabil.*, vol. 14, no. 1, pp. 1–18, Dec. 2017.

[50] T. Rose, C. S. Nam, and K. B. Chen, "Immersion of virtual reality for rehabilitation—Review," *Appl. Ergonom.*, vol. 69, pp. 153–161, May 2018.

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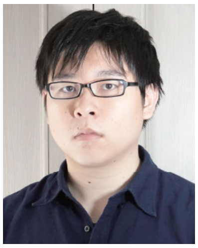

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