BALANCE TRAINING IN AN IMMERSIVE VIRTUAL REALITY ENVIRONMENT FOR LOWER EXTREMITY EXERCISE AND REHABILITATION

by

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A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Honors Bachelor of Science in Computer Science with Distinction

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I certify that I have read this thesis and that in my opinion it meets the academic and professional standard required by the University as a thesis for the degree of Bachelor of Science.

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ABSTRACT

Balance training is essential for physical rehabilitation procedures, as it can improve functional mobility and enhance cognitive coordination. However, conventional balance training methods may have limitations in terms of motivation, real-time objective feedback, and personalization, which a virtual reality (VR) setup may better provide. This work presents an immersive VR training environment for lower extremity balance rehabilitation with real-time guidance and feedback. The VR training environment immerses the user in a 3D ice rink model where a virtual coach (agent) leads them through a series of balance poses, and the user controls a trainee avatar with their own movements. The application includes two coaching styles: positive-reinforcement and autonomous-supportive, and two viewpoints of the trainee avatar: first-person and third-person. We evaluated the proposed environment in a user study with healthy, non-clinical participants (n=16, 24.4 +- 5.7 years old, 9 females). The results show that participants exhibited stronger performance in the positive-reinforcement style compared to the autonomous-supportive style. Additionally, in the third-person viewpoint, the participants exhibited more stability in the positive-reinforcement style compared to the autonomous-supportive style. For viewpoint, participants exhibited stronger performance in the first-person viewpoint compared to third-person in the autonomous-supportive style, while they were comparable in the positive-reinforcement style. There were no significant effects on the foot height and number of mistakes. Furthermore, we report the analysis of user performance with balance training poses, as well as subjective measures based on questionnaires to assess the user experience, usability, and task load. The proposed VR balance training could offer an interactive, adaptive, and engaging environment and open new potential research directions for lower extremity rehabilitation. We also take steps towards a future direction of this work by modifying

the system for clinical use, sharing the system with an expert in biomechanics and older adults with balance impairments, and receiving their qualitative feedback to initiate the process of a formal clinical study.

Chapter 1

INTRODUCTION

1.1 Motivation

Balance is a critical skill for physical health, especially for older adults who are at a higher risk of falling. In older adults, balance naturally declines with age due to diminishing muscle mass and strength, loss of vision, and deficits in proprioception, vision, and vestibular senses [50]. Moreover, neurological and musculoskeletal diseases limit a large population of older adults from maintaining the necessary balance for daily activities. Current effective balance training assessments include exercises such as standing on one leg, balance board exercises, standing with eyes closed, and forward/backward walking [45]. One among other balance training strategies is to allow the user to perform with continuous visual feedback [55]. Visual feedback, also referred to as *virtual coaching*, involves collecting performance data, monitoring the position and movement, and then providing real-time feedback, e.g., progress, orientation, and audio feedback. However, despite there being several effective methods for balance training with desktop-based systems, patients often struggle with low motivation and adherence due to the unengaging, repetitive nature of such exercises.

Previous research demonstrates that virtual reality (VR) and augmented reality (AR) have various benefits for rehabilitation over conventional approaches. Such benefits include increased motivation and engagement, higher training intensity and task specificity, greater performance improvements, streamlined expenses, minimized hazards for users, useful real-time biofeedback from sensors, and the ability to remotely monitor the patient and their progress [9, 35, 42]. Studies also show that virtual coach avatars can be implemented into virtual therapy applications to form social-emotional relationships with users. However, more work is needed on how the presence of verbal feedback from a coach within a virtual therapy environment can influence a user's sense of presence, experience, and performance. There is also a lack of research on how a user's point of view within an avatar-based virtual therapy system influences the user experiences, perceptions, and performance within the virtual environment.

1.2 Research Goals

In this paper, we introduce a VR balance training environment with virtual trainee and coach avatars, alongside real-time body tracking capabilities. The user is immersed in a virtual 3D ice rink environment with a virtual coach, which guides them through a series of balance poses, and a trainee avatar, which the user controls in real-time via a Microsoft Azure Kinect depth-sensing body tracking camera. The participant can perform the activity either by sharing the field of vision of the trainee avatar in a *first-person* viewpoint, or watching their trainee avatar displayed in front of them in a *third-person* viewpoint The game encourages still, steady posture during various one-legged standing balance poses while being both entertaining with the immersive ice rink environment and engaging through the coach's instruction and input. Moreover, we aim to investigate how a user's viewpoint within the environment and a coach's leadership style impact the user's balance training performance and experience, as well as their sense of social presence within the environment. We conducted a user study ($n = 16$) to assess user performance, usability, task load, and user experience.

Our main contributions include design and implementation of a VR balance training environment with integration of available assets, e.g., avatars and body tracking, to create a new and creative environment for balance training. We developed training scenarios with different poses for various coaching styles and user viewpoints for balance rehabilitation, which can be extended to various communities such as older adults and individuals with neurological or musculoskeletal injuries. Additionally, we evaluated the environment in a user study to assess the effects of viewpoint and coaching style within the immersive VR environment on user performance and experience.

Results of the pilot study (n = 16) provide insights into usability, task load, and balance training performance in a comparison between coaching styles and viewpoints of the trainee avatar. The results could indicate which coaching style and viewpoint are the most beneficial within this balance training system and its future development. Additionally, we collected and summarized qualitative feedback to demonstrate features, advantages, and current limitations motivating potential future research directions. Finally, we explored the future research direction of adapting the system for clinical use, specifically in stroke rehabilitation. We carried out system modifications, received feedback on the system, and explored other target populations with whom to potentially test the system with in the future.

Chapter 2

BACKGROUND

In this section, we review previous works related to VR/AR rehabilitation and balance training with and without a virtual coach, as well as how various coaching styles can impact training performance and experience. We also explore the user experience in such virtual environments, specifically in terms of embodiment, control, and presence.

2.1 VR-based Balance Training Systems

In the context of lower extremity therapy, active participation in balance training is crucial for patients. A decline in balance ability can affect all age groups and may be due to physiological deterioration, pathological factors, problems of ambulation, and endurance reduction [40, 42]. This deterioration of the neurotransmitter system, muscle mass, and strength is a major health problem because it may lead to a higher risk of falling injuries, a rise in chronic diseases, and cognitive decline [11].

Both AR and VR have been effective tools in balance training studies. Yang et al. [54] compared home-based VR balance training and conventional home balance training in community-dwelling patients with Parkinson's Disease (PD). The results show that VR balance training methods are equally as effective as conventional methods in improving balance, walking, and quality of life among community-dwelling patients with PD and can be easily integrated into a home-based therapy plan; this benefits those living in areas with limited access to rehabilitation services. Prasertsakul et al. [40] studied the effect of VR-based training on two conditions: motor learning and postural control. They found that compared to conventional exercises, the exercises in a VR system can facilitate better postural control and better prevent future falls in healthy adults. Blomqvist et al. [11] used AR-based visual-interactive guidance through a Microsoft HoloLens holographic display to train seven older adults with impaired balance under the supervision of a physiotherapist. They found that the use of AR technology increased motivation and feedback amongst most participants.

What makes VR effective in exergames is its ability to increase motivation and its fully immersive experience [47]. However, we should also acknowledge the potential risks and disadvantages of using VR for training. Shaw et al. [47] highlights challenges that negatively impact the user, which can include motion sickness, the health and safety concerns of exercising in an immersive technology, and physical feedback latency. Specifically, these challenges may affect user balance because of visual conflicts, postural instability, and disequilibrium. Despite these concerns, studies can still be effective and safe for users as long as the correct precautions are taken. Shaw et al. found their design was effective at handling the concerns identified earlier in the paper, as no participants fell and nobody got caught on the wire connecting the VR headset to the computer that allows the application to display in the headset. [47].

Esculier et al. [16] addressed safety concerns in their study with a detailed explanation of the program and supervision of the first complete training session by two members of the research team who specifically checked the safety of the subjects in their homes. They also made the platform as easy to use as possible to avoid issues for patients.

Therefore, more research is needed in the integration of VR for training because current barriers include lack of conclusive evidence and quality of software [51]. It is important that new studies like ours address these issues and take user safety into account. In this study, we ensure that our participants are in an area clear of tripping hazards, do not have any tangled wires that may interfere with their movements, and are informed that they can stop participation at any time if the fully immersive headset causes motion sickness or vision problems.

2.2 Effects of Viewpoints in VR Balance Training

In video games, two visual viewpoints are generally available to users: a first-person viewpoint through the avatar's eyes, and a third-person viewpoint where the user views the avatar from an adjustable distance and angle of view [43]. Salamin et al. [44] look into these viewpoints for VR and AR applications and investigate which one users prefer when using an immersive Head Mounted Display (HMD). In general, participants preferred third-person for displacement actions, interactions with moving objects, evaluating distances, and anticipating/extrapolating trajectories. However, users preferred first-person when they needed to look down or just in front of them for hand manipulations with immobile objects. Based on their results that preference depends on the current action of the user, they conclude that both viewpoints are needed during the simulations composed of varying actions and that a switch between viewpoints could be very useful for such future applications. Galvan Debarba et al. [18] had a similar conclusion that the ability to alternate viewpoints is associated with a strong sense of embodiment, which is important for the design of any embodied VR experience. However, when alternating viewpoints is not an option, the users prefer a third-person viewpoint due to the mirroring body ownership when sensorimotor contingencies are present. Additionally, when the virtual avatar is facing a threat in the virtual environment, it is better for users to experience it in a third-person viewpoint than first-person.

In another study [43], users reported a preference for the third-person viewpoint because the navigation task was spread across different stages. Participants could see their bodies, so they found it easier to complete the task. The third-person viewpoint training can lead to quicker adaptation of distance evaluation in the extra personal space. However, there are some drawbacks to the third-person viewpoint, such as it being the more uncommon viewpoint and that it could introduce biases, e.g., occlusions due to the participant body. Regardless, the authors believe that the usage of a third-person viewpoint is comparable to a first-person viewpoint for sports-related VR training methods and can be a viable and efficient solution that positively impacts effectiveness and optimal performance.

Emmerich et al. [15] support that first-person and third-person viewpoints are preferred in different types of VR game environments. Participants tend to prefer a first-person viewpoint in environments that involve themselves interacting with other characters and objects in the environment. They felt that seeing themselves in third-person was obstructive in this setting. However, in certain games, the participants appreciated seeing the user in action, and felt it gave them a stronger understanding of the game and its goals. The study also reveals that the third-person perspective can mitigate motion sickness for individuals experiencing discomfort in the first-person viewpoint. Different people also have different preferences on viewpoints that are not influenced by the VR game itself. The first-person view is preferred by spectators who want to feel like they are playing the game themselves and who want to see "through the player's eyes". Notably, some participants explicitly articulate a "preference for the original perspective," citing increased involvement as the predominant reason for favoring the first-person viewpoint.

2.3 Balance Training with Virtual Coaching

Virtual coaching refers to the use of a virtual avatar to provide feedback and coaching to individuals during exercise in an immersive environment. Virtual coaching proves particularly effective in assisting individuals with balance improvement and lower extremity rehabilitation [3]. The VR training environments with virtual coaching include tasks that require the individual to maintain their balance, and their performance can be observed and measured by various sensors. A strong advantage of using VR as a training tool is to not only provide an engaging and enjoyable environment but to enhance performance and provide visual feedback on their posture and balance in real time [51].

When proper precautions are taken, virtual coaching in VR provides a safe and controlled environment for individuals to practice their movements. Besides the real-time feedback, it can help individuals customize and make adjustments to the coaching to meet their specific needs and movements. Esculier et al. [16] investigated the effectiveness of home-based balance training for individuals with Parkinson's Disease. They found that the home-based training led to improvements in balance, gait, and overall mobility. Akbas et al. [1] reviewed studies and applications of VR in sports training, focusing on cognitive training, motor skills training, and rehabilitation. They concluded that the use of VR with virtual coaching provides realistic and challenging scenarios that enhance athletes' movements for optimal performance. They concluded that VR has great potential for training and performance enhancement. Similarly, Tropea et al. [53] provided an overview of the applications of virtual coaching in clinical settings. The results show that most of the virtual coaching applications addressed the topic of physical therapy, while other applications were focused on managing the overweight and different clinical conditions. Although virtual coaching applications for physical activity have been proposed, scenarios for rehabilitation are still underrepresented.

2.4 Leadership Styles in Coaching

Building off of the idea of virtual coaching, it is important to understand how different coaching styles can impact a person's experience and performance. In sports, there are several leadership styles coaches adapt to motivate and better their athletes. In healthcare, health coaches utilize reinforcement techniques that aim to foster intrinsic motivation in their patients.

While there are many different coaching styles with different focuses, a few common leadership styles in sports coaching are autonomous-supportive, positive-reinforcement, and negative-reinforcement. Autonomous-supportive style is pro-social behavior that acknowledges feelings/emotions, the ability for athletes to make their own choices and take initiative with independent work while fostering intrinsic motivation [33]. Amorose et al. [2] found that autonomy-supportive coaching style (i.e., providing athletes with choices and options), promotes a mastery motivational climate, provides social support, and positively influences the athletes' perceptions of autonomy, competence, and relatedness. Reinforcement styles, such as positive-reinforcement and negative-reinforcement, focus heavily on the verbal feedback given to the athlete. Reinforcement coaching styles focus on fostering extrinsic motivation. Positive-reinforcement, such as rewards, scholarships, stipends, endorsements, and continuous praise, are external reinforcements of motivation. Positive-reinforcement coaching styles may initially provide the necessary extrinsic motivation for an athlete to succeed, but over time will foster internal motivation [41]. Smith et al. [48] found that coaches who give high amounts of technical instruction and positive reinforcement would be more likely to create a task-involving motivational climate on their team, which allows for the possibility of each athlete feeling successful. Negative-reinforcement, or controlling coaching, is characterized by anti-social unapproachable behavior, excessive verbal feedback, pressure on athletes, negative feedback/criticism that may include punishments) [33]. Ragogna et al. [41] also explore the idea of no verbal feedback, stating that either negative feedback or no feedback from a coach can have detrimental effects on an athlete. Athletes often want to be rewarded for their success, even for small contributions to the team.

The coach's leadership style with their athletes can also impact team dynamics; an autonomous-supportive coaching style led to an autonomous motivation within an athlete, which was associated with prosocial behavior toward teammates; a controlled motivation was associated with antisocial, unapproachable behavior toward both teammates and opponents, mediated by moral disengagement [37]. Controlling coaches tend to provide a surplus of verbal feedback, often negative, without allowing the athlete to find independence in their motivation and performance. These leadership styles affect not only the coach-athlete relationship, but also the athlete's personal factors and relationships with others.

Additionally, preferred coaching styles change with new generations. In a study [38], youth athletes view a great coach's qualities as (1) does not yell and remains calm, (2) caring and encouraging, (3) having knowledge of the sport, and (4) involving the team in decision making; most of these traits resemble the autonomous-supportive and positive-reinforcement leadership styles. In order to guide young athletes, coaches must look at the most effective leadership styles currently.

Health coaching is an effective patient education method that can be used to motivate and take advantage of a patient's willingness to change their lifestyle and to support the patient's home-based self-care. It is patient-oriented and motivates patients to achieve goals that improve their quality of life and improve their health [28]. Typical healthcare coaching involves reinforcement for self-care behavior, and fostering an awareness for self-care goals. While external motivators may be implemented in the coaching, the overall goal is to foster intrinsic motivation over time [28]. Olsen et al. [36] found through reviewing several studies that health coaching may positively impact other health risk factors and the mental health of study participants. Coaching sessions can take place across various platforms, such as over the phone, through email, or in person. Regardless of the format, the health coaching relationship is designed to be patient-centered, with coaches providing education, feedback, and support to enhance self-awareness, motivation, accountability, and self-efficacy [36]. However, it is ultimately the patients who provide direction for learning and implementing changes. Thus, effective health coaching seeks to foster long-term intrinsic motivation in patients so that they can successfully adhere to and benefit from healthy routines.

2.5 Avatar Embodiment and Sense of Control and Presence

Avatar embodiment can enhance the effectiveness of balance training and rehabilitation by providing a more immersive and engaging training experience [14, 7, 6]. Borrego et al. [12] conducted a comparative study to determine perceived embodiment and presence in VR between healthy subjects and individuals with stroke. The results show that the sense of embodiment and presence were effectively experienced in both groups. However, the sensed body-ownership and presence were higher for healthy subjects, especially for the first-person viewpoint with the VR headset. Steed et al. [49] presented a study on presence and embodiment in VR using consumer VR headsets. They found that the sense of presence and embodiment was influenced by the quality of the VR experience, and participants who experienced a more realistic and engaging

VR environment reported higher degrees of presence and embodiment. Grassini et al. [21] evaluated the use of VR to improve skill training performance compared to the traditional approach using instructional video. The results show that there was no significant difference in performance measures. However, participants in the VR training condition reported a significantly higher sense of presence, which was highly correlated with performance matrices. Hence, the avatar embodiment can play a crucial role in the effectiveness of balance training and rehabilitation.

2.6 Balance Training Systems for Stroke Rehabilitation

Strokes are a serious medical event which cause the victim to suffer from severely impaired bodily control, including impaired balance. Stroke rehabilitation requires a great amount of inpatient visits for physical therapy, as well as adherence to a strict at-home regimen. Numerous studies have explored the efficacy of VR in improving the physical therapy experience and bodily control of post-stroke patients.

Seregni et al. [46] evaluated a novel virtual coaching system for various target populations, including stroke patients, based on personalized clinical pathways. According to the majority of patients, the rehabilitation service through the solution was interesting, engaging, entertaining, challenging and useful for improving impaired motor functions, and making patients aware of their cognitive abilities. Hyun et al. [25] explore how sit-and-stand training combined with real-time visual feedback impact lower limb muscle strength, balance, walking, and quality of life in stroke patients. The participants were divided into two groups; one group received classic sit-to-stand training, and the other received sit-to-stand training combined with real-time visual feedback using a Wii Balance Board. The results showed that the visual-feedback group showed greater improvements in lower extremity muscle strength, balance ability, walking ability, and quality of life.

At-home rehabilitation is worth exploring for stroke patients in order to reduce the number of in-person visits required for physical therapy. Cikaljo et al. [26] explore balance training in a clinical setting with VR telerehabilitation in stroke patients. The participants each completed two weeks of clinical training, and one week of VR telerehabilitation training. The telerehabilitation approach in VR improved balance in stroke patients and patients had similar postural improvement as in a clinical setting. Over time, telerehabilitation would reduce the number of outpatient visits needed, while providing similar effectiveness as in-person clinical rehabilitation. Cameirão et al. [13] presented a study on two different home-based solutions for stroke therapy; one system was based on gaming, while the other was based on coaching and encouragement. The participants (20 healthy subject, 5 chronic stroke patients) performed an elbow extension and flexion task in both modes. Healthy subjects reported that they preferred the gaming mode but found the coaching mode more useful, and exhibited better movement quality in the gaming mode. Stroke patients exhibited higher activity levels in the coaching mode, but better movement quality in the gaming mode. Overall, gaming led to more enjoyment and increased movement quality, but coaching led to higher activity levels. They concluded that different patients with different background would benefit differently from each mode.

Virtual Reality mirror therapy is a technology that allows patients to see a projection of an affected limb in order to trick the brain into thinking movement has occurred without pain, or to create positive visual feedback of a limb movement [27]. In et al. [27] explored virtual reality mirror therapy in stroke rehabilitation. Their Virtual Reality Reflection Therapy (VRRT) system applies the principles of mirror therapy; movements of the unaffected side were recorded with a camcorder, allowing the patient to look at the projected image on the monitor above their affected limb. There were statistically significant improvements in the VRRT group compared to the control group for the Berg Balance Scale, Time Get Up and Go test, and Functional Reaching Test, as well as postural sway and 10 meter walking velocity. This shows that VRRT alongside conventional balance training can be more beneficial than conventional rehabilitation alone in stroke rehabilitation.

Chapter 3

MATERIALS AND METHODS

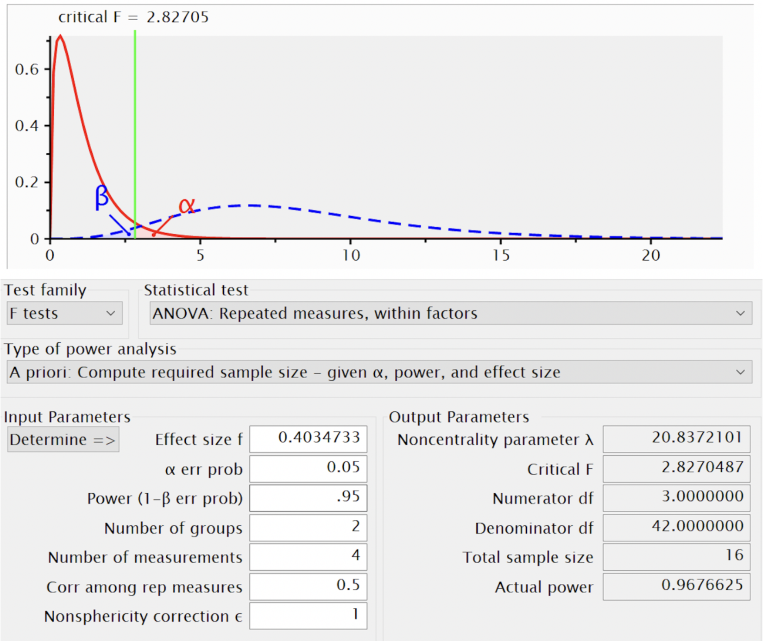
In the following sections, we describe the participants, apparatus, study design, hypotheses, and procedure of the user study.

3.1 Participants

We used a statistical G*Power analysis with power 0.95 to determine the sample size with a partial $\eta_p^2 = 0.14$ for two groups and four measurements, which results in a total sample size of 16 [17] (see Figure 3.1).

Our participant pool came from non-clinical volunteers from the University of Delaware with no neurological issues, no history of lower limb injury that impacts weight-bearing and/or balance, and no visual impairment beyond the correction of glasses or contacts (see Table 3.1). We confirmed that participants met these physical health requirements through a brief pre-survey.

The 16 participants were an average of 24.4 +- 5.7 years old, with 9 females. Six out of 16 participants (37.5%) have Caucasian or White ethnicity, eight (50%) have Asian or Pacific Islander ethnicity, one (6.25%) has African American or Black ethnicity, and one (6.25%) reported mixed ethnicity. Most participants had prior VR experience (68.75%). Three participants (18.75%) have previously experienced a severe lower-body injury, either due to sports or other incidents. However, only two of them (12.50%) needed to participate in rehabilitation sessions to recover. When asked how often they exercise for a minimum of >20 minutes per session, four (25%) did so daily, five (31.25%) did so 4-5 times a week, three (18.75%) did so three times a week, three (18.75%) did so less than three times a week, and one (6.25%) never did any. Specifically with physical activities that target standing balance, one (6.25%) did them



Test family: F tests

Statistical test: ANOVA: Repeated measures, within factors

Type of power analysis: A priori: Compute required sample size – given α, power, and effect size

Input Parameters		Output Parameters	
Effect size f	0.4034733	Noncentrality parameter λ	20.8372101
α err prob	0.05	Critical F	2.8270487
Power (1-β err prob)	.95	Numerator df	3.0000000
Number of groups	2	Denominator df	42.0000000
Number of measurements	4	Total sample size	16
Corr among rep measures	0.5	Actual power	0.9676625
Nonsphericity correction ϵ	1		

Figure 3.1: G*power analysis with power of 0.95.

daily, four (25%) did them three times a week, five (31.25%) did them less than three times a week, and six (37.5%) never did them.

3.2 Apparatus

For our study, we designed an interactive VR environment using the Unity game engine (version 2019.4.7f1). We utilized the HP Windows Mixed Reality Headset Developer Edition VR1000-10 and a Microsoft Azure Kinect DK depth sensing RGB body

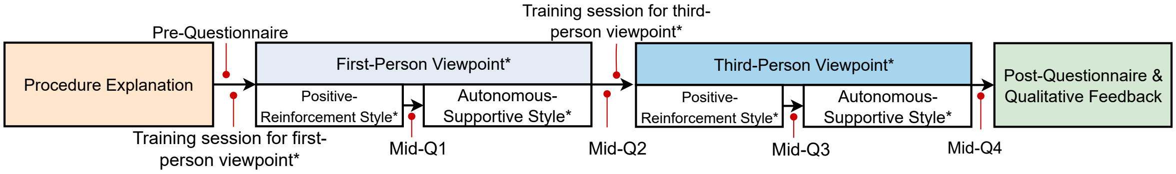


Figure 3.2: Overview of our study procedure. The order of the coaching styles and viewpoints marked with * were counterbalanced. *(Mid-Q: Mid-Questionnaire)*

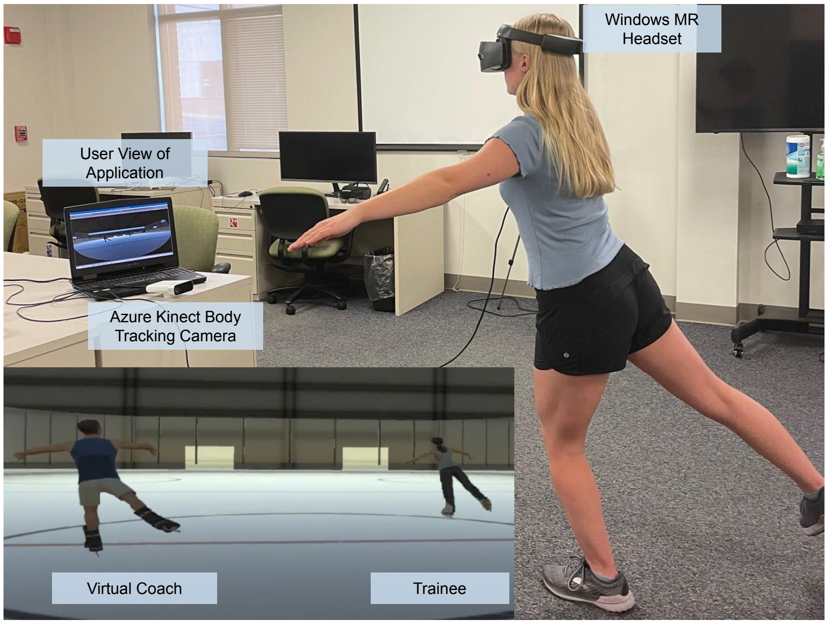


Figure 3.3: The experimental setup. The bottom left corner shows the virtual coach and trainee avatars that the user can see in the headset (in a third-person viewpoint). The Kinect tracks the user's movement in real-time.

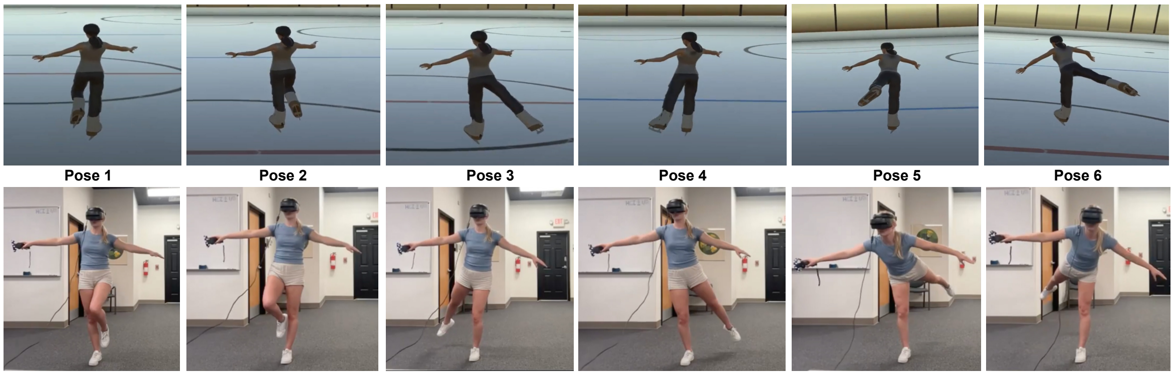


Figure 3.4: The participants were asked to perform six balance training poses. The user (bottom row) is controlling the trainee avatar (top row) in the third-person viewpoint. *The virtual coach is not shown in these images.*

tracking camera to record the animations for the coach avatar using the movements of real humans (see Figure 3.3). The Kinect DK has a capture rate of 30 frames per second, and the user stands 2 m away from the camera. The camera field of view was

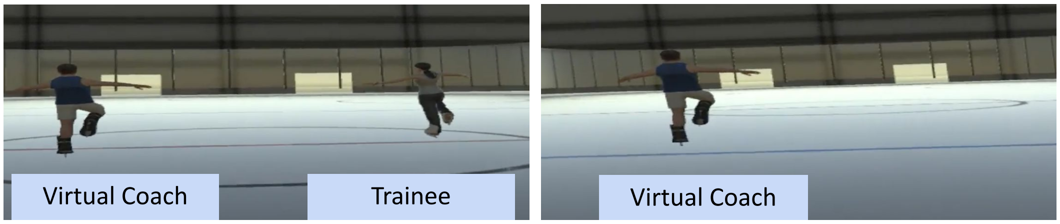


Figure 3.5: Balance training poses with two viewpoints: (a) the third-person viewpoint, where the user sees the coach and trainee avatars in front of them, and (b) the first-person viewpoint, where the user embodies the trainee avatar and sees the coach avatar.

Table 3.1: Participant background and characteristics ($n = 16$). *Measurements of height and weight are in feet (ft) and pounds (lbs).*

Characteristics	Value	Mean
Age	[19-40]	24.4 ± 5.7
Height	[59-72]	65.6 ± 3.7
Weight	[100-192]	148.0 ± 28.7
Gender		
Male	7	(44%)
Female	9	(56%)
Education		
Bachelor's program	8	(50%)
Master's program	7	(44%)
Doctoral program	1	(6%)
VR experience		
None	5	(31%)
A few times	2	(13%)
Several times	9	(56%)
Handedness		
Left	1	(6%)
Right	15	(94%)

75°x65 with an operating distance of 0.5 - 3.86 m [1]. The Kinect was turned on at least 10 minutes prior to data collection. Additionally, each user completed a short practice session before data collection where the Kinect was used but was not saving movement data. We used the Hockey Kit Pack unity package [2] from the Unity asset store as our 3D ice skating environment. Both the coach and trainee avatars are

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[1] https://learn.microsoft.com/en-us/azure/kinect-dk/hardware-specification

[2] https://assetstore.unity.com/packages/3d/environments/hockey-arena-stadium-kit-174749

from the Microsoft Rocketbox Avatar Library [20], and they were animated using the Movebox for Microsoft Rocketbox Capture Studio [19]. We used this Capture Studio with the Kinect to track the participant's body movements in real-time to animate the trainee avatar, and to collect quantitative movement data. The movement data is analyzed in real-time, prompting the coach avatar to offer verbal feedback while the participant is performing the activity. These verbal segments were generated with the Text to Speech Free website [3].

3.3 Study Procedure

An overview of the study procedure is shown in Figure 3.2. The IRB approval number for this study is 1982586-1. Before each participant came to the lab, we ensured that they understood the purpose and possible risks of the study. Upon the participant's arrival at the lab, they received further explanation of the procedure, and were asked to fill out a brief pre-questionnaire consisting of questions regarding demographic information, experience with VR, and physical fitness. Upon completion of the pre-questionnaire, the experiment proctor once again described the purpose of the study, the participants' rights and responsibilities, and asked them to sign a consent form before beginning the activity.

The participants were then asked to complete the first training session in either first-person or third-person view, both with positive-reinforcement style (verbal feedback from the coach). The training scenes were a shortened version of the real task, with a slightly different, less immersive rink environment and only one balance pose, performed on each foot. No data was collected during the training. Then, the participants were then asked to complete the balance training tasks (positive-reinforcement style and autonomous-supportive style) within the viewpoint they trained in.

After the completion of each condition, the users were asked to sit down and complete a mid-questionnaire. The mid-questionnaire consisted of questions regarding

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[3] https://ttsfree.com/text-to-speech

enjoyment, difficulty, social presence, and avatar embodiment. Following the completion of both coaching styles and mid-questionnaires, the participants were then instructed to begin the training session for the second viewpoint. This procedure was repeated for the second viewpoint. After completing the two training sessions, four conditions, and four mid-questionnaires, the participants were asked to fill out an additional post-questionnaire regarding the overall system and experience. Upon finishing this final questionnaire, participants were invited to share any verbal feedback or comments regarding their experience, which was recorded in writing by the experiment proctor.

3.3.1 Balance Training Poses

There are six balance training poses which were developed in this VR balance training environment (see Figure A.1). The poses were derived from typical poses in ice skating; specifically, one foot glides, stroking, and spirals in figure skating. However, these poses may provide useful for balance training for non-ice skaters as well due their challenging nature. The participants were instructed to replicate the coach's movements to the best of their ability as the coach led them through these six poses. The coach holds each pose for 10 seconds, with a short rest period of about six seconds between each pose. The total training time for all six poses and rest periods between poses was 90 seconds for each condition, as each condition includes the same poses for the same duration and in the same order.

- *Pose 1*: Standing on the right foot, the left leg is lifted up and bent at the knee.
- *Pose 2*: Standing on the left foot, the right leg is lifted up and bent at the knee.
- *Pose 3*: Standing on the right foot, the left leg is lifted low behind the body
- *Pose 4*: Standing on the left foot, the right leg is lifted low behind the body.
- *Pose 5*: Standing on the right foot, the left leg is lifted high behind the body.
- *Pose 6*: Standing on the left foot, the right leg is lifted high behind the body.

3.4 Study Design

We used a 2 × 2 within-subject design outlined in the following sections. We defined two independent variables, coaching style and viewpoint, which created four possible study conditions to test. We also defined numerous qualitative and quantitative dependent variables. The independent and dependent variables are expanded upon in the following section

3.4.1 Independent Variables

The two factors were defined by two independent variables: *coaching style* and user's *viewpoint* of trainee avatar.

The two main coaching styles are reflected in our system through the inclusion and exclusion of audio feedback in the form of constructive criticisms/encouragements. In the autonomous-supportive style, the virtual coach provides no audio feedback, allowing participants more independence in their exercises. The coach silently guides participants through the six poses. In the positive-reinforcement style, the virtual coach provides participants with audio feedback based on their performance. The coach offers three main types of verbal feedback with visual motions; suggesting ways to regain balance when high unsteadiness is detected, suggesting that the participant raises their leg higher when low foot height is detected, and praise when the participant is mirroring the coach steadily and accurately.

The virtual environment was adjusted to be able to show the user in both the first-person and third-person point of view. We aim to investigate whether the user's perception of themselves as the avatar influences performance and overall experience. We prepared both a first-person viewpoint setting and a third-person viewpoint setting for the application. In both settings, the user directly controls the trainee avatar with their own movements. In the first-person viewpoint, the trainee avatar is located where the user is standing, with the user's field of vision set at the avatar's eyes. The user embodies the trainee avatar. In the third-person viewpoint, the trainee avatar is located in front of the user and next to the coach. The user can view the trainee's entire body.

This adds an element of visual feedback that shows the user how they look in real-time, and can possibly alert the user to issues with their pose that they may not be able to feel themselves. They are able to see if they are unsteady, if their foot is low, or if they are making a mistake.

3.4.2 Dependent Variables

For our study, we recorded both objective and subjective measures to assess the users' perception of the VR balance training application and their performance under different conditions. We used a Microsoft Azure Kinect to collect joint movement data from each user pose.

We measured the steadiness of the participant during each balance pose, focusing on the variation in hand height throughout the pose. The movement of each hand was individually tracked using two static points, that were set on the user two seconds after the coach initiated a pose. This allowed the user a moment to start the pose and find their balance. These static points were set at the current position of the participant's left and right hands at that moment, and remained fixed as the participant executed the rest of the pose, moving forward along with the avatar across the ice. The x, y, and z distance (in meters) from each reference point to its respective hand was recorded at each frame (50 times per second) in a CSV file. However, the y distances were the only values we used in our final steadiness calculations. Steadiness was calculated through two separate calculations of left hand position and right hand position. We calculated the change in y distance from each hand to it's respective initial static point for each frame, and calculated the average of these distance values for each hand. We then take the absolute difference between these values for each hand, and use this as our steadiness calculation. If the user maintained steadiness, the height of their hands should not deviate significantly from these static points. Therefore, we measured the average of these changes in distance to calculate our average steadiness score for each pose and each condition. Thus, our steadiness measure quantifies the amount of vertical hand height variation. This is an exploratory formula for calculating steadiness throughout a balance pose. There are numerous other measures and formulas which are worth exploring in the future, which are expanded upon in the future work section.

To evaluate balance pose quality, the height of the participant's foot off the ground was measured at each time frame (50 times per second). For a pose in which the user is standing on their right leg, the height of their left leg was measured by calculating the y position of the left foot minus the y position of the right foot (in meters); for a pose in which the user is standing on their left leg, the height of their right leg was measured by calculating the y position of the right foot minus the y position of the left foot (in meters). These foot height measurements were recorded in a CSV file. It is expected for foot height to differ amongst poses, as the different poses do not all have the foot raised to equal heights. In the positive-reinforcement coaching style, the coach frequently encourages the user to raise their foot higher, as this would make the pose more difficult and could contribute to more effective balance training. No target foot heights were set directly, so we only collect this foot height data to see if there are significant differences in foot height between coaching styles and viewpoints.

To quantify the number of mistakes made by the participant during each balance pose, the experiment proctor manually counted the instances where the participant's non-standing foot touched the ground. This count could be cross-referenced with the number of times the participant's foot height was 0 (on the ground). This means the participant lost balance and lowered their raised leg from the pose the coach instructed them to hold before completing the pose.

It must be noted that the steadiness (as measured through hand position), foot height, and number of mistakes were our only metrics for determining pose quality, and do not fully capture whether a pose has been performed accurately compared to the coach's pose. This is expanded upon in the limitations and future work sections.

3.4.3 Questionnaires

The mid-questionnaire was used to assess the participant's social presence with the virtual coach, avatar embodiment, and their experience that could be influenced by coaching styles and viewpoints.

We measured the participants' sense of presence within the virtual environment for each condition by asking the user if they agreed with statements such as "I feel like the coach is watching me and is aware of my presence." We customized the questions from Bailenson et al. to fit our study design and virtual environment [4]. We used eight questions with a 5-point Likert-scale ranging from *strongly disagree* to *strongly agree.*

We measured the participants' sense of avatar embodiment by asking questions such as "I felt like I could control the virtual body as if it was my own body." We customized the questions from Peck and Gonzalez-Franco to fit our study design and virtual environment [39]. We used 17 questions with a 5-point Likert-scale ranging from *strongly disagree* to *strongly agree.*

We measured how much each participant enjoyed each condition by asking one custom question, "I enjoyed this condition of the activity", which was scored on a 5-point Likert-scale ranging from *strongly disagree* to *strongly agree.*

We measured the participants' perceived difficulty of each condition by asking one custom question, "I felt that this condition of the activity was difficult", which was scored on a 5-point Likert-scale ranging from *strongly disagree* to *strongly agree.*

We measured the participants' perception of the virtual coach avatar for each condition by asking the user if they agreed with statements such as "I felt that the coach cared about my experience and enjoyment" and "I felt that the coach cared about my performance." We used two custom questions with a 5-point Likert-scale ranging from *strongly disagree* to *strongly agree.*

We measured the participants' willingness to recommend the virtual environment for each condition by asking the user "I would recommend this system to a friend or family member looking to improve or regain their balance." This one custom question was scaled from *1 = not at all* to *10 = extremely agree.*

3.4.4 Hypotheses

The following hypotheses were established with respect to two factors: coaching styles and viewpoints of the trainee avatar.

H1 : For *coaching styles*, the participant's balance performance will be improved with the *positive-reinforcement style* of real-time verbal feedback from the coach compared to *autonomous-supportive style*.

H2 : The participant's subjective experience will be better with the *positive-reinforcement style* of real-time verbal feedback from the coach compared to *autonomous-supportive style*.

H3 : Regarding *viewpoint*, the participant's balance performance will be improved with the *third-person* compared to the *first-person* viewpoint.

H4 : The participant's subjective experience will be better with the *third-person* compared to the *first-person* viewpoint.

Chapter 4

RESULTS

Here, we describe the results of statistical analysis for user performance, questionnaire results, and general feedback.

4.1 User Performance

The summary of descriptive results for objective measures from the user performance is shown in Table 4.1. We used *RStudio* with R for computing for statistical analysis with a repeated measures two-way analysis of variance (ANOVA) for dependent variables (see Table 4.2 and Figure 4.2).

We also performed pairwise-t tests to further explore the signficant differences and their interaction effects. For these calculations, we use independent measures. Each combination of participant, coaching style, viewpoint, and pose is considered it's own data point. Thus, we use 16 data points and 15 degrees of freedom for calculations of the interaction effect of coaching style and viewpoint within an individual pose. When looking at the combined performance data among all poses, we use 192 data points and 191 degrees of freedom to analyze differences within just the two coaching styles and just the two viewpoints, and 96 data points and 95 degrees of freedom to analyze the various interaction effects between coaching style and viewpoint.

4.1.1 Steadiness

There were statistically significant differences in the steadiness (as measured by more/less vertical hand height variation) between the coaching style in the steadiness variable ($F(1,\ 15) = 9.547,\ p = 0.007,\ \eta_p^2 = 0.094$). Participants exhibitied significantly greater steadiness in the positive-reinforcement coaching style compared to the autonomous-supportive coaching style. For viewpoint, significant effects were also found ($F(1, 15) = 16.607$, p <0.001, $\eta_p^2 = 0.238$), with participants exhibiting greater steadiness in the first-person viewpoint compared to the third-person viewpoint. Lastly, We found signficant differences in the interaction effect between coaching styles and viewpoint ($F(1, 15) = 26.830$, p <0.001, $\eta_p^2 = 0.1715$).

We further analyzed the effect of coaching style with a pairwise t-test to find their differences. We found the differences between the coaching styles: *autonomous-supportive style* and *positive-reinforcement style* ($t = 3.91$, $df = 191$, $p < 0.001$). Regarding viewpoint, further analysis with a pairwise t-test show the differences between the two viewpoints: *first-person* and *third-person* (t = -6.41, $df = 191$, $p < 0.001$), Regarding the interaction effect of coaching style and viewpoint, the results show differences between coaching styles within the *third-person* viewpoint ($t = 6.12$, $df = 95$, $p < 0.001$). There was also a significant difference between both viewpoints within the *autonomous-supportive style* (t = -8.24, $df = 95$, $p < 0.001$). The results could indicate that participants exhibited stronger performance in the *positive-reinforcement style* with audio feedback from the virtual coach than in the *autonomous-supportive style*. Furthermore, changing the user's viewpoint doesn't influence the performance within the *positive-reinforcement style*. However, both users' viewpoints between *first-person* and *third-person* had significant differences and could influence the performance in the *autonomous-supportive style*. We observe large standard deviations and numerous outliers in steadiness, likely due to both intra-subject and inter-subject variability. We also noticed a learning curve as participants improved their ability to perform the six balance poses throughout the four conditions. Since participants completed the four conditions in different orders, this learning curve occurred in different condition orders between participants. Additionally, we expect participants to have different general balance abilities based on age, physical fitness, and frequency of performing balance-improving exercises. Our limited number of participants also contributed to the large number of outliers we had in comparison to the small number of participants.

We observed significant differences between coaching styles in *pose 2* ($t = 5.31$,

Table 4.1: Summary of descriptive results of user performance. All entities are in the format: mean value (standard deviation) [standard error].

Variable	Steadiness (m)	Foot Height (m)	Number of Mistakes
Autonomous-Supportive Style	0.130 (0.107) [0.008]	0.307 (0.144) [0.010]	0.880 (1.069) [0.077]
First-Person Viewpoint	0.081 (0.070) [0.007]	0.298 (0.134) [0.014]	0.938 (1.103) [0.113]
Third-Person Viewpoint	0.178 (0.117) [0.012]	0.317 (0.154) [0.016]	0.823 (1.036) [0.106]
Positive-Reinforcement Style	0.099 (0.090) [0.007]	0.308 (0.135) [0.010]	0.833 (1.045) [0.075]
First-Person Viewpoint	0.094 (0.093) [0.009]	0.296 (0.141) [0.014]	0.823 (0.973) [0.099]
Third-Person Viewpoint	0.104 (0.088) [0.009]	0.320 (0.129) [0.013]	0.844 (1.118) [0.114]

df = 15, $p < 0.001$), *pose 4* (t = 6.04, df = 15, $p < 0.001$), and *pose 6* (t = 4.88, df = 15, $p < 0.001$) in the *third-person* viewpoint. It could reveal that the poses that required lifting the right foot, including *pose 2*, *pose 4*, and *pose 6*, were performed better with the *positive-reinforcement style*. The participants, however, performed similarly with both styles on other poses: *pose 1*, *pose 3*, and *pose 5*, while lifting their left foot. For viewpoint, significant differences were found between the viewpoints of *pose 1* (t = -3.43, df = 15, $p < 0.001$), *pose 2* (t = -7.58, df = 15, $p < 0.001$), *pose 4* (t = -4.84, df = 15, $p < 0.001$), and *pose 6* (t = -4.86, df = 15, $p < 0.001$) in the *autonomous-supportive style*. The results show that participants demonstrated greater stability in the *first-person* viewpoint compared to the *third-person* viewpoint. However, other poses were comparable and had slight differences. Moreover, the participants were more stable (had less vertical hand height variation) while using the right foot to stand and lifting the left foot.

4.1.2 Foot Height

There were no significant differences in the *foot height* variable between the coaching style, viewpoint, and their interaction effect.

4.1.3 Number of Mistakes

We found no significant differences between the main effect of coaching style and viewpoint, as well as their interaction effect. The results could indicate that the coaching styles and viewpoints are comparable in terms of making mistakes.

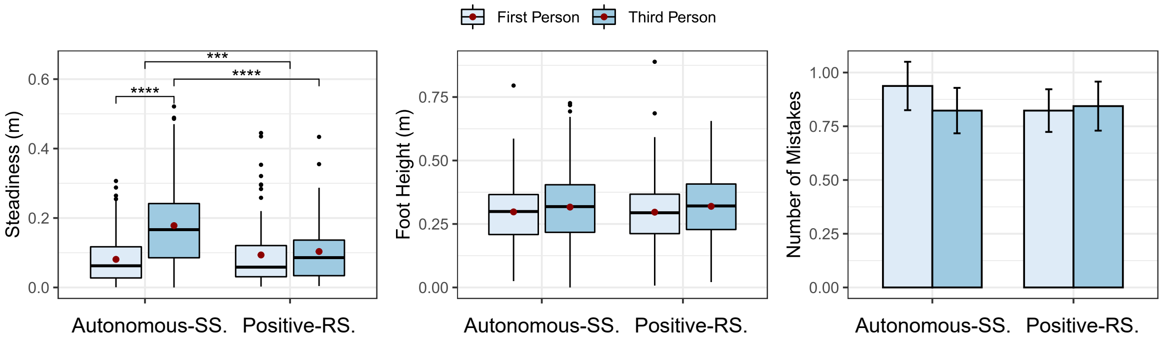

Figure 4.1: Results of user performance (n = 16), including (left) steadiness (*lower is better*), (middle) foot height (*higher is better*), and (right) number of mistakes *(Autonomous-SS: Autonomous-Supportive Style; Positive-RS: Positive-Reinforcement Style). (Red dots in the box plots are mean values)*

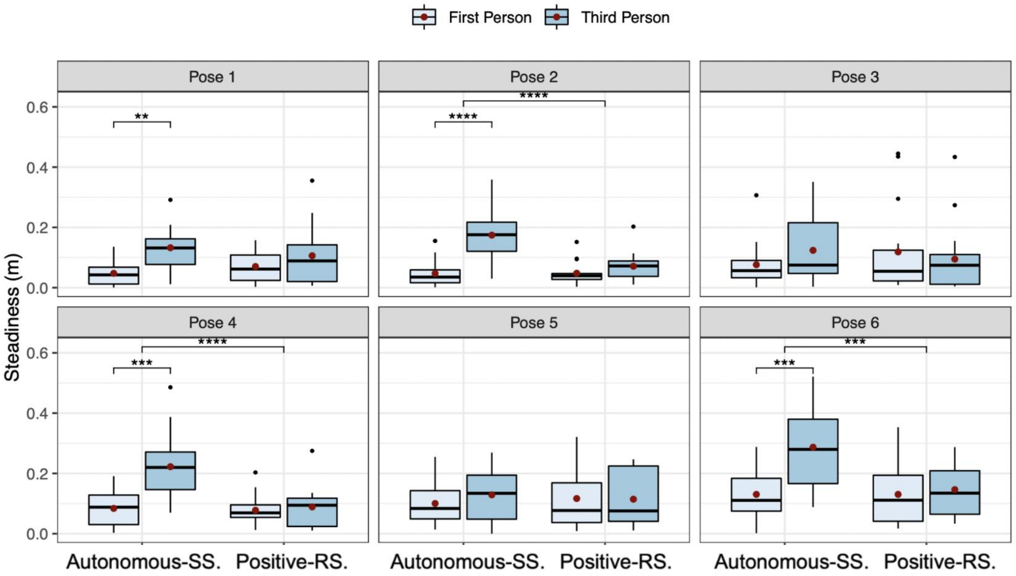

Figure 4.2: Results of steadiness for each specific pose *(Autonomous-SS: Autonomous-Supportive Style; Positive-RS: Positive-Reinforcement Style). (Red dots in the box plots are mean values)*

Table 4.2: Summary of statistical results using ANOVA ($p < .05$).

Variable	DFn	DFd	F	p	Sig.	η_p^2
Steadiness						
Coaching Style	1	15	9.547	0.007	*	0.094
Viewpoint	1	15	16.607	0.0009	*	0.238
Coaching Style * Viewpoint	1	15	26.830	0.0001	*	0.1715
Foot Height						
Coaching Style	1	15	0.030	0.864		
Viewpoint	1	15	3.375	0.086		
Coaching Style * Viewpoint	1	15	0.053	0.820		
Number of Mistakes						
Coaching Style	1	15	1.226	0.285		
Viewpoint	1	15	0.183	0.674		
Coaching Style * Viewpoint	1	15	0.403	0.534		

4.1.4 Mid-Questionnaire Results

We analyzed the mid-questionnaire data with the pairwise t-test between the coaching styles and viewpoints among the following six categories of the questionnaire (see Figure 4.3). Notably, the results of social presence and embodiment were based on a 7-point scale, the recommendation was based on a 10-point scale, and other categories were based on a 5-point scale.

Descriptive results show average score for *first-person* ($M = 4.21$, $SD = 0.87$) and *third-person* ($M = 4.24$, $SD = 0.75$) in the *autonomous-supportive style*, and *first-person* ($M = 4.24$, $SD = 0.84$) and *third-person* ($M = 4.45$, $SD = 0.79$) in the *positive-reinforcement style*. We observed no significant effect on social presence between the coaching styles and viewpoints.

The embodiment questions aimed to assess the effects of the self-avatar (trainee avatar), which is controlled with the user's body in the VR environment. The results show average scores of embodiment questions: *first-person* ($M = 4.05$, $SD = 1.22$) and *third-person* ($M = 4.35$, $SD = 0.90$) in the *autonomous-supportive style*, and *first-person* ($M = 4.04$, $SD = 1.22$) and *third-person* ($M = 4.36$, $SD = 1.14$) in the *positive-reinforcement style*. We observed a significant difference between the *viewpoints* ($t =$ -2.78, $df = 31$, $p = 0.009$). However, no significant differences were found between the

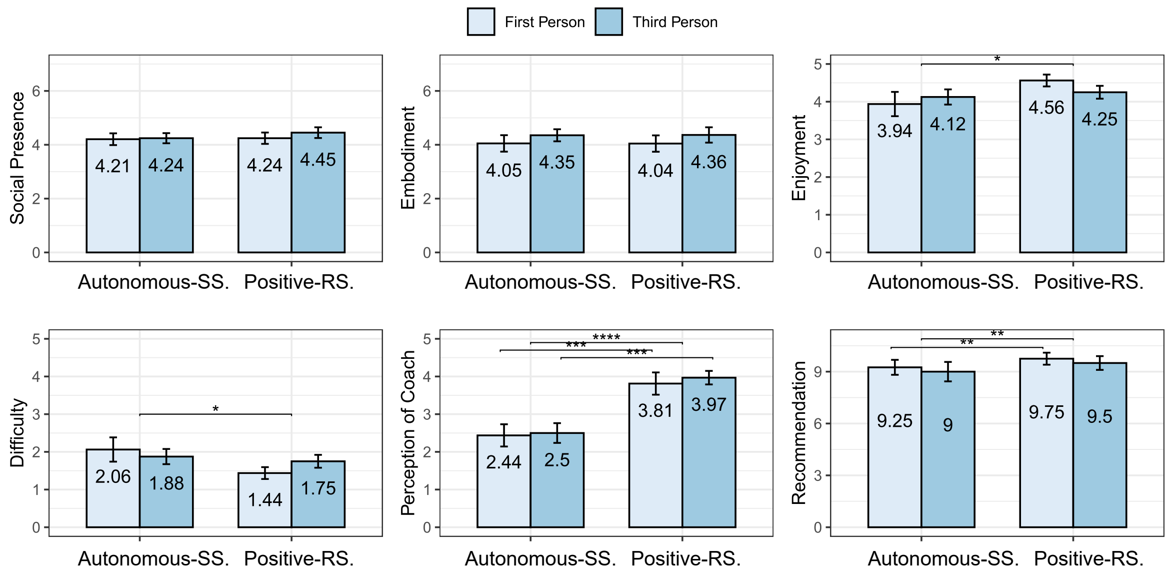

Figure 4.3: Results of mid-questionnaire used to assess the social presence, embodiment, enjoyment, difficulty, perception of coach, and willingness to recommend the proposed VR balance training environment *(Autonomous-SS: Autonomous-Supportive Style; Positive-RS: Positive-Reinforcement Style*).

coaching style and their interaction effect.

The average scores of enjoyment for the *first-person* (M = 3.94, SD = 1.29) and *third-person* (M = 4.12, SD = 0.81) in the *autonomous-supportive style* were on average lower than the *first-person* (M = 4.56, SD = 0.63) and *third-person* (M = 4.25, SD = 0.68) in the *positive-reinforcement style.* No significant effect was observed between the *viewpoints.* For *coaching style*, however, the *positive-reinforcement style* was rated better than the *autonomous-supportive style* (t = -2.17, df = 31, p = 0.037).

Participants were asked to rate the difficulty of the tasks within the coaching styles. We observed average scores of the *first-person* (M = 2.06, SD = 1.29) and *third-person* (M = 1.88, SD = 0.81) in the *autonomous-supportive style*, and the *first-person* (M = 1.44, SD = 0.63) and *third-person* (M = 1.75, SD = 0.68) in the *positive-reinforcement style.* We only found a significant difference between the *coaching styles* (t = 2.17, df = 31, p = 0.037).

The mean scores of perception of coach show the *first-person* (M = 3.81, SD = 1.18) and *third-person* (M = 3.97, SD = 0.72) in the *positive-reinforcement style* were higher than the *first-person* (M = 2.44, SD = 1.18) and *third-person* (M = 2.50, SD = 1.05) in the *autonomous-supportive style*. The statistic tests show the participants had a stronger perception of the coach in the *positive-reinforcement style* than the *autonomous-supportive style* (t = -6.87, df = 31, $p < 0.001$). Additionally, there were significant differences in the *first-person* (t = -4.42, df = 15, $p < 0.001$) and *third-person* (t = -5.19, df = 15, $p < 0.001$) between both coaching styles.

We observed average scores of recommendation of the *first-person* (M = 9.25, SD = 1.73) and *third-person* (M = 9.00, SD = 2.25) in the *autonomous-supportive style*, and *first-person* (M = 9.75, SD = 1.39) and *third-person* (M = 9.50, SD = 1.59) in the *positive-reinforcement style*. We found the *positive-reinforcement style* was rated higher than the *autonomous-supportive style* (t = -3.52, df = 31, $p = 0.001$), however, no significant difference was found between viewpoints. Between the coaching styles, there was a significant difference within the *first-person* viewpoint (t = -3.16, df = 15, $p = 0.006$).

4.1.5 Post-Questionnaire Results

The post-questionnaire was used to evaluate the overall experience concerning the usability and task load of the proposed environment. The post-questionnaire results were analyzed descriptively as the following.

Results of system usability using the SUS questionnaire show the average score (M = 79.31, SD = 15.81), which could classify as relatively easy to use. An average score higher than 68 is above average [5]. This could reveal the potential benefits of the proposed VR environment in terms of usability.

The subjective task load using VR balance training was assessed using an unweighted (raw) *NASA-TLX* questionnaire. Descriptive results show average scores for all six categories (see Figure 4.4). Results show that the performance (M = 68.17, SD = 22.60) was rated as the highest among other categories, followed by physical demand ($M = 63.50$ $SD = 30.08$), effort ($M = 62.56$, $SD = 23.22$), mental demand ($M = 36.78$, $SD = 30.78$), and temporal demand ($M = 32.72$, $SD = 29.84$), while frustration ($M = 31.72$, $SD = 21.98$) had the lowest score.

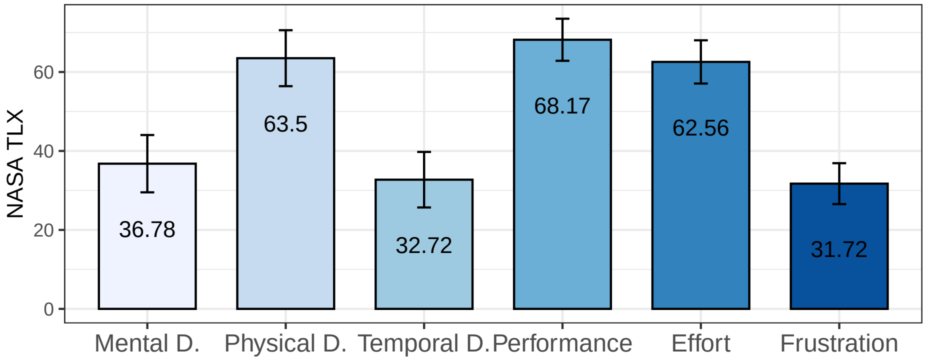

Figure 4.4: Results of task load using NASA-TLX questionnaire of the participants performed in the VR balance training environment. *(D: Demand)*

The majority of participants opted to provide optional feedback on their experience with the activity. Two participants commented that they typically wear glasses, but felt uncomfortable wearing the glasses inside the headset and opted to not wear them, reducing their clarity of vision for the activity. Four participants commented that they felt the avatar was not mirroring their movements accurately. One participant said that throughout the activity, they felt themselves adjusting their movements to try to make the avatar behave more like they wanted it to, which could be frustrating. This could be due to the participant wearing loose-fitting clothing, or the participant moving from their original location on the ground to an area that the Kinect couldn't record as accurately. Two participants said that they did not find themselves paying any attention to the trainee avatar in the first-person viewpoint conditions. Four participants shared that they preferred the third-person viewpoint, with one participant stating that "third-person is easier because it is like a mirror", and that it is harder to control balance without seeing yourself.

Numerous participants found the system was easy to use and had little confusion upon completion of the training sessions. There was much variation among comments on coaching style, with some participants stating they liked the coach's comments, some saying the comments made it harder, and some saying that the comments did not accurately reflect their performance. One more significant comment that some participants made was that they felt that their balance performance increased throughout the activity as they became more familiar with the system and the poses. Steadiness did not consistently increase throughout poses 1 to 6, which may be due to the fact that the poses get increasing difficult through the activity. It would certainly be worthwhile to conduct more in-depth analysis on change in performance across poses throughout the activity.

Chapter 5

DISCUSSION

In this section, we summarize the main findings and discuss the implications of the results described in the previous section.

5.1 Effect of Coaching Style

Our results on the objective measures partially support *H1*. The coaching style significantly impacted steadiness, but had no significant impact on foot height nor the number of mistakes. Our results showed that the participants were significantly more steady in the positive-reinforcement coaching style. It is notable that only steadiness was significantly impacted by the coaching style, as other balance performance measures were not significantly impacted. It is imperative to consider the context of our study, which primarily involved healthy young adults. The observed success in steadiness is noteworthy, especially considering that the participants were predominantly young adults, a demographic known for their inherent steadiness. Additionally, we measure steadiness only through hand height variation throughout a pose, which does not account for other types of body movement that may occur when stability is lost or when a pose is performed incorrectly.

Furthermore, our subjective results support *H2*. Numerous subjective measures show that the positive-reinforcement coaching style provides a more positive user experience than the autonomous-supportive coaching style. There were significantly higher feelings of enjoyment and a greater perception of the coach in the positive-reinforcement coaching style as opposed to autonomous-supportive. The positive-reinforcement condition was also reported to be less difficult than the autonomous-supportive coaching style. There were no significant differences between feelings of embodiment or social presence between the coaching styles. Additionally, participants reported a higher average likelihood to recommend the positive-reinforcement style compared to the autonomous-supportive style. Overall, the majority of subjective measures show that user experience is more positive in the positive-reinforcement coaching style. These results offer insight that a positive-reinforcement style of coaching that involves lots of audio feedback for the patient may improve users' steadiness and subjective experience in lower extremity VR therapy.

5.2 Effect of Viewpoint

Our results on the objective measures do not support *H3*. The viewpoint significantly impacted steadiness, but had no significant impact on foot height nor the number of mistakes. Our results showed that the participants exhibited greater steadiness in the first-person viewpoint, while we expected greater steadiness in the third-person. This difference between viewpoints was significant within the autonomous-supportive coaching style. Similarly to our findings on the effect of coaching style, we note that only steadiness was significantly impacted by the viewpoint, while other balance performance measures were not significantly impacted. We predicted that better performance would be exhibited in third person, so our hypothesis was not supported.

Results from subjective measures do not support *H4*. There was no significant difference in difficulty, enjoyment, or willingness to recommend rating between the first and third-person. We predicted that the experience would be more positive in the third-person viewpoint, so our hypothesis was not supported. The experience was neither more positive nor more negative in the first-person compared to the third-person. This suggests that users had a similar experience in both viewpoints. Or, user experience due to viewpoint may differ depending on the user and their personal preferences.

5.3 Limitations

It is crucial to acknowledge the study's limitations when interpreting its outcomes. Firstly, the accuracy of the study depends on the capabilities of the Kinect sensors to capture participants' movements. The sensors might not consistently track certain poses or movements with precision, leading to potential errors or imprecise data. The Kinect has some known limitations, such as tracking body movements less accurately when a person is wearing all dark or loose-fitting clothing. The Kinect also has been reported to track ankle position less accurately than other joint positions. We used raw measurements for the steadiness and foot height calculations. Feet are typically occluded, which can cause extra deviations in the measurements, but no smoothing algorithm was used to account for this. We explored the device specifications of the Azure Kinect, and some studies that further quantify the error of the Kinect, and acknowledge that these errors could have affected our results. The Azure Kinect hardware specifications [1] state that the device has standard deviation $\leq$17 mm, and distance error <11 mm up to 3.5 m distance from the sensor. Tölgyessy et al. [52] state that the Kinect must be warmed up for at least 40-50 minutes to provide the most stable results, where we let the Kinect warm up for only about 10-15 minutes before data collection. Additionally, they confirm the officially stated values for Kinect error; standard deviation $\leq$17 mm, and distance error <11 mm. Since our measurements were small regarding the steadiness measurement, this level of potential error could have significant impacts on the accuracy of our data. Users were never more than 3.5 m away from the Kinect, which keeps the error in this specified range. Bertram et al. [10] explores the accuracy of the Azure Kinect in comparison to previous Kinect sensors, and finds that the Azure Kinect provides an overall more accurate measurement of movement. Thus, the Azure Kinect [10], provided better results than if we had chosen a different Kinect body tracking camera.

In addition to the Kinect tracking limitations, we were also limited in our ability to fully capture body position and movement during a pose due to selecting a just the hands and feet to track. While we tracked hand position to determine steadiness, and average foot height, these metrics do not provide complete insight into whether the

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[1] https://learn.microsoft.com/en-us/azure/kinect-dk/hardware-specification

participant is performing a pose accurately or not. They may have their foot high and be moving their hands very little, but be performing a pose that is very different from the pose the coach is instructing them to perform. Regarding the foot height measurements, the participant's height was not accounted for. This means that taller participants will naturally lift their leg higher than shorter participants, and we used no calculations to standardized this data. Additionally, while the coach held each pose for 10 seconds, the amount of time the participants held each pose for was not measured. It was not measured if the participants began the poses exactly when the coach did, or if they held the pose throughout the same duration as the coach.

The study's sample size was constrained due to limited resources and time constraints. Consequently, the generalizability of the findings could be affected, as the results may not be representative of the broader population. Our sample also had one outlier due to age (age = 40), which may have also skewed results.

Participants who were required to remove their glasses may have encountered difficulties in accurately performing the poses and reported more negative opinions in the questionnaires, particularly if they relied heavily on their glasses for visual guidance, introducing data biases.

Regarding the analysis for the steadiness data, the analysis calculations for the pairwise t-tests were not performed correctly, which impacts our understanding of the results. While we used repeated measures for the ANOVA test, we used independent measures for the pairwise t-tests. Repeated measurements on the same participant are not independent and we were not adequately controlling for type-I error. We should have used repeated measures for the pairwise t-tests to accurately analyze the steadiness data.

The study participants may have experienced a learning curve as they progressed through different conditions and poses. Initially, they might have struggled to understand the requirements of certain poses or become familiar with the system's feedback. Over time, their performance could have improved due to increased familiarity with the system and enhanced comfort with the poses. Although efforts have been made to mitigate this by counterbalancing some conditions, learning effects are inevitable in within-subject study designs.

Additionally, the footedness of the participants was unknown, as we only inquired about handedness in the pre-survey. While handedness and footedness are often the same, this is not always the case.

5.4 Future Work

To further enhance the findings of this study, several avenues of future research can be explored. Firstly, it would be valuable to delve into investigating the source error of motion tracking introduced by the Kinect sensor. We will also explore potential triggers that cause inaccuracies in the Kinect tracking and identify manners of controlling the issues. This exploration could also involve examining alternative sensor technologies or establishing improved algorithms to enhance pose recognition and movement tracking capabilities [32].

Future research should also prioritize expanding coach feedback by incorporating real-time visual cues [29], auditory instructions [30], collaboration [23], and haptic feedback to enhance pose execution and coaching experience [8]. This may require the development of advanced algorithms and machine-learning techniques that deliver personalized guidance tailored to each participant's specific needs. There could be the addition of stronger pose detection capabilities than can go beyond just measuring steadiness and foot height, and determine if a participant is performing a pose to sufficient accuracy based on the position of their entire body.

The way we chose to measure steadiness also poses itself as a limitation. In the future, it could be useful to measure steadiness with the mean squared difference in hand height, as this may provide a more accurate representation of the performance metric and its significant differences. Additionally, it would be worthwhile to explore additional measures such as pose accuracy, and the duration the pose is held without a mistake. These measurements would require tracking of many more joints in order to capture the position of the entire body rather than just the hands and feet. There would need to be measurements regarding the position of each body part in relation to each other, and additional calculations to determine how similarly the user is performing the pose compared to the coach avatar. In order to make these calculations as accurate as possible, the differences in size between different participants must also be considered and accounted for in these calculations. For example, a tall person will naturally be able to lift their foot higher than a short person, so a future direction could be to determine formulas to standardize body position data compared to height. These formulas should also detect when a participant starts and stops a pose so that pose duration can be measured.

It is also worth exploring the adaptation of the Kinect system for clinical use, for example, integrating it into rehabilitation programs or clinical settings to enhance therapy outcomes and patient engagement [24, 31, 34]. We began modifications of this system for stroke rehabilitation, in which further detail is provided in Appendix A. The preliminary work on this stroke system included IRB approval for conducting a study with stroke patients, system modifications, consulting experts in biomechanics, and outreach with older adults. In the future, the lab will work to further improve this stroke rehabilitation apparatus further, and conduct a formal study with stroke patients.

Lastly, it is also worth comparing user experience and performance data from this VR system with real-world data from performing the same tasks. This could provide insights into how this VR system impacts experience and performance compared to a comparable training program without VR.

Chapter 6

CONCLUSION

Conventional clinical practices for balance training often struggle with low motivation and adherence due to the repetitive nature of the exercises. We have introduced a VR balance training environment that utilizes virtual trainee and coach avatars equipped with real-time body tracking for lower extremity rehabilitation. The proposed environment incorporates different coaching styles and viewpoints for the trainee avatar, offering a unique and immersive approach to balance training. The environment was evaluated in a user study ($n = 16$), primarily consisting of young, healthy adults, comparing two coaching styles and two viewpoints of the trainee avatar. Through the comparison of different settings for trainee avatars, we were able to gain a deeper understanding of how the VR environment impacts user experience and task performance outcomes. Moreover, the results provide insights into task load and usability. The proposed environment could offer an adaptive, interactive, and engaging setting for home-based therapy exercises. Future work aims to explore adapting this system into a safe, appropriate rehabilitation system for post-stroke patients. We have gained insight on how to further improve the system, ideas for other target populations with which to test the system, and plans to conduct a study with stroke patients in the future.

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Appendix A

EXPLORATION OF CLINICAL ADAPTATIONS

A.1 System Modification Goals

Upon the conclusion of our VR balance training system with healthy subjects, we received much useful feedback from both the study participants, and from manuscript reviewers. Our next step was to use this feedback to determine system modifications to make for the next iteration of our balance training system. We also chose our modifications in a way to point the project in the direction of clinical use, which we discussed in our future work section. Our main priorities for this new version of the system were to make the system appropriate and safe for post-stroke patients as opposed to healthy adults, and to track the movement of more body parts in order to better encapsulate the user's pose accuracy and balance performance.

A.2 System Modifications

Upon feedback received from study participants and paper critiques, we made system modification to both improve the overall quality and experience of the system, and adapt the system to be appropriate for stroke patients. Our modifications for general improvement of the system focused on collecting data from more joints in the body, rather than just the hands and feet. Hand steadiness does not encapsulate the movement of the entire body, and does not provide the strongest metric for overall balance. We added data collection for the head, the spine, and the pelvis in order to have more measurements from which balance may be calculated.

We made two primary adaptations to the system to make the exergame fit for stroke patients. Firstly, we switched the format to a 2D screen display, rather than a 3D immersive virtual reality headset. The healthy participants in our study stated

Figure A.1: The modified system targeted for stroke population. The 2D screen display replaces the original 3D immersive headset. Balance poses are also all much simpler.

that the 3D headset made it harder for them to balance. Since stroke patients already have severely impaired balance, we did not deem the 3D headset as safe for them to perform balance training exercises in.

We also simplified the balance training poses. In the healthy subjects study, the six balance training poses users were guided through were relatively challenging, with the participants visibly struggling on many of them, and making a large number of mistakes. Since stroke patients have severely impaired balance, it's important to ensure that the balance poses do not pose a high risk of falls. So, we simplified balance poses to all be on two feet instead of one. We took some of the poses from the SEBT (Star Excursion Balance Test) [22], a standard balance test developed for stroke rehabilitation.

A.3 Qualitative Feedback

Upon completing the intended system modifications, we interviewed a biomechanics expert with experience working with post-stroke patients about their opinions on the system, and what they would change to create a better, more effective balance rehabilitation experience for stroke patients. A main comment that they had about the system was that the transitions were too fast, and that not enough rest time was provided. While the balance poses were simple enough to be safe for stroke patients, stroke patients need their rehabilitation exercises to be at a slow pace, with adequate rest between exercises. Additionally, since strokes impact different parts of the body in different people, it would make sense to have a variety of options for exercises, because while the poses we selected may be of appropriate difficulty for one stroke patient, the same may not be true for a different patient. In the current system, the coach is holding his arms out to the side for each balance pose, and this could provide difficulty and frustration for stroke patients as they have difficulty with lifting their hand on the side of their body impacted by stroke. It would be best to have the virtual coach leave their arms at their side, or only have a very slight lift. Additionally, since there are no controllers utilized in this 2D screen version of the system, the way to trigger the start of the activity is to raise your hand above your head, rather than to use a controller to click a button as in the original VR system. Lifting an arm above the head is quite difficult for stroke patients, so an alternative way to trigger the start of the activity must be implemented. The best idea may be to have the experimental proctor have a way to trigger the start upon verbal conformation from the patient that they are ready to begin. Another comment was that the Kinect may not be the most effective way to measure balance in stroke patients. Typically, EMG sensors are used in balance studies with stroke patients. It would be useful to explore using EMG sensors along with the Kinect for additional balance data, and therefore more accurate balance performance metrics. Finally, she said that while it would be possible to make these changes to adapt the system for stroke patients, the system in its current state would be better suited for people with Parkinson's disease. Unlike in stroke, people with Parkinson's disease have use of all of their limbs, but experience tremors and unsteadiness. Additionally, the system could be useful for people with ADHD or autism. She emphasized that in the future, it is very important to continue meeting with and receiving feedback from rehabilitation specialists who are familiar with the needs of our target patients. It is important that before testing this system with a vulnerable population such as stroke victims or people with Parkinson's disease, that the experimental proctor understands the needs of whom they are working with, and how to ensure that they give the user a safe, comfortable experience.

In order to receive a different perspective on our system, we went and shared the system with older adults at a senior center to receive their feedback. An older adult with no major health issues impacting balance (aside from the natural decline of balance in old age) confirmed that the balance poses utilized in the system were of similar difficulty, and perhaps even a bit easier, than what she performs in her regular exercise classes. She said she also is capable of performing one-foot balance exercises with support, and that the inclusion of such supported exercises in the system could make it more engaging. Additionally, she commented that while the system was entertaining, she finds exercise to be the most engaging when in a group setting. Possibly, this system could be adapted for multiplayer use so that multiple people at a time may engage with the system. One way to approach this could be to utilize multiple Kinects and multiple trainee avatars, so that users may use the system while physically together, and have their avatars displayed on screen together, as well.

A.4 Limitations and Next Steps

Due to time constraints, we were unable to collect any quantitative performance data from patients with the modified system. The next step for this system is to implement the changes suggestive by our interviewees, and then to collect balance performance and user experience data on this new system. The following step will be to collect data from older adults who naturally have impaired balance due to aging. This study will be run similarly to the study on healthy subjects described in this paper, where participants perform each conditions, and fill out mid-questionnaires and a post-questionnaire on their experience. Additional communities that we plan to test with in the future include post-stroke patients, Parkinson's patients, people with ADHD, and people with autism. While our system was initially intended to be adapted for stroke patients, the feedback received from physical therapists support that the system may be better adapted for different communities with balance impairments in its current state, and that additional modifications are necessary in order for the system to be safe, appropriate and useful for post-stroke patients.