Virtual Ability Simulation: Applying Rotational Gain to the Leg to Increase Confidence During Physical Rehabilitation

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Abstract

This paper investigates a concept called Virtual Ability Simulation (VAS) for people with disability due to Multiple Sclerosis (MS), in a virtual reality (VR) environment. In a VAS people with a disability perform tasks that are made easier in the virtual environment (VE) compared to the real world. We hypothesized that putting people with disabilities in a VAS will increase confidence and enable more efficient task completion. To investigate this hypothesis, we conducted a within-subjects experiment in which participants performed a virtual task called "kick the ball" in two different conditions: a no gain condition (i.e., same difficulty as in the real world) and a rotational gain condition (i.e., physically easier than the real world but visually the same). The results from our study suggest that VAS increased participants' confidence which in turn enables them to perceive the difficulty of the same task easier.

CCS Concepts

*• **Human-centered computing** → **User studies;** Walkthrough evaluations; Empirical studies in HCI;*

1. INTRODUCTION

There are many reasons why people need rehabilitation. For example, suffering from diseases like Multiple Sclerosis (MS), which can reduce strength in the extremities. MS is an unpredictable, often disabling disease of the central nervous system that disrupts the flow of information within the brain, and between the brain and body. Both the cause and the cure of MS is still unknown but one common way to mitigate the symptoms is through physical therapy. However, maintaining motivation in rehabilitation is a challenge because exercises are often repetitive and difficult. Patients could benefit from a method to help alleviate the perception of difficulty and the resulting frustration often experienced at an acute rehabilitation center [Cal04].

To meet this need, Virtual ability simulation (VAS) is a technique designed for people with disabilities (PwD) where the user performs tasks that are made easier in the VE compared to the real world. The primary goal of VAS is to increase motivation for PwD towards their rehabilitation task. In VAS, similar to redirected touching [KWB12] and movement scaling [DHHW13], we can add rotational gains to a joint of the virtual avatar so that its limb appears to move through the full range of motion, while the user's real limb only moves through a partial range. For example, imagine a participant sitting on a chair and an object is hanging about the knee height in front of her, and she wants to kick that object (figure 1). The full range of motion would be the motion of the participant's foot necessary to kick that object in the real environment while the partial range would be some portion of the full range and

would take less energy to complete. In VR, we can make these two conditions visually identical, even though one is physically easier than the other. Thus, this could give a user the perception that she is able to complete the exercise easily, which could have a positive effect on her motivation towards future similar tasks.

One important aspect of the VAS concept is that the rotational gain for virtual avatar could be controlled by either the patient (in case of self-moderated exercise) or the therapist. There is potentially a twofold advantage in using VAS for rehabilitation exercise. From the perspective of the patients, VAS would be a great fit to not only free them from boredom but also the positive feedback they get from completing the task would motivate them to do the rehabilitation exercise more [GDME17]. From the perspective of a therapist, it could also be used to modulate the difficulty of the exercise interactively based on the current progress of the patient. In our study, the participants were not aware of the rotational gains and thus makes our study task similar to a therapist controlled version.

It is not clear how VAS will affect people with MS. Based on the literature that demonstrated the motivational effects of perceiving fitter self-avatars during exercise [FB09] and scaled upper extremity exercise for stroke patients [DHHW13], we hypothesized that VAS can be an effective means to motivate and boost the confidence for people with MS.
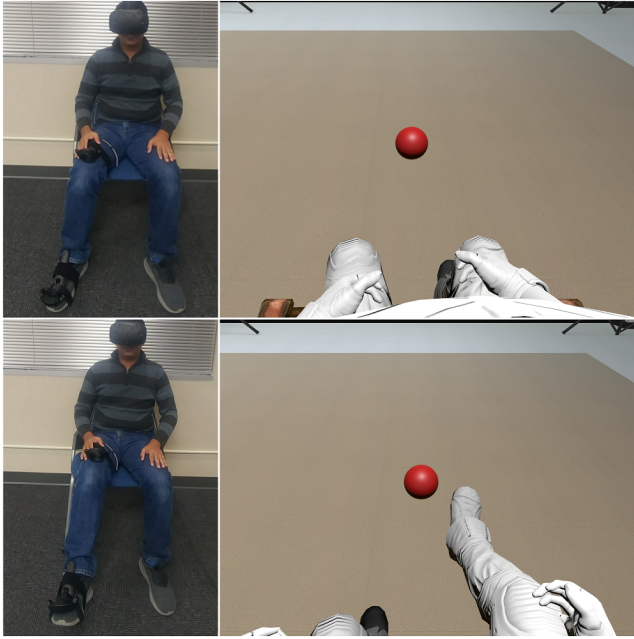
Figure 1: *Participant playing the game in our virtual ability simulation. Left column showing the participant and right column showing corresponding Virtual Environment view of the participant.*

2. BACKGROUND AND RELATED WORK

This section reviews the primary areas where we identify a gap in knowledge between VR self-avatars, and VR rehabilitation. VR self-avatars research has rarely investigated the impact on users with disabilities. VR rehabilitation research has minimally investigated self-avatars' potential impact on rehabilitation. Moreover, self-modeling literature suggests potential psychological benefits of viewing oneself successfully performing a task. There are only a few instances of VR enabled self-modeling, most of which minimally involve persons with physical impairments.

2.1. Self-Avatars in VR and Self Modeling

Self-avatars can induce a strong perceptual illusion of virtual body ownership - virtual embodiment. This virtual embodiment illusion requires that people accept a virtual human-like representation as their own body. The first work supporting the plausibility of such plasticity of the human brain is known as the rubber-hand illusion [BC98]. The rubber-hand illusion demonstrated that humans are able to accept a rubber hand as their own hand. For example, if the rubber hand is "injured", the participant my try to pull their hand out of the way, even though it has no real connection to the rubber hand. This work was later adapted to full body-swap illusions using a real-world manikin and a video camera headset [PE08], and virtual full-body-swap illusions using a virtual avatar, a humanoid character, in a fully-immersive VE [SSSVB10].

Self-modeling is a psychological intervention that uses observation of oneself engaged in adaptive behavior [Dow99]. Currently, self-modeling is almost always facilitated with short videos, which

are repeatedly reviewed to learn skills (e.g. social skills) or adjust to difficult environments as part of training or therapy. For example, video based self-modeling has been used with autistic children to improve social communication, teach daily living skills, and increase imaginative play [BA07]. VR-enabled self-modeling has been used to train people on how to deliver bad news [ABZ*10]. Results from previous study suggests that self-avatars running on a treadmill in an immersive VE can encourage physical activity, especially if the avatar loses weight while running [FB09].

2.2. VR Rehabilitation

Although VR based simulation has minimally been used for persons with disabilities before, VR, in general has been shown to have significant benefits for persons with disabilities in rehabilitation. A VE is not subject to the dangers and limitations of the real world [MPB*06], which expands the types of exercises that patients can practice, while still having fun in the case of VR games. VR and VR games have measurable benefits for rehabilitation performance and motivation, which, for example, has been shown to improve balance in persons with spinal cord injury [BDN*07, VR08].

Similar to VAS, augmented and virtual reality rehabilitation applications have been used to improve the condition of upper extremity (UE) motor impairment for people who suffered a stroke. In [DHHW13] the authors introduced the use of a VR game called "Duck Duck Punch" to create a post-stroke neurorehabilitation environment for UE impairment that encourages extended task practice and provides expert action observation. In "Duck Duck Punch", the user controls a virtual arm on the screen to reach out and hit targets. The user accumulates points and unlocks new themes as gameplay progresses, encouraging the user to continue reaching. The virtual arm compensates for reaching impairment to provide the stroke survivor with expert action observation. Similarly, in [RMO*11] authors amplified the movement of one hand of the participants to play several rounds of the virtual memory game. One of the reasons the memory game was chosen is that it can be used to evaluate reaching and selection performance.

While both of the diseases MS and Stroke affect the brain, they do it for very different reasons. A stroke and MS may present themselves similarly and that is why it's so important to recognize the key differences and treat them appropriately. Statistics tell us that 75% of stroke survivors are unable to successfully practice reaching tasks, due to the severity of the impairment of elbow and wrist movements [DHHW13], which can be categorized as UE motor impairment. In contrast, MS more often affects the lower body [VPW02]. In our approach of using VAS for a rehabilitation exercise task, we focus on lower extremity (LE) motor impairment for people with MS.

3. HYPOTHESES

The primary goal of this research is to investigate the effect of VAS on confidence in a VE for persons with MS. We applied rotational gains at the knee joint while participants kicked a virtual ball. These hypotheses are influenced by previous work, such as Duck Duck Punch [DHHW13], where the authors scaled virtual reaching to effectively train UE reaching tasks for persons in

stroke rehabilitation. In contrast, we scaled virtual kicking - i.e. we applied a rotational gain to the leg - for persons with MS and investigate the effect on confidence in LE exercises.

H1: When an avatar has a rotational gain applied to the leg, users with LE motor impairment due to MS, will move their real leg less as compared to an avatar with no gain.

H2: When an avatar has a rotational gain applied to the leg, users with LE motor impairment due to MS, will feel more confident about successfully completing future leg movement repetitions than with no gain.

While these hypotheses seem trivial, in case of people with MS, they are not. Previous research showed that people with MS do not perceive the virtual world like the same way as people without MS does. In [SGQ16] the authors discussed how latency in a VE can affect how people with MS perceive VE. The authors suggested that people with MS perceive latency due to head motion less than people without MS [SGQ16].

4. METHODS

4.1. Participants

We recruited 11 participants (four male) with MS to investigate the effect of VAS. All participants were similar weight, height, and demographic background. The mean age of the participants was 53.30 years (SD 4.87). Every participant had a normal or corrected to normal vision. A series of questions from the scale was used to determine participants' Expanded Disability Status Scale (EDSS) score [Kur83]. Participants with an EDSS score greater than 4.5 were excluded from the experiment. EDSS is measured from 0 to 10 in 0.5 unit increments, where 0 means normal neurological state and 10 means death due to MS. The cutoff point of EDSS was set at 4.5 as we wanted to keep the participant group uniform. Any person who had any of severe blurred vision, vestibular diseases (non-MS related), psychiatric disorders, cognitive impairment, or cardiovascular and respiratory disorders were excluded from the study.

4.2. Apparatus

The VE was designed in Unity 5, a multi-platform game development engine from Unity Technologies. We used an HTC Vive head mounted display (HMD) in our user study. The Vive has a resolution of 2160 x 1200 (1080 x 1200 per eye) with a refresh rate of 90 Hz and a 110 degree field of view. A high performance computer was used in this study to render the VE. The system was equipped with Intel (R) Core (TM) i7 processor (2.60 GHz), 16GB DDR4 RAM, NVIDIA GeForce GTX 1070 display card with 8GB (GDDR5) of dedicated video memory, and a 64-bit Windows 10 operating system.

In both of our conditions (sec. 4.3.1), we used two controllers provided with HTC Vive to track the foot and knee of the participant as shown in figure 1. The positions of the controllers are tracked by the Vive base stations. Figure 2 shows a typical room setup for the Vive.
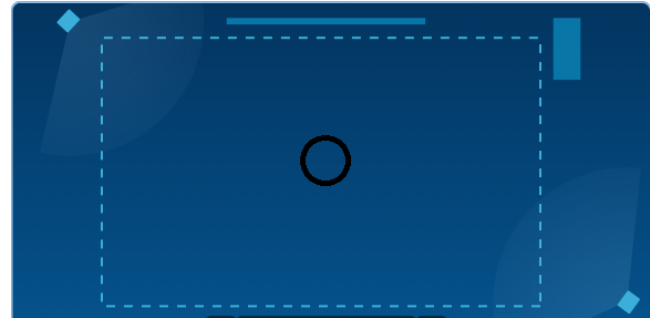
Figure 2: *A typical room setup with Vive base stations. Dotted line shows the tracking space. Black circle denotes the position of the participant.*

4.3. Study Design

We conducted a within-subjects study with two independent variables: 1) Gain with two levels and 2) trial. The gain conditions were experienced in counterbalanced order. The following sections present the details of the two independent variables and the virtual environment.

4.3.1. Independent Variable: Gain

In our study, the task was to repeatedly kick a virtual ball placed in front of the participant in the VE. The study had two within-subjects conditions: No Gain Condition (NGC) and Rotational Gain Condition (RGC) (see figure 3). In both conditions, the participant's MS affected leg (identified by the participant) was being tracked with the controllers from the HTC Vive. The difference between these two conditions was how much additional lift (i.e. rotational gain) their virtual avatar's leg was getting in the VE. For example, in NGC, if the participant lifted her real leg X cm, the virtual avatar also lifted it's leg X cm; but in RGC, the virtual avatar's leg was lifted higher than the real leg (X + Y) cm where Y was a function of X, how much the participant lifted the feet. In the calibration phase, we calculated the height of the ball to be placed in the VE (max height). While kicking the ball, the feet passed 20% of the max height, we start adding rotation gain. The max rotational gain was limited to 10 degrees. The highest gain was added at the point when the participant's feet is about 75% of the highest point.

4.3.2. Independent Variable: Trial

In each gain condition, the participant experienced 11 trials of kicking the ball. We treated the trial as an independent variable to examine learning effects across trials.

4.3.3. Virtual Environment

We developed a VE that was a virtual representation of the room where the experiment took place. Both the virtual room and our lab had the same set of identical furniture. Studies have shown that participants experiencing a VE similar to the surrounding physical room increases their presence [BDCL*06]. Figure 1 shows the participant's view of VE in our user study. The participants could move their lower body to move the avatar's lower body in the VE.
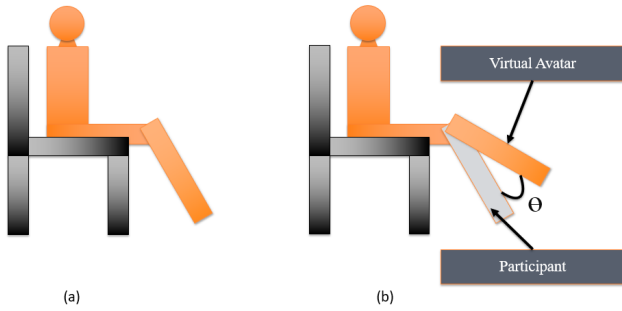
Figure 3: *Two conditions: (a) No Gain Condition (NGC) and (b) Rotational Gain Condition (RGC).*

The avatar's body joints from hips and below were controlled by the tracking data of two Vive controllers tracked by the HTC base stations. The participant's upper body (except the head) remained in a fixed position during the game. Figure 1 shows a participant's view when she looks down to see her body and extends her leg to experience the responsiveness of the avatar's leg movement. We used two HTC Vive controllers and placed them on one leg - one controller placed on the knee and the other one on the foot. This means that only one of the avatar's legs was responsive, and the remaining leg was still.

In every 30 seconds, a red ball appeared in front of the participant and her job was to kick the ball. When the participant kicked the ball, it turned into particles and vanished. At the same time, the participant felt a vibration in their feet from the Vive controller placed there.

4.4. Procedure

The study procedure consisted of the following three consecutive steps:

4.4.1. Consent and Pre-Study Questionnaire

At the beginning of the study, each person had to sign an ethics board approved consent form to participate in the study. After that, a brief introduction was given about the system and what they were expected to do in the study. Before they started the VR experience, the participants filled out a Simulator Sickness Questionnaire (SSQ).

4.4.2. Study Experience

Next, the participant was asked to sit on the designated chair and put the HMD on. When the participant was comfortable enough to start the study, we started the VR experience. First, we calibrated the kick height of the participant by asking them to extend their leg as high as they felt comfortable. For all participants, we tracked the leg that they claimed was most affected by MS. We saved the highest point in terms of controller tracking data to place the red ball, which they had to kick in each trial.

Then we begin the trials of our user study. The condition order was chosen randomly. Each condition had 11 trials (first trial was

for training purpose). In total there were 22 trials, but we excluded the first trial of each new condition from our analysis as the first trial was counted as training. Participants had two minutes of rest time between the conditions.

During the study, after each kick, the participants were asked two Likert scale questions: a) How difficult do you think the last kick was? and b) How confident are you that you will successfully be able to complete the next kick? They rated each questions in a scale of 0 to 10. To answer these questions, the participants did not had to remove the headset. At the end of the 22 trials, we asked the participants whether they noticed any difference between the first half and the last half of the trials to get the sense whether they were able to differentiate the RGC from NGC.

4.4.3. Post-Study Questionnaire

After finishing the VR experience, the participants filled out an SSQ one more time. In general, the whole study (VE experience + questionnaires) took approximately 45–50 minutes per participant. Each participant received a payment of $50 as a compensation for her time in our study.

4.5. Metrics

4.5.1. Difficulty and Confidence Questionnaire

We used following two Likert scale like questions to measure their confidence and perceived difficulty in VE: a) How difficult do you think the last kick was? and b) How confident are you that you will successfully be able to complete the next kick? We asked them to rate each answer of the questions from 1 to 10. For difficulty, 1 was the easiest and 10 was the hardest. For confidence, 1 was the least and 10 was the most confident.

4.5.2. Kick Height and Kick Time

As a performance measurement of the task given to the participants, we tracked the controller's (which was attached to the participant's foot) position in terms of a series of vectors (i.e., positionX, positionY, and positionZ). We used the positionY to measure the highest position a participant lifted her leg for a particular kick. We also calculated the time taken in each trial while kicking the ball.

4.5.3. Simulator Sickness Questionnaire (SSQ)

The Simulator Sickness Questionnaire (SSQ) is a standard 16 items questionnaire where each item asks about participants' different physiological discomfort [KLBL93]. Each item can be rated from "None" to "Severe" where "None" quantifies as 0 and "Severe" quantifies as 3 towards the calculation of SSQ score. SSQ has three sub-scales of scores-***nausea***, ***oculomotor***, and ***disorientation***. The ***SSQ total*** score was calculated from these three sub-scales.

5. RESULTS

5.0.1. Confidence Questionnaire

A two-way repeated measure Anova was conducted that examined the effect of gain and trial on participant's confidence towards completion of a subsequent kick. There was a statistically significant interaction between the effects of gain and trial number on participant confidence, $F_{(9, 90)} = 3.48$, $p = 0.001$, q partial $\eta^2 = 0.258$

We found significant main effects of gain with $F_{(1, 10)} = 45.38$, $p = 0.001$, q partial $\eta^2 = 0.819$. This result suggests that in the RGC participants were more confident in their ability to finish future kicks.

We also found significant main effects of trial with $F_{(9, 90)} = 192.59$, $p = 0.001$, q partial $\eta^2 = 0.951$. This result suggests that participants' confidence increased over time when they successfully finished their previous kick.

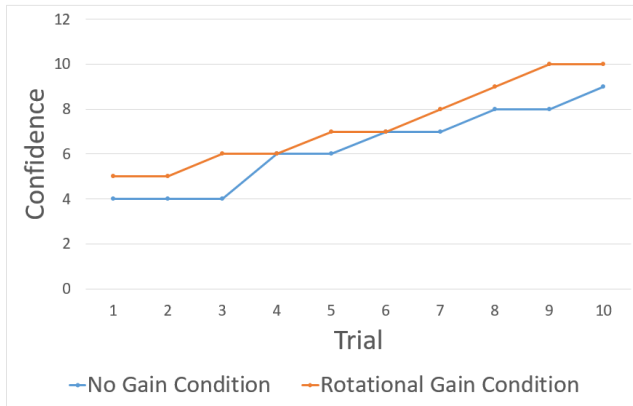Figure 4 shows the confidence change respectively for participants throughout the trials.

Figure 4: *Graph showing the change in confidence over trial for participants.*

5.0.2. Difficulty Questionnaire

A two-way repeated measure Anova was conducted that examined the effect of gain and trial on each participant's perception of the difficulty of the last kick. There was a statistically significant interaction between the effects of gain and trial number on interest in participant's perception of difficulty of the task, $F_{(9, 90)} = 3.85$, $p = 0.001$, q partial $\eta^2 = 0.278$.

We found significant main effects of gain with $F_{(1, 10)} = 344.42$, $p = 0.001$, q partial $\eta^2 = 0.972$. This result suggests that participants found NGC as more difficult than RGC.

We also found significant main effects of trial with $F_{(9, 90)} = 304.93$, $p = 0.001$, q partial $\eta^2 = 0.968$. This result suggests that participants' perception of difficulty decreased over time when they successfully finished their previous kick.

Figure 5 shows the perceived difficulty change respectively for participants throughout the trials.
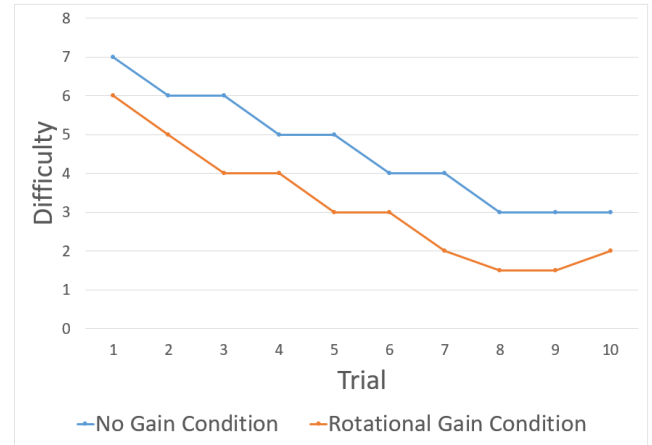
5.1. Kick Height and Kick Time Result

A two-way repeated measure Anova was conducted that examined the effect of gain and trial on kick height - the average displacement (in meters) of each participant's foot along the Y-axis. There was a statistically significant interaction between the effects of gain and trial on the average kick height (along the Y-axis), $F_{(9, 90)} = 2.29$, $p = 0.023$, q partial $\eta^2 = 0.187$.

Figure 5: *Graph showing the change in perceived difficulty over trial for participants.*

We found significant main effects of the factor gain on kick height with $F_{(1, 10)} = 15.07$, $p = 0.003$, q partial $\eta^2 = 0.601$. This result suggests that the participants kicked their feet in higher in NGC than RGC. Figure 6 shows the average height per trial basis. However, there was no main effect of factor trial number on kick height.

In addition, a similar 2-way repeated measure Anova was conducted to compare average kick time per trial. However, the difference between the time (in seconds) taken in NGC (M = 0.879, SD = 0.15) and RGC (M = 0.806, SD = 0.20) was not statistically significant.
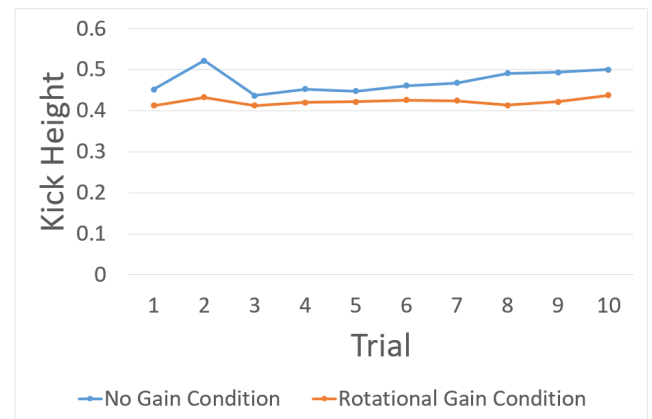

Figure 6: *Chart showing mean kick height in meters for each trial for the participants.*

5.2. Cybersickness Result

To compare the cybersickness experienced by the participants, we ran paired samples t-tests on different SSQ sub-scales (i.e., nausea, oculomotor, and disorientation) and total SSQ scores collected before and after the study. There was a significant difference in all of

the sub-scales and the total SSQ scores for pre-SSQ vs post-SSQ score. These results suggest that participants experienced symptoms of cybersickness during the VR experience. Table 1 lists all the results from our SSQ data.

Table 1: *Descriptive statistics for SSQ.*

Sub scale	Pre Mean (SD) Post Mean (SD)	t	p
Nausea	8.204 (8.586) 25.853 (10.618)	-5.461 (10)	0.002
Oculumotor	16.221 (24.142) 38.961 (19.784)	-6.874 (10)	0.001
Disorientation	7.934 (10.955) 27.84 (11.359)	-4.804 (10)	0.003
SSQ Total	13.352 (16.845) 36.876 (12.297)	-7.266 (10)	0.001

6. DISCUSSION

In this section, we discuss our hypotheses (sec. 3) based on the statistical analysis (sec. 5) found in our study and compare our results to previous literature.

Based on the results from our game performance analysis in section 5.1 we can accept our hypothesis **H1**: When an avatar has a rotational gain applied to the leg, users will move their real leg less as compared to an avatar with no gain. In the rotational gain condition, there was a rotational gain attached to the avatar's leg. Thus, participants did not have to lift their foot as high as was required in the no gain condition (NGC). Again, we need to keep in mind that while the virtual avatar had a rotational gain attached to the leg, visually both conditions were the same.

However, we discovered a surprising result when we observed the questionnaire answers for "whether they noticed any difference between the first half and the last half of the trials". Here, the first and last half of the trials represent two conditions (i.e., RGC, NGC) which were random in order. Nine out of 11 participants (81.8%) were unable to differentiate these two halves of the trials, even though participants rated the NGC trials as more difficult in their response during the study. Future work is needed to understand the reason for this discrepancy. However, it is possible that this is due to the wide variability of symptom severity and individual differences in MS. Moreover, many persons with MS exhibit some perceptual deficits in VR [SGQ16], which could have contributed to this result.

Based on the result from our analysis of confidence and difficulty comparison for MS affected leg in section 5.0.1 and 5.0.2 we can accept our hypothesis **H2**. That is, the RGC increased confidence more than the NGC even though the two were visually the same. Although one might conclude that this is an obvious result based on normal human behavior where people feel more confident when they successfully accomplish a task [GDME17]. However, the fact that the two conditions were visually the same and that most of the participants could not tell the difference makes this result interesting. Moreover, our results are similar to "Duck Duck Punch" used to treat people whose upper limb is affected

from stroke [DHHW13]. However, our results are focused on the lower extremity and a different population - people affected by MS.

Results from section 5.2 suggest that participants experienced cybersickness symptoms while playing the VR game. However, it did not severely affect the gameplay as all of our participants finished the game without any interruption.

6.1. Study Limitations

In this study, we investigated the ability simulation in a virtual reality environment for persons with MS. However, due to the small sample size and the single task, it may not be the case that the results from our study are generalizable to all types of rehabilitation exercise. Moreover, additional work is needed to generalize this result to other types of disabilities. Also, there was an effect of the trial on users' perception of difficulty and confidence, which means that repeatedly measuring difficulty and confidence had an effect on their later perception of difficulty and confidence. However, this was expected, as such an effect would likely be present while performing repetitive exercises in rehabilitation exercise.

7. Conclusion

In this paper, we presented a within-subjects study that investigated the effects of VAS for persons with MS, whose strength, proprioception, control, and range of motion of limbs, especially LE, are affected by MS. The results from our study suggest that VAS does make the task easier due to reduced range of motion requirements and elicits more confidence in participants' future tasks. Thus, this technique could potentially have benefits to increasing confidence in performing rehabilitation exercises, which could lead to improved motivation and better rehabilitation outcomes.

8. Future work

In our future research, we aim to widen our scope and investigate virtual ability simulation for people with different types of disabilities and difference exercises or rehabilitation tasks to generalize our results. We also plan to investigate long term effects of VAS on people with disability. The VAS simulates someone having more range of motion than they do in reality, and they may not even realize that the system is doing so. Thus questions we plan to investigate in the future could be: Is there a possibility that someone would overestimate their abilities and physically hurt themselves when trying to use these abilities later? Though promoting confidence initially, would repeated use compared to real world experience ultimately leave people more frustrated than they would have been without the system? In the future, we plan to include a mechanism to control how much rotational gain applied to the virtual avatar. In this way, we can decrease the gain over time when the participant feels more confident. This will help to better understand how the virtual ability technique can best be used in rehabilitation.

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