Locomotion in Virtual Reality for Individuals with Autism Spectrum Disorder

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ABSTRACT
Virtual reality (VR) has been used as an effective tool for training individuals with autism spectrum disorder (ASD). Recently there have been an increase in the number of applications developed for this purpose. One of the most important aspects of these applications is locomotion, which is an essential form of human computer interaction. Locomotion in VR has a direct effect on many aspects of user experience such as enjoyment, frustration, tiredness, motion sickness and presence. There have been many locomotion techniques proposed for VR. Most of them were designed and evaluated for neurotypical users. On the other hand, for individuals with ASD there isn't any study to our knowledge that focuses on locomotion techniques and their evaluation. In this study, eight locomotion techniques were implemented in an immersive virtual reality test environment. These eight VR locomotion techniques may be categorized as follows: three commonly used locomotion techniques (redirected walking, walk-in-place and joystick controller), two unexplored locomotion techniques (stepper machine and point & teleport) and three locomotion techniques that were selected and designed for individuals with ASD based on their common characteristics (flying, flapping and trackball controller). A user study was performed with 12 high functioning individuals with ASD. Results indicated that joystick and point & teleport techniques provided the most comfortable use for individuals with ASD, followed by walk in place and trackball. On the other hand, flying and hand flapping did not provide comfortable use for individuals with ASD.

Keywords
Locomotion; Virtual Reality; Human Computer Interaction; Autism

1. INTRODUCTION
Autism spectrum disorder (ASD) is a form of developmental disability which may cause behavioral, social and communication difficulties. Currently there are more than 3.5M individuals with ASD only in the United States [4]. According to the Centers for Disease Control and Prevention, the identified prevalence of ASD was 1 in 68 births in the United States in 2012, which shows an increase of almost 120% since 2000 [5]. Because of social and communication differences, individuals with ASD often have difficulties in getting employed and sustainability. 34.9% of young (aged 19-23) individuals with ASD neither have a job nor received a postsecondary education [39]. It was also reported by the same study that the employment rate for individuals with ASD is significantly lower than the employment rates for individuals with other forms of disabilities such as learning disabilities, mental retardation and speech/language impairment.

Virtual reality (VR) is a powerful tool for training and rehabilitation since it offers safety, real time feedback, structured training, repetition, customization of scenarios and reduced transportation costs to real work places. However, little research has been performed on applying VR to training and rehabilitation of individuals with ASD. With the new generation head mounted displays such as Oculus Rift [31] and HTC Vive [15], the affordability and the availability of the VR technology improved significantly. Many applications are being developed for neurotypical users as well as individuals with ASD. For these applications to provide maximum benefit to their audience, all components need to be well designed. Human computer interaction is an important aspect of VR applications that may have a direct impact on user experience. Locomotion is one of the most commonly used and important interaction components of virtual reality. Locomotion is defined as travel in a virtual environment which is controlled by self-propulsion [14]. Almost every VR application requires some sort of travel in the virtual environment. Locomotion technique may have an effect on user experience [44]. A wrong choice or design of locomotion technique may limit the benefits offered by the application. Hence, it is important to choose a locomotion technique that is well suited for the targeted audience and the context of the application.

Since the early days of virtual reality, many different locomotion techniques have been developed and studied. However, almost all of these studies were designed for and studied on neurotypical users. No locomotion study to our knowledge focused on individuals with ASD. This paper addresses this gap in the literature by evaluating eight different locomotion techniques with 12 high functioning individuals with ASD. Analysis of the results implied the choice of the following for the future VR applications targeting high functioning individuals with ASD: joystick for controller based interaction, point & teleport for gesture based interaction, point & teleport for gesture based interaction, walk in place for exercise aimed interaction in small tracked areas, and redirected walking for exercise aimed interaction in small tracked areas. Locomotion that is triggered with continuous hand gestures and automatic movement turned out to be practices that should be avoided in VR applications targeting individuals with ASD.

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2. RELATED WORK

Many different locomotion techniques have been designed and developed for neurotypical users. One of the studies compared flying technique with real walking and walk-in-place techniques [48]. The results showed that flying technique was inferior as compared to the other techniques in terms of realism and sense of presence. Furthermore, real walking received the best scores for naturalness as compared to the flying and walk-in-place techniques. Another study examined the virtual walking trajectories for different controllers; joystick, joypad and keyboard [6]. The results showed that the conformity of the continuous controllers (joystick and joypad) to the real walking trajectories were higher than the binary controllers (keyboard). Another study compared the joystick controller with real walking in a CAVE environment with HMD for perceptual-motor coordination tasks [13]. The locomotion speed was found to be different with the different locomotion techniques; joystick controller resulted in higher locomotion speed than walking. Another study compared real walking with joystick locomotion and real rotation with joystick [33]. The results were similar in terms of task performance for real walking and real rotation with joystick locomotion techniques.

Locomotion techniques were also compared based on different cognitive criteria for neurotypical users. As the results for learning tasks that were performed in complex maze environments were compared, virtual locomotion techniques received similar scores as the real walking [46]. Another study compared flying, real walking and joystick controller techniques [52]. Real walking turned out to be better than the two other techniques in terms of understanding the application.

While similar studies that evaluate different locomotion techniques do not exist for individuals with ASD, many VR training and rehabilitation applications have been built for this population. These VR applications that target individuals with ASD utilized either real walking or standard controllers such as gamepads, joysticks or keyboards. Real walking was used in different forms; some studies used electromagnetic tracking in a CAVE environment [10, 51], some studies used Microsoft Kinect for tracking and TV [1, 12] or projection [32] for display. In all of these previous studies, real walking was used in a tracked area of limited size. No algorithms were utilized to keep the users in the tracked area (such as in the redirected walking) and thus movement in the virtual world was limited by the size of the tracked physical area. Some applications targeting individuals with ASD used standard controllers instead. In some studies, a HMD was used with a gamepad [2] or joystick [45]. Other studies used TV displays with mouse [38], keyboard [19, 20], both mouse and keyboard [45] or joystick [28]. However, these studies mainly focused on the effectiveness of VR in training individuals with ASD and did not evaluate or consider the effects of the locomotion techniques on user experience. Fornasari et al. studied the differences between children with autism and neurotypically developed children in terms of navigation in a computer based virtual environment [11]. In the study, navigation was performed with mouse. The researchers found no differences between the two groups for the exploration with a goal; however, found that children with autism spent less time for the free exploration task.

3. LOCOMOTION TECHNIQUES

In this study, eight locomotion techniques were implemented and evaluated with high functioning individuals with ASD. These techniques involve three commonly used VR locomotion techniques, two locomotion techniques that hadn't been explored deeply in the literature, and three locomotion techniques that were selected and designed specifically for individuals with ASD considering their characteristics (Figure 1). Speed of the locomotion in all of the eight techniques were kept as similar to each other as possible for the sake of obtaining comparable results. For example, the locomotion speed of the flying method was equal to the locomotion speed of the joystick as the joystick was pushed to its physical limit. The size of the tracked area was 8ft by 8ft.

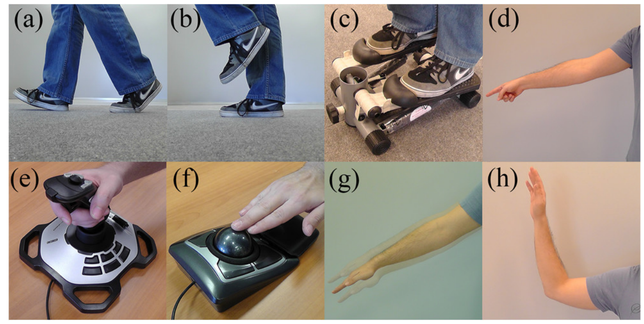

Figure 1. Representative photos of the locomotion techniques used in the study: (a) redirected walking, (b) walk-in-place, (c) stepper machine, (d) point & teleport, (e) joystick, (f) trackball, (g) hand flapping, and (h) flying.

3.1 Commonly Used Locomotion Techniques

Three commonly used locomotion techniques were implemented and evaluated in this study: redirected walking, walk-in-place and joystick control.

3.1.1 Redirected Walking

It is usually considered ideal to use real walking for locomotion in virtual environments, but real walking may not be suitable for virtual environments that are larger than the tracked area in the real world. In these cases, some modifications need to be made in order to overcome the physical limitation of the tracked area. One solutions may be using virtual environments that are not larger than the tracked physical area, but this approach puts a limitation on the design of virtual training applications. Another approach may be using algorithmic modifications that enable real walking by directing the user so that they do not step outside of the tracked physical area. Redirected walking [35] is one of the most widely used techniques for this purpose. It manipulates the visual cues of the users to keep them in the tracked physical area. These manipulations are performed by applying varying gains to the user's displacement data (position and orientation). These gains can be translational, rotational, and curvature. With the gains applied, the virtual translational or rotational speed could be lower or higher than the real translational or rotational speed. Furthermore, virtual environment may be slightly rotated to direct the users to walk in circles while they think that they walk straight. Redirected walking alone does not provide a total remedy for the physical limitation of the tracked area. If the user comes close to the edge of the tracked area, some form of warning or manipulation needs to be done in order to forward them towards the center of the tracked area. For this purpose, Williams at al. proposed three different methods called "freeze backup", "freeze-turn" and "2:1-turn" [49]. Freeze backup and freeze-turn methods stopped the application as the user approached to the edge of the tracked area and asked the user to move backwards or make a 180 degree turn. 2:1-turn method asked the user to make a full rotation and applied a doubled virtual rotational speed while the user rotated. Another repositioning method was proposed by Peck et al. [34]. They used virtual distracters to get the user's attention and direct them towards the center of the tracked area. The authors reported that this method helped in avoiding interruptions which may result in breaks in the presence and degrade the user experience.

In this study, redirected walking locomotion technique was implemented with dynamic translational, rotational, and curvature gains. These gains were applied continuously with dynamically changed values based on user's position and direction in the tracked area. A virtual wall was used for repositioning the users towards the center of the tracked area. Once the user reached to the edge of the tracked physical area, a virtual wall popped up from the ground. In that case, the user needed to walk around the virtual wall, during which the user was redirected and hence was kept inside the tracked area.

3.1.2 Walk-in-Place

As opposed to real walking, some VR locomotion techniques were designed to be controlled with body gestures. One of the most popular gesture based locomotion techniques - walk-in-place - uses the marching gesture to be performed in the same place without moving forward or backward [40]. Walk-in-place gesture is described as one of the closest gestures to real walking [44]. Walk-in-place is found to be cost effective [9], easy to learn [42], and providing proprioceptive feedback to the users [41]. In walk-in-place, locomotion direction can be defined by the direction of the head, the torso or the feet [29]. Walking speed can be controlled using step frequency, step height or leaning [3, 22]. In this study, walking speed is controlled with the frequency of the steps. The length of one step is assumed to be 1.64ft and the user needed to step in every 0.7 seconds for a continuous movement. The locomotion direction was controlled with the head direction of the user.

3.1.3 Joystick

Many VR applications use standard controllers such as joysticks, joypads or touchpads. These controllers are low cost, easy to implement and easy to use since many users are familiar with these controllers from their daily lives. In this study, a Logitech Extreme 3D Pro Joystick [25] was used to control locomotion. When the joystick was pushed forward, the locomotion was performed in the user's head direction. Turning could be done either pushing the joystick sideways or rotating the head.

3.2 Unexplored Locomotion Techniques

Two locomotion techniques that were implemented and evaluated in this study have not been deeply explored in the literature previously. These techniques are stepper machine and point & teleport.

3.2.1 Stepper Machine

Some locomotion techniques use special devices to control the locomotion and keep the users in a secure place. Omni-directional treadmills were designed and developed for this purpose [7, 16, 37]. These treadmills sense walking in any direction and keep the user at the center. Another approach was to create a low friction surface with ball bearings and place them on a concave surface [18, 47]. The design of this device made it possible to walk without a displacement in the real world. There were also some experimental devices such as human size hamster balls [27] or robotic tiles [17]. These devices provided locomotion in virtual environments but they were large and expensive, hence were not found to be convenient for an affordable training application.

In this study a cheaper alternative - stepper machine - was used as a VR locomotion device. Although it is affordable and it provides proprioceptive feedback, there is not much research done on the usability of stepper machine in VR locomotion. Matthies et al. used stepper machine with a microcontroller [26]. As it was compared with balance board and joystick, stepper machine received the highest scores for enjoyment and immersion. Nilsson et al. compared stepper machine, Wii Balance Board, keyboard and mouse in a virtual skiing game [30]. The results indicated that the stepper machine was found to be the most enjoyable and the second easiest to use. In our study, the movement of the stepper machine was tracked by an optical motion tracking system with the use of a reflective marker. The stepping movement on the machine was transferred to the virtual world as locomotion by means of a marker that was attached on the pedal. The locomotion direction was defined by the user's head direction. An additional automatic rotation feature was triggered if the head was rotated more than 45 degrees. This way, the virtual environment could be rotated around the user so that the user did not need to turn their heads back while their body faced forward.

3.2.2 Point & Teleport

Locomotion techniques mentioned so far required continuous input for locomotion. Some techniques may use instantaneous input instead. One example is point & teleport technique. With this technique, the users point to wherever they want to be in the virtual world, and the virtual viewpoint is instantaneously teleported to that position. The triggering can be done with a gesture or a controller. In this study, no additional controllers were used, teleportation was done with the pointing gesture. The teleportation was triggered when the user pointed to the same position on the ground for two seconds. When the user kept their arms lowered, the teleportation became inactive, so that they could stay at the same position as long as they wanted. A virtual ring on the ground and a virtual laser beam that was cast from the hand of the user towards the pointed location were used as visual cues. The users could point anywhere on the ground without a distance limitation. However, the users could not point the obstacles or the surrounding virtual walls.

3.3 ASD Specific Locomotion Techniques

The techniques mentioned so far have been designed for and evaluated with the neurotypical users in the literature. For individuals with autism, there is no study to our knowledge that has focused on the design or evaluation of VR locomotion techniques. Although we believe that some of these well-established locomotion techniques would cater for individuals with ASD as well as the neurotypical individuals, we wanted to design new locomotion techniques and alter the existing locomotion techniques considering the characteristics of individuals with ASD. In this study, the following three additional locomotion techniques were designed and implemented: flying, hand flapping and trackball control. To design these locomotion techniques for individuals with ASD, the research team collaborated with ASD experts - professional job coaches. Job coaches work with individuals with ASD on a daily basis to understand their needs and unique abilities, and match them to appropriate vocations. Job coaches gave significant input throughout the design process of these three locomotion techniques.

3.3.1 Flying

Individuals with ASD may not handle extensive cognitive load well, especially when paired with other tasks to perform. Hence, flying was selected as a locomotion technique to be suitable for individuals with autism. Flying is one of the simplest locomotion techniques. It gets an input from the user to move the viewpoint in the virtual environment [36]. The input can be either continuous to keep moving or instantaneous to start or stop the movement. For the input, a controller button or a body gesture can be used. In our study, in order to avoid the cognitive load of an additional controller, a hand raising gesture was selected for triggering the automatic locomotion in virtual environment. The same gesture was used to stop the locomotion as well. To reduce the physical load, raising the hand up to the shoulder level was defined as the trigger threshold. Hand raising gesture was selected because of its resemblance of indicating that an action is needed to be done such as raising hand to request an action. The walking speed was constant with 0.8m/s.

3.3.2 Hand Flapping

Individuals with autism commonly engage in self-stimulating (stimming) behaviors such as flapping arms and hands or rocking [8]. These movements are observed to provide soothing for them. Hence, the hand flapping technique was designed in which the hand flapping movement was used for the locomotion. The flapping motion was kept independent from the position of the hand. It could be performed wherever was more comfortable for the user such as near the hips, near the shoulder or in front of the torso. As long as the user flipped their hand, the viewpoint in the virtual environment was moved. This technique was thought to provide the users soothing and help in practicing controlling the unintentional stimming behaviors since the user needed to stop the stimming to stop moving in the virtual world.

3.3.3 Trackball

Individuals with autism are commonly characterized to be fascinated by or obsessed with spinning objects, such as wheels of toys or washing machines [8]. For that reason, a new locomotion alternative was designed in this study with a Kensington Expert Trackball [21] controller. This controller has a smooth surfaced large ball that can be span in any direction. The spinning of the ball controlled the locomotion in the virtual environment. Forward spinning resulted in forward movement and side spinning (left/right) controlled the rotation. The user needed to keep spinning to move the virtual world viewpoint. One rotation of the ball provided a movement of one step in the virtual world. The user could spin the ball fast or slow, resulting in more or less rotation, and more or less movement in the virtual world respectively.

4. EXPERIMENT

An immersive virtual reality experiment was designed and implemented to evaluate the eight different locomotion techniques with individuals with ASD.

4.1 Experiment Design

A within-subjects experiment was designed with the independent variable of locomotion technique having eight levels: redirected walking, walk-in-place, joystick control, stepper machine, point & teleport, flying, hand flapping and trackball control. All of these eight locomotion techniques were tried by all users with a randomly assigned order. Counterbalancing was applied to have a distribution close to equal for all combinations of ordering. For each technique, the locomotion direction was defined as the head direction and the head rotation could be used for rotating the virtual viewpoint. For the controller based techniques, the virtual rotation could be controlled via the controller and/or the head rotation. All applicable techniques (point & teleport, hand flapping and flying) were implemented to work with either left hand or right hand to cater for both right handed and left handed users.

4.2 Virtual Avatar

The user was represented with two hand and two feet models in the virtual environment. The users were able to see these virtual hands and feet in the virtual environment, which moved according to their real hand and foot movement. The reason for this was to give feedback on their position and orientation. For an accurate representation, marker sets were attached to the hands and the feet of the user. The physical space that user's body occupied in the virtual environment was defined as a vertical capsule with a 0.5m diameter that was placed at the weighted center of the user's two feet and the head.

4.3 Virtual Environment

To evaluate the eight locomotion techniques, a simple yet realistic looking outdoor virtual environment with 16m by 16m dimensions was designed. The virtual environment was restricted on all sides with virtual walls of 2.2m height. The users initially appeared in the center of the virtual environment. They were free to move inside the virtual environment but they could not go beyond the virtual walls. The virtual environment was designed plain to avoid exerting additional cognitive load to the users, overwhelming or distracting them (Figure 2). A simple, relaxing outdoor sound was played in low volume to increase the immersion. A basic ambient light was used along with low intensity directional lights to create a good visibility from all sides of the virtual environment.

4.4 Objective

The users were asked to go to ten destination points with each locomotion technique. Once arrived to a destination point, the users needed to wait inside until the marking objects around them disappeared. The disappearance of the marking objects was done after three continuous seconds starting when the user stepped inside the destination point area. The clearance of the destination points was not designed to be instantaneous since user's control on stopping the locomotion technique was also desired to be observed and evaluated. The objective of the experiment was kept as simple as possible to be able to evaluate the user experience on locomotion techniques without the additional effects that may come from different factors.

After the sixth destination point, 21 obstacles in the form of cylindrical roman pillars appeared in the virtual world. Each obstacle was of 0.4m diameter and 2.4m height and was 1.77m away from the neighboring obstacle, which gave enough space to the user to move around them. The reason behind these obstacles was to observe and evaluate the user's control on making turns with the locomotion techniques. The users were supposed to go to the destination points without colliding with the obstacles. Without the obstacles, the users could reach to the destination points with movements close to straight lines. The placement of the obstacles and the destination points were designed so that the users required to make turns to avoid collision with the obstacles. The positions of the pillars were identical across all trials.

4.5 Destination Points

The destination points were marked with a circle on the ground having 1.2m diameter, a semi-transparent cylinder with 2m height and 1.2m diameter, and a 3D arrow above the cylinder oscillating in the y-axis to point to the destination point (Figure 2). All these objects were designed to be easily seen and identified even from the longest distance in the virtual environment. The marker objects were designed in orange to be easily visible. Once the user gets inside the destination point area, the objects immediately turned to green to give feedback to the user. If the user stayed inside the destination point area, the color of the objects gradually turned to blue. If the user left the area, the color turned back to orange. For each technique, a different set of destination points were used to eliminate any possible learning effect that might be caused by memorization. The set of destinations points of each technique were the same for all participants; however, the placement of the destination points was kept similar in terms of distance and rotation. The first destination point appeared 2 meters away from the user. After the first one, each new destination point appeared 4 meters away from the previous one. Furthermore, each destination point required 180° ± 30° turns to be reached after the previous one.

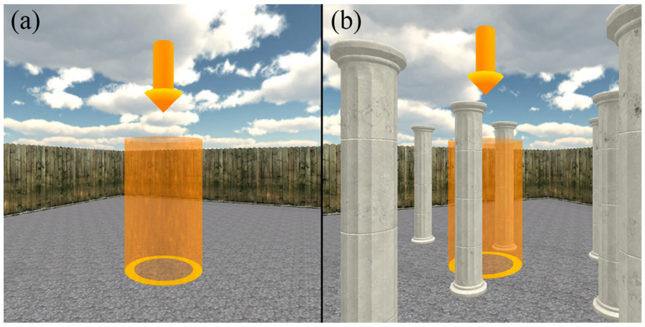

Figure 2. Virtual environment and destination points (a) without, (b) with obstacles.

4.6 System

The PC used for the user study had an AMD FX-8150 3.61Ghz Eight-Core CPU, an AMD FirePro W600 GPU, and a 16GB memory. The motion tracking was performed with twelve OptiTrack V100R2 cameras. The tracking space was 8ft by 8ft. A high resolution VR2200 head mounted display was used for viewing the virtual world. MotionTrack software was used to track five marker sets: one for head tracking (placed on the HMD), the other four mostly used for the hands and the feet. For the stepper machine, one of the hand marker sets was used to track the movement of the stepper machine. For the point & teleport, non-dominant hand marker set was attached to the shoulder of the dominant hand to accurately track the user's pointing direction. All implementation was done using Unity game engine and C# codes.

4.7 Participants

12 individuals who were diagnosed with high functioning autism participated in the study (9 male, 3 female). All participants were older than 18 years old with ages ranging from 18 to 41 with a mean age of 23.9 (SD = 5.99). 8 participants' dominant side was right and 4 participants' dominant side was left. Most of the participants (11 out of 12) had no prior VR experience while only 1 participant had minimal prior VR experience.

4.8 Procedure

The participants arrived at the research laboratory. They read and signed the IRB approved consent form and filled out a demographics questionnaire. Then, research staff explained the VR system and their objective in the experiment to the participants. The destination points, color changing dynamics of the destination point visibility elements and the obstacles that appear after the sixth destination point were explained to the participants. They were requested to try not hitting the obstacles. Then, research staff helped the participants to wear the HMD, and hand and feet marker bands for motion tracking. The experiment then started. Participants tried one of the randomly assigned eight locomotion techniques. When they completed all 10 destination points with the assigned locomotion technique, a user experience survey was given to the participants for evaluation of the tried technique. After all of the locomotion techniques were tried, an overall survey was given to the participants that requested them to rank the locomotion techniques according to their preference. The experiment lasted around one hour per participant, with 3 minutes of VR exposure followed by 5 minute breaks to fill out the surveys for each locomotion technique. Experiment sessions were video and audio recorded and are kept confidential.

4.9 Hypotheses

Following null hypotheses were constructed: $\mathbf{H_{1,0}}$**:** All locomotion techniques will result in similar performance in terms of average time to reach to the destination points. $\mathbf{H_{2,0}}$**:** All locomotion techniques will result in similar ranking scores.

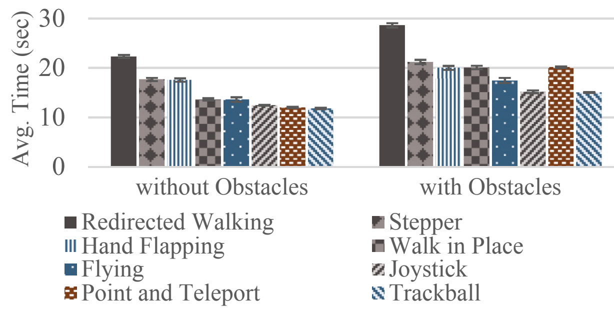

Figure 3. Average time to reach to the destination points without and with obstacles for eight locomotion techniques.

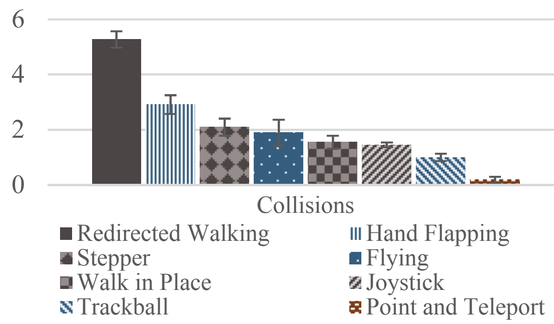

Figure 4. Total number of collisions.

4.10 Measurements and Surveys

During the user study, timestamps for clearing each destination point and collision with obstacles, and virtual locomotion paths of each user was stored for each locomotion technique. After the completion of each technique trial, the users were asked to fill out a survey about their experience with that locomotion technique. The questions included the following aspects: ease of understanding, ease of operating, required effort, tiredness, being in control, enjoyment, being overwhelmed and frustrated; questions about motion sickness and presence. The survey was constructed as modified a version of Loewenthal's core elements of the gaming experience questionnaire [24], Pensacola Diagnostic Criteria survey on motion sickness [23] and Witmer and Singer's questionnaire on presence [50].

After completing the testing of all eight locomotion techniques, the users were asked to rank the eight techniques according to their preference by placing the representative photos of the locomotion techniques on a paper with blank spots. This ranking technique was utilized to decrease the cognitive effort required to rank eight locomotion techniques, with the recommendation of the professional job coaches of individuals with ASD.

5. RESULTS

5.1 Data Results

We analyzed the data of the time it took for the users to reach to the destination points in two groups according to the presence of

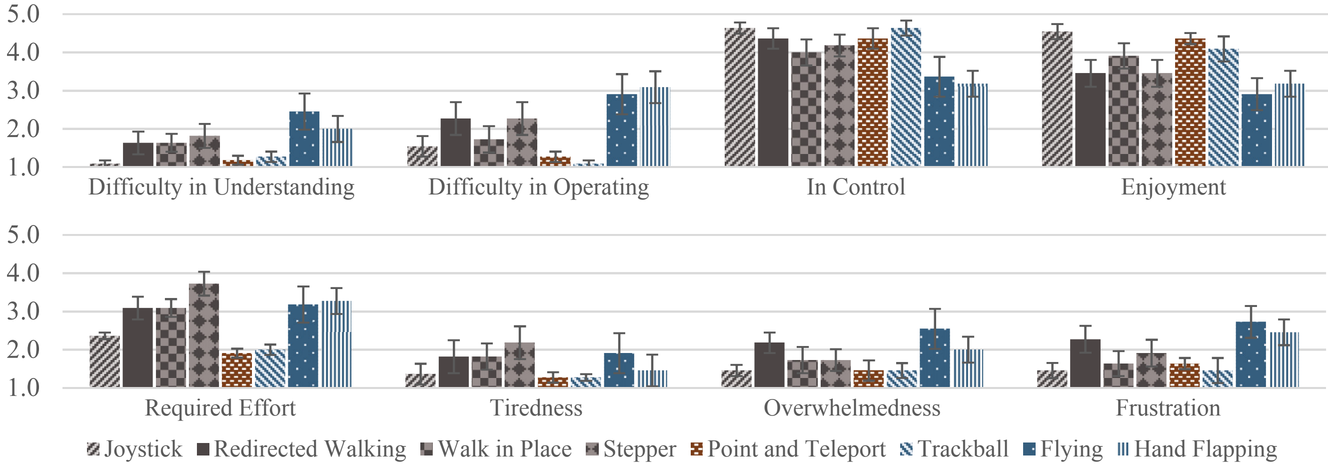

Figure 5: Survey results for the eight locomotion techniques.

obstacles in the virtual world. The results are presented in Figure 3 (error bars in all of the charts represent standard error of the mean). As one way ANOVA with repeated measures was performed, significant difference was found in the time to reach to the destination points for both of these cases: $F(7, 4) = 6.54$, $p = 0.005$ for without obstacles case, and $F(7, 4) = 8.72$, $p = 0.0004$ for with obstacles case. Mauchly's sphericity test failed and Greenhouse-Geisser correction was done for both cases. As paired t-tests were performed, for without obstacles case, the largest significant mean difference was between redirected walking and point & teleport (μ difference = 11.29, $p = 0.016$), and the smallest significant mean difference was between walk-in-place and trackball (μ difference = 10.265*, $p = 0.008$). For with obstacles case, the largest significant mean difference was between redirected walking and joystick (μ difference = 13.303*, $p = 0.0009$), and the smallest significant mean difference was between walk in place and flying (μ difference = 2.922*, $p = 0.039$).

Number of collisions with the static obstacles in the virtual environment were also analyzed (Figure 4). Additional dynamic obstacles of the redirected walking technique in the form of pop-up walls aiming to keep the users inside the tracked area were not included in this analysis. One way ANOVA with repeated measures yielded statistically significant difference between the techniques: $F(7, 4) = 7.94$, $p = 0.001$, Mauchly's sphericity test failed and Greenhouse-Geisser correction was done. The largest significant mean difference in the paired t-tests was between redirected walking and point & teleport (μ difference = 4.778*, $p = 0.0019$), and the smallest significant mean difference was between walk in place and trackball (μ difference = 0.778*, $p = 0.043$).

5.2 Survey Results

Usability part of the survey included questions on eight categories: difficulty in understanding the locomotion method, difficulty in operating the method, feeling of being in control while using the method, required effort to use the method, feeling of tiredness the method caused, feeling of enjoyment the method caused, feeling of being overwhelmed the method caused and feeling of frustration the method caused. The questions had answers on a 5 point Likert scale (1: not at all, 5: very much). Results of these categories are presented in Figure 5. One-way ANOVA with repeated measures analysis was performed for each category yielding the results that are presented in Table 1. All categories other than tiredness and overwhelmedness resulted in statistically significant difference. Results of the paired t-tests that yielded the largest and the smallest significant mean differences are presented in Table 2.

There were also questions on motion sickness and presence. These questions had answers on a 4 point Likert scale (0: none, 3: major). Results for these two categories are presented in Figure 6. One way ANOVA with repeated measures revealed that there wasn't any significant difference between the techniques for motion sickness ($F(7, 4) = 0.95$, $p = 0.43$) and presence ($F(7, 4) = 1.4$, $p = 0.259$). Mauchly's sphericity test failed and Greenhouse-Geisser correction was done for both motion sickness and presence data.

After the testing, participants were requested to rank the locomotion techniques according to their preference. Results for preference ranking are presented in Figure 7. One way ANOVA with repeated measures resulted in significant difference for the preference results ($F(7, 4) = 3.82$, $p = 0.001$, sphericity assumed). Then, paired t-tests were performed to find out differences between the technique pair combinations. The largest significant mean difference was found to be between joystick and flying (μ difference = 3.333*, $p = 0.00007$), and the smallest significant mean difference was found to be between joystick and trackball (μ difference = 1.333*, $p = 0.025$).

Table 1. One-way ANOVA results for usability survey data.

	Correction	df	df Err.	F	Sig.
Difficulty in Understanding	Greenhouse-Geisser	3.301	33.013	3.007	0.040
Difficulty in Operating	Sphericity Assumed	7.000	70.000	5.784	0.000
In Control	Greenhouse-Geisser	3.126	31.262	4.499	0.009
Enjoyment	Sphericity Assumed	7.000	70.000	4.354	0.000
Required Effort	Sphericity Assumed	7.000	70.000	5.068	0.000
Tiredness	Greenhouse-Geisser	2.691	26.908	2.208	0.116
Overwhelmed-ness	Greenhouse-Geisser	2.518	25.178	2.548	0.087
Frustration	Greenhouse-Geisser	3.269	32.687	3.043	0.039

5.3 Participant Comments

Participants were encouraged to share their comments, suggestions, likes and dislikes about any aspect of the experiment on the surveys. Some of these comments are shared in this subsection. Joystick received many positive comments from the participants: User 22: "Joystick is what my favorite tech is and it's perfect for walking in virtual world." User 25: "Awesome!" Many participants made positive comments for point & teleport as well: User 7: "I do enjoy the technology used." User 22: "Teleport is really the way to walk.” User 25: “I wanna buy this game.” User 26: “It’s teleporting! It was really cool!” Trackball received mostly positive comments: User 7: “I liked that it was super easy. I want to play this one again.” User 8: “It was very fun. Rolling it was like moving around on an office chair.” User 22: “Very interesting indeed.” User 26: “I liked that when you’re trying to walk and turn all you had to do is use your hand.” One user on the other hand, made a negative statement about trackball: User 24: “It was a bit difficult to move the ball to keep walking all the time.” Redirected walking received mixed comments from the users: User 8: “I liked it a lot. It was fast changing and challenging in a positive way.” User 22: “I liked walking in virtual world, it was so interesting.” User 23: “It was good to really walk.” User 26: “I liked it since it felt like I was really in the game. User 22: “I walk fast in real world yet I can’t control my speed in virtual world.” User 25: “It was close to the edge and a bit confusing.” Stepper machine also received mixed comments from the participants: User 16: “I liked it the most because it made me to exert the most effort.” User 25: “I wanna do it again!” User 22: “It wasn’t so easy to do stepping machine in virtual world.” User 26: “I liked that one but it felt a bit tiring at the back of my legs.” Walk in place also got mixed comments from the users: User 24: “It was realistic.” User 25: It helped to keep me in the center and I liked it.” User 28: “Really interesting concept.” User 26: “I didn’t like this method because it was like real walking but not so.” Hand flapping received mostly negative comments: User 22: “Hand flapping for walking is harder than I thought.” User 23: “It was a bit hard to use flapping.” User 24: It was a little hard to control.” User 26: “It was not so realistic to use hand flapping for walking.” User 25: It was comfortable.” Flying also received mostly negative comments from the participants: User 14: “It was completely frustrating.” User 22: “It’s hard to control it.” User 25: “I didn’t like this one.”

6. DISCUSSION

6.1 Summary of the Results

Time to Reach to the Destination Points: It took less time to reach to the destination points with joystick and trackball independent of the presence of obstacles in the virtual world, in alignment with [11]. Point & teleport provided short times without the presence of obstacles whereas providing long times with the presence of obstacles, hence the null hypothesis $H_{1,0}$ was rejected. We interpret the reason behind this as multiple teleportations needed to move around the obstacles requiring waiting times for the activation of the teleportation. Redirected walking yielded the longest times to reach to the destination points for both with obstacles and without obstacles cases. We interpret the reason behind this as the additional time it took for the participants to overcome the dynamic obstacles that appeared when the users got close to the edges of the tracked area.

Collisions: Point & teleport, trackball and joystick resulted in the least amount of collisions with static obstacles whereas redirected walking resulting in the most. We interpret this as the point & teleport, trackball and joystick providing more control to the users whereas redirected walking providing the least. Gains that were applied in redirected walking may have caused exaggerated movements resulting in unintentional hits to obstacles.

Survey Metrics: Flying resulted in the most difficulty in understanding whereas joystick, point & teleport and trackball provided the least difficulty, in alignment with [46]. Hand flapping and flying were the most difficult to operate whereas trackball, point & teleport and joystick were the least difficult to operate. Joystick and trackball shared the feeling of most being in control whereas flying and hand flapping provided the least feeling of being in control. Joystick, point & teleport and trackball provided high level of enjoyment whereas flying and hand flapping provided significantly lower levels of enjoyment. Stepper machine resulted in the most required effort whereas point & teleport and trackball resulted in the least. Tiredness and overwhelmedness wasn’t significantly different for all of the techniques. Flying, hand flapping and redirected walking caused the most frustration whereas joystick and trackball and causing the least. Low results for flying was in alignment with [42]. There wasn’t any significant difference between the locomotion techniques in terms of motion sickness and presence, in alignment with [40, 42].

User Preference: Participants preferred joystick and point & teleport the most, that was followed by walk in place and trackball. Flying and hand flapping were preferred the least. The null hypothesis $H_{2,0}$ was also rejected.

Table 2. The largest and the smallest significant mean differences from paired t-test results of usability survey data.

		µ Diff.	Std. Err.	Sig.
Difficulty in Understanding				
Flying	Joystick	1.364*	0.509	0.023
Hand Flapping	Point & Teleport	0.818*	0.296	0.020
Difficulty in Operating				
Flying	Point & Teleport	1.636*	0.527	0.011
Redirected Walk.	Trackball	1.182*	0.483	0.034
Stepper	Trackball	1.182*	0.464	0.029
In Control				
Joystick	Hand Flapping	1.455*	0.366	0.003
Trackball	Hand Flapping	1.455*	0.366	0.003
Walk in Place	Hand Flapping	0.818*	0.182	0.001
Enjoyment				
Joystick	Flying	1.636*	0.453	0.005
Point & Teleport	Redirected Walk.	0.909*	0.315	0.016
Point & Teleport	Stepper	0.909*	0.285	0.010
Required Effort				
Stepper	Point & Teleport	1.818*	0.377	0.001
Walk in Place	Joystick	0.727*	0.304	0.038
Frustration				
Flying	Joystick	1.273*	0.407	0.011
Flying	Trackball	1.273*	0.449	0.018
Flying	Stepper	0.818*	0.325	0.031
Hand Flapping	Point & Teleport	0.818*	0.325	0.031

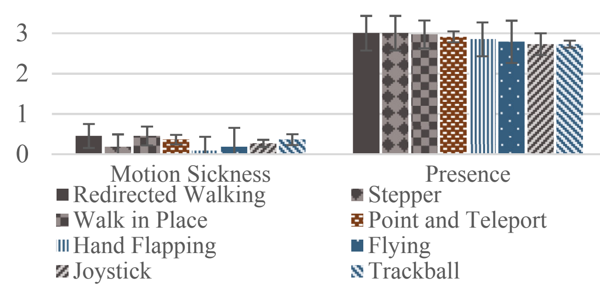

Figure 6. Motion sickness and presence scores.

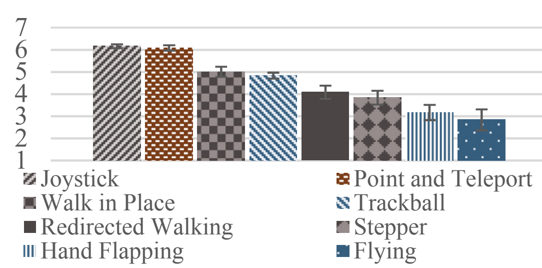

Figure 7. Weighted averages of the preference ranking data.

6.2 Implications of the Results

Analysis of the results, observations throughout the user study sessions and comments from the participants shaped our interpretation on the implication of the results. For virtual reality applications targeting high functioning individuals with ASD, we recommend using joystick, point & teleport, redirected walking or walk in place under different circumstances.

Joystick: Users liked the feeling of being in control, the simplicity of use and the translation of movement into the virtual world (pushing forward to go forward). Its reminding of video games and familiarity may be another positive factor for joystick, considering that individuals with ASD feel more comfortable using familiar objects. Although most of our participants didn't have any prior VR experience, more than half of them mentioned that they frequently played video games in real life. We recommend that in VR applications where accuracy of the control is important, joystick can be used for locomotion.

Point & Teleport: This technique created excitement in our participants. Many users made positive statements such as *'Wow'*, *'So cool'* when only heard its name or when we explained them how the technique worked. We interpret that affinity of individuals with ASD to technology may have contributed to this. Since teleportation is a term reminding of technology, users may have felt sympathy for this technique. Beyond this, we observed that they were comfortable in using this technique and embraced it very quickly as well. Pointing to where they wanted to be in the virtual world provided a simple form of representation. However, point & teleport may not be applicable in virtual environments that contain many elements that the user needs to move around. In VR applications with vast environments that require long travel distances, we recommend using point & teleport for high functioning individuals with ASD.

Redirected Walking: It may result in long times to reach to the destination points when implemented on smaller tracked areas. The reason behind this is that in smaller tracked areas, there will be more frequent appearances of the dynamic obstacles that are used for directing users towards the center of the tracked area. These additional obstacles will yield longer travel times since the users need to overcome them by walking around. Hence, in applications in which time to complete the tasks is important, we do not recommend using redirected walking in smaller tracked areas. However, if there is a large tracked area around 40m by 40m as recommended by the literature [43], redirected walking can be used in applications that encourage exercise for high functioning individuals with ASD.

Walk in Place: It turned out to be a good alternative to redirected walking. Since it urged the users to stay in the same place, the size of the tracked area did not impose a limitation. The users were quick to grasp the concept. Hence, we recommend using walk in place in applications that encourage exercising for high functioning individuals with ASD however size of the tracked area is small. Stepper machine gave the users a similar experience with walk in place however did not provide additional comfort or ease of use. Hence, we recommend selecting walk in place over stepper machine for high functioning individuals with ASD.

Other Techniques: In our study, locomotion that required continuous input from the hands or feet did not provide convenient use for the participants. For flying, which required the users to release their hands after triggering the movement by raising it up, it was difficult for users with ASD to put their hands down in the idle pose. They tended to keep their hands close to their chests while waiting, which resulted in unintentional movements and problems in deactivation. Hence, we suggest that incorporating relaxed hand pose into gesture controlling for individuals with ASD may not work well. Another hand gesture controlled locomotion, hand flapping also didn't provide comfortable use. We observed that some users had difficulty in keeping their hands still while waiting for the destination points to disappear, which caused unintentional movements. Some users did the hand flapping motion with their hands around their chest level but tried to touch their bodies with their hands after stopping doing the flapping motion. This made the virtual viewpoint move more since moving the hand back to touch the body for the idle pose elongated the flapping motion, causing overshoots. We recommend that gesture design for locomotion should give individuals with ASD concrete poses (such as putting their hands on the body or making a specific gesture). More abstract concepts such as releasing the hands and stopping making the flapping motion did not work in our study.

To sum up, for high functioning individuals with ASD, in VR applications with motion tracking, we do not recommend using locomotion that is triggered or maintained with continuous movement of the hands. Instead, controller based locomotion (such as joystick) or locomotion with instantaneous hand gesture control (such as point & teleport) would be more suitable for high functioning individuals with ASD. In applications with the aim of physical activity, redirected walking can be used in large tracked areas and walk in place can be used in smaller tracked areas.

6.3 Limitations

It should be noted that this study focused on the high functioning individuals with ASD. Since Autism is a spectrum based disorder, individuals on the different sides of the spectrum may have different needs and characteristics. Hence, the results of this study may not be applicable to the medium and low functioning populations with ASD. Number of participants in this study was 12 high functioning individuals with ASD. Although this number is not as high as it was desired by the authors to be able to see statistical differences with high power, it should be noted that finding participants belonging to special populations is more difficult than finding typical participants. The number of participants in this study was aligned with the previous studies that focused on this area [1, 2, 10] however, we still think that the low number of participants is a limitation of this study. Redirected walking was implemented on an 8ft x 8ft tracked area in this study, which is considered smaller as compared to the large tracked areas recommended in the previous studies on redirected walking [30]. The main concern of the previous studies while recommending large tracked areas was the motion sickness that would be induced by the large gains that are needed to be applied in smaller areas. In our study, although there wasn't any significant difference between the locomotion techniques in terms of motion sickness, redirected walking received a relatively higher score. Hence, the small tracked area is considered as a limitation of the study. A final limitation is some differences imposed by the different locomotion techniques such as possible differences in the time to complete the trials due to the adjustable locomotion speed with some techniques (redirected walking, walk in place, stepper machine, point & teleport, trackball and hand flapping) and the constant maximum locomotion speed with some techniques (joystick and flying).

7. CONCLUSION and FUTURE WORK

In this study, eight VR locomotion techniques were implemented and evaluated with high functioning individuals with ASD. These techniques were: redirected walking, walk-in-place, joystick, stepper machine, point & teleport, flying, hand flapping, and trackball controller. The locomotion techniques were implemented in an immersive VR environment and a user study was performed with 12 high functioning individuals with ASD. Results indicated that for high functioning individuals with ASD; joystick, point & teleport, redirected walking and walk in place are suitable VR locomotion alternatives whereas continuous hand gesture based (such as hand flapping) and automatic movement based locomotion techniques (such as flying) are not convenient for them. Future work will consist of evaluating different versions of the locomotion techniques that resulted in high preference scores in this study, such as point & teleport with controller, point & teleport with non-linear paths, wireless hand held joystick and redirected walking in large tracked areas. The aim of these evaluations will be providing more comfortable VR experiences for individuals with ASD. Evaluating these VR locomotion techniques with low and medium functioning individuals with ASD would also be important. Moreover, a comparison study between high-functioning individuals with ASD and neurotypical individuals is planned as future work, with the goal of clarifying the similarities and differences between the abilities of the two groups for VR system designers.

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