VRGaitAnalytics: Visualizing Dual Task Cost for VR Gait Assessment

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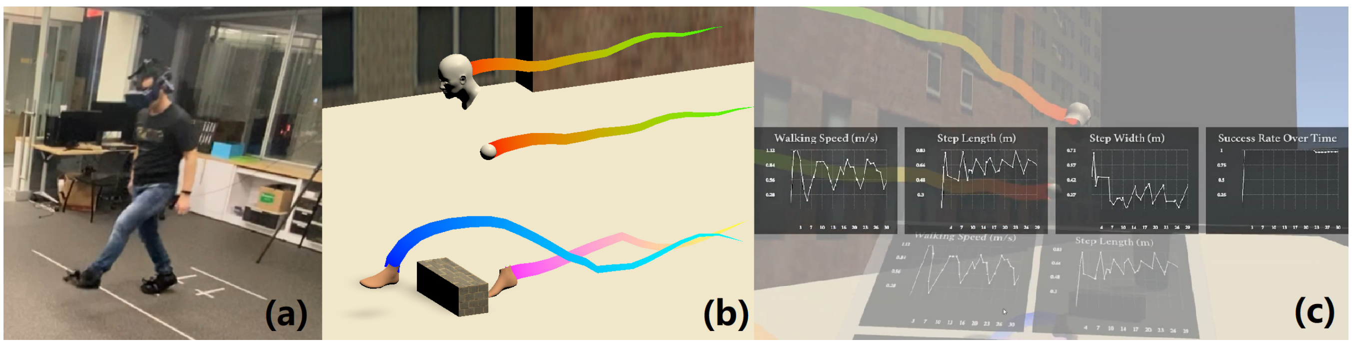

Figure 1: (a) Participant in obstacle crossing; (b) VR playback and motion trajectory; (c) The analytics mode showing data plots of outcome measures and in-situ VR playback

ABSTRACT

Among its many promising applications, Virtual Reality (VR) can simulate diverse real-life scenarios and therefore help experimenters assess individuals' gait performance (i.e., walking) under controlled functional contexts. VR-based gait assessment may provide low-risk, reproducible and controlled virtual environments, enabling experimenters to investigate underlying causes for imbalance by manipulating experimental conditions such as multi-sensory loads, mental processing loads (cognitive load), and/or motor tasks. We present a low-cost novel VR gait assessment system that simulates virtual obstacles, visual, auditory, and cognitive loads while using motion tracking to assess participants' walking performance. The system utilizes in-situ spatial visualization for trial playback and instantaneous outcome measures which enable experimenters and participants to observe and interpret their performance. The trial playback can visualize any moment in the trial with embodied graphic segments including the head, waist, and feet. It can also replay two trials at the same time frame for trial-to-trial comparison, which helps visualize the impact of different experimental conditions. The outcome measures, i.e., the metrics related to walking performance, are calculated in real-time and displayed as data graphs in VR. The system can help experimenters get specific gait information on balance performance beyond a typical clinical gait test, making it clinically relevant and potentially applicable to gait rehabilitation. We conducted a feasibility study with physical therapy students, research graduate students, and licensed physical therapists. They evaluated the system and provided feedback on the outcome measures, the spatial visualizations, and the potential use of the system in the clinic. The study results indicate that the system was feasible for gait assessment, and the immediate spatial visualization features were seen as clinically relevant and useful. Limitations and considerations for future work are discussed.

CCS CONCEPTS

• **Human-centered computing** → **Visualization toolkits**.

KEYWORDS

Spatial visualization, virtual reality, playback, gait balance, obstacle crossing

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1 INTRODUCTION

Falls are a significant public health problem [49], particularly among older adults [35, 39, 42, 48, 50]. Effective fall prevention programs should address the underlying mechanisms leading to the fall [16, 19, 27, 41]. For example, tripping over an obstacle may account for approximately 34-60% of falls among older adults [11, 14]. A decline in the ability to perform obstacle crossing was found to progress with age [18, 20]. Dual tasking (DT), i.e., "performing two tasks concurrently", such as, walking while talking, is also known to influence fall risk in older adults [3, 8, 52, 55]. Our day-to-day life requires performing concurrent cognitive tasks while walking [3, 8, 10, 55]. Walking and texting, walking and navigating a busy street, are all examples of dual tasking that combine walking with cognitive abilities, more specifically, attention capacity [3, 10, 13, 22, 47, 55]. Performing two tasks concurrently might require more than a person's total attention capacity, hence interfering with the performance of either task or both. This is called the "dual-task interference cost" (DTC) [3, 8, 52, 55]. Attentional resources are therefore critical for stable walking, and reduction in attentional resources may impair the maintenance of balance and increase the risk of falling [10, 47, 51, 55]. It has been demonstrated that older adults with a high fall risk slow down and may become less stable when they are required to walk while performing another task [21, 22, 55]. The ability to allocate additional resources during walking is even more crucial in complex environments. For example: areas with rapidly moving vehicles present, busy or crowded surroundings, or obstacles that must be crossed. [10, 18, 47, 52, 55].

To improve the evaluation and analysis of balance and gait, rehabilitation clinicians and researchers began to use VR to set up complex environments and simulate sensory (e.g., visual, auditory) stimuli that people may encounter in real life. In addition, using VR, clinicians can utilize motion tracking to assess participants' gait while participants experience dual task or sensory overload in a safe environment without fear or concern of experiencing a fall. VR systems can also be used to simulate obstacle crossing [51]. Wang et al. presented a VR assessment system to investigate anticipated or unanticipated virtual obstacle crossing with multisensory load and cognitive load [51]. The system utilized a floor sensing walkway to get participants' ground reaction force. But the system did not track participants' foot kinematics or provide any visualization. Here we present a novel platform to assess gait with obstacle crossing, cognitive load, and multisensory load. Specifically, the current work has the following contributions:

(1) The gait assessment system is a novel analytics platform with instantaneous spatial data visualization including motion playback and data plots for outcome measures in VR. This feature helps visualizing, for example, dual task cost on walking performance. A major hurdle in applying VR-based assessment in the clinic is that the system collects raw data and relies on data analysis with external statistical analysis software, rather than exploit VR's visualization abilities and engagement. Therefore, the immediate visualization greatly enhances the clinical relevance of the system. With spatial visualization and immediate output, the clinician can use to modify their program and track patients' performance.
(2) In addition, we collected input from 7 participants with professional Physical Therapy (PT) background. They evaluated the system and provided feedback on the outcome measures, the spatial visualizations, and the potential use of the system in the clinic.

2 RELATED WORK

There are several clinical assessments of gait that can help determine the fall risk of an individual[17, 40]. Some of these assessments include observing gait with a secondary task [29, 46] or stepping over an obstacle [17, 53]. For example, The Dual-Task Time Up and Go test (DT-TUG) relies on the time of completion assessed by a stopwatch. Subjects will be instructed to stand up from their chair, walk at a comfortable pace a distance of 10 feet, turn 180, walk back to the chair and sit down while performing another mental task, such as counting backward by 3 from a number between 20 and 100 [29, 46]. The cut off times to discriminate between fallers and non-fallers older adults is > 15 seconds [46]. For assessing obstacle crossing, the Functional Gait Analysis (FGA), offers one item of obstacle crossing. The participant is crossing over one height level shoe box while the therapist scores on a scale of 0 (severe impairment) to 3 (normal) [53]. Although these assessments are commonly used, they have some limitations. First, they do not allow for modifications of the environment. This is important because falls typically occur within changing and complex visual and auditory environments and as a result of unexpected external forces [11, 14, 18, 52, 55]. Moreover, they provide information about general performance (e.g., duration) rather than more specific spatiotemporal evaluation. This is important for walking assessment because spatiotemporal gait parameters may reveal differences between fallers and non-fallers older adults [23, 33, 38]. Several studies have attempted to close this gap by adding VR to fall risk assessments. Almajid et al, added visual stimulus to the traditional TUG test using a head-mounted display (HMD) to measure the effects of age-related visual dependence on motor performance [4]. The addition of HMD to the TUG allows for evaluating performance in a complex visual environment. It also provides data on head kinematics, potentially revealing quantitative age-related differences in motor behavior. VR could add another value in diagnosis of disorders that are typically undetectable by traditional clinical tests. One example could be Persistent-Postural Perceptual Dizziness (PPPD), which is a recently defined diagnosis of chronic vestibular symptoms exacerbated by exposure to moving objects and self-motion. Recent studies found differences in head kinematics strategies of PPPD compared to healthy young adults adding VR to the Four-Square Step Test VR (FSST-VR) [1, 2], a test to measure dynamic balance of older adults by stepping over cross-shaped canes in clockwise and counterclockwise directions [17]. Our VR setup therefore focuses on assess of walking performance in semi-real-life situations utilizing challenges of a day-to-day life such as obstacles crossing (expanding and building on the FGA examination), allowing measuring several turns while walking (like in the TUG test) and to measure not only head kinematics but also feet and waist kinematics from the VIVE trackers.

Visualization can benefit data interpretation and help participants understand their performance. Amundsen et al. presented a fall risk assessment system with a sensor-embedded floor, Kinect, and visualization to monitor the risk of falling. Their visualization included skeleton reconstruction and gait parameters[5]. Anwary et al. presented a tool to quantify and visualize gait in real-time with Inertial Measurement Unit (IMU)[6]. They mounted one IMU on each participant's foot, collected gait data, and visualized the metrics in 2D plots.

Differences in gait between overground walking and walking in VR are typically attributed to the field of view and inaccurate depth perception. Nevertheless, several studies showed that walking with VR was almost identical to regular over-ground walking [24, 32]. Martelli et al. [30] observed differences in a few gait parameters, such as the length of the stride and overall speed, they still recommended VR as a useful approach to quantifying response to different perturbations. Two recent studies examining virtual obstacle crossing during treadmill-walking found that participants learned to cross virtual obstacle safely and that this learned skill transferred to real-world locomotion [26, 28]. In addition, virtual obstacle training using various heights has led to an improvement in gait speed and obstacle crossing performance in different patients such as: post-stroke hemiplegia [54], multiple sclerosis [7], Parkinson's disease [31], and older adults with poor mobility [45].

3 REQUIREMENTS ELICITATION

Our team consists of two Computer Science researchers and two Physical Therapy researchers. After literature review and experiment analysis, we discussed and summarized the requirements for the system design:

R1: Motion capture for the head, waist and both feet. The kinematics of the head, waist, and feet are essential information for analysis of balance control. Spatio-temporal gait parameters, obtained from the feet, are sensitive in detecting older adults who had previously fallen [33, 38]. Acceleration variability of the waist, measured via wearable inertial sensors, showed that older adults who are fallers demonstrate a less smooth and less stable gait compared with non-fallers [38]. Finally, recent studies suggest that head kinematics can shed light on balance performance patterns, and identify those who are more prone to balance instability such as people with vestibular disorders [1, 2]. Two recent literature review demonstrate that wearable inertial sensors (WIS) locations such as the head, chest, waist, thigh, and ankle can objectively identify gait characteristics of older adults with a high fall risk [12, 38]. The number of inertial sensors used varied from one to five sensors, and a single WIS located at the waist was the most common one [12, 38]. Another study found that the waist region was the most suitable location to detect falls, with 99.96% sensitivity when testing 14 healthy young adults during an actual fall [37]. Also, the waist location solely is sufficient to successfully determine several gait differences among "faller" older adults such as: slow walking speed, short step lengths as well as reduced acceleration root mean square [12, 38].

R2: Portable, low cost and simple setup. The low cost and portability will improve the system's potential outreach to multiple clinics and patients at fall risk. The portability will make it potentially applicable to home use in the longer term.

R3: Capture participants' motion during a trial, and playback with embodied graphic body parts in VR. Motion capture and VR playback can replay and simulate the motion with embodied graphic head, waist, and feet in VR. Then, the experimenter or participant can observe the playback from different perspectives and positions in VR. In addition, VR playback records motion, and does not have disclosure risk of photos or videos. Moreover, it is possible to replay multiple trials in-situ. Compared to the full-body motion capture setup, the tracked and visualized body segments that our system utilizes are limited. However, according to literature, the most critical body segments for fall detection and balance assessment are covered within our setup (see R1). Therefore, our system could be sufficient for walking assessment along with minimal requirements of sensors setup, making it more convenient to both the participants and the tester.

R4: Full control of the playback. Similar to controlling a traditional video recording, observers can pause/resume, speed up/slow down, and move a seek slider.

R5: Simultaneous playback of two trials for trial-to-trial comparison. The system can load two trials' playback data and visualize two trials' playback in situ and the same time frame.

R6: Visual Motion trail effect for each body segment motion. The trajectory of the motion can be visualized per each graphic body segment. This allows for simple observation of each segment's progress in space and time alone and relative to other body segments. .

4 SYSTEM DESIGN AND IMPLEMENTATION

We developed the system in C# with Unity3D (2019.4.16f1). The Implementation uses SteamVR plugin for VR support and GraphAndChart plugin for graph and chart display in VR.

4.1 Apparatus

We use the HTC Vive Pro with a wireless adapter to accomplish the untethered experience. The setup had 4 Lighthouse base stations to cover a 6 meter x 4 meter walking area. There were 3 Vive trackers respectively attached to the mid lumbar, top of the left foot, and top of the right foot.

4.2 Virtual environment

The virtual environment (VE) contains a city-like scene which consists of a street sidewalk and urban blocks. People encounter this type of scenario in day-to-day. The system has an obstacle generation feature with obstacle heights varying from 25mm, 50mm, 75mm, 100mm, 125mm, 150mm, and 190mm (190mm is the maximum height of a standard stair as per the Stairbuilders and Manufacturers Association). The obstacle's width is 60cm, and depth is 20cm.

The system provides virtual avatars as visual stimuli on the street walking from one side to the other. There are 3 levels of visual stimuli: no virtual avatars, medium load of avatars with slow walking speed and high load of avatars with fast walking speed. The scene uses simple graphics because an overwhelming visual images could distract participants from their task of crossing obstacles and potentially can evoke cybersickness.

The auditory stimuli include ambient (background) sounds, and object sounds such as foot steps and foot crossing feedback (i.e. sound for success, sound for failure). The system recognizes which foot involves collision and can choose different audios to play for left/right foot collisions. The audio SDK in the system supports spatial audio, and the audio feedback could come from the ear corresponding to the foot involved in the collision. However, we preferred to use different tones over sound localization. During pilot testing, we found that providing separate feedback per foot was not helpful to users, possibly because the feet were too close during walking. Our goal is to observe natural performance when providing as little feedback as possible for assessment. However, since VR does not provide somatosensory input that helps participants know if a collision has happened, we had to compromise and add current immediate auditory feedback.

Despite the high ecological validity of testing obstacle crossing in VR, VR systems cannot provide somatosensory input of the foot to simulate the impact when participants hitting the obstacle. To overcome this challenge, we modeled the feet in the VE so participants can visually detect their own feet and therefore identify whether their foot cleared the obstacle or not. In addition, we provided an auditory feedback for success or failure of clearance. Nevertheless, according to our experience with the implementation, participants were unable to see which part of the foot collided with the obstacle when the collision was not within the participant's field of view, such as the heel, the bottom of the foot, or the back of the foot. Another feature of our system, immediate visualization, can solve this gap.

4.3 Immediate visualization

The immediate visualization shows the participants a VR playback that can help them see which foot and what part of the foot collided with the obstacle. When watching their own performance, participants can learn how to plan a successful obstacle crossing and perform the task better.

Clinical assessments of balance and gait typically combine quantitative and qualitative approaches. In order to get immediate visual feedback, physical therapists (PTs) often use video recording. These recordings help PTs examine the quality of movement, and strategies that may not be captured with quantitative metrics. VR playback may present several advantages over video playback. First, VR playback does not have disclosure risk of photos or videos compared to video recording. Second, the video recording's point of view (POV) relies on the camera's position and perspective, and not on the observers' prospective. Successful tracking of motor tasks might require the camera to move and follow the participant during the trial. If the subject walks a long distance, for example, it will require the camera to be positioned a little further in order to capture the whole trial. This is one aspect that the motion capture VR playback can provide unlike the video recording. Moreover, the motion capture VR playback can replay and simulate the motion with embodied graphic of the head, waist, and feet. Thus, the experimenter or the participant can watch the playback as an observer POV, displaying the participant own perspective and position in VR. Third, researchers can compare the impact on participants' performance, for example, with/without dual task, a form of cognitive load. In the VR playback, researchers can go specifically to the frame where participants turned, crossed the obstacle, or where collision happened, in order to figure out the position of body segments and compare between different metrics at that moment.

Watching the visualization while wearing VR headset, as opposed to on a 2D computer screen could be more natural for viewers since they don't need to use a mouse/keyboard to maneuver the viewing position/angle. Nevertheless, clinicians/patients can choose to view the performance on any 2D screen, which might be a better fit to daily clinic workflow.

4.4 Dual task

The system has an embedded dual-task paradigm where participants walk with or without negotiating obstacles while performing another auditory task. The auditory task requires them to listen to 5 sentences containing numbers that are randomly selected from a 45 pre-recorded bank of sentences. In a 30-seconds walking trial they have to memorize the numbers they hear and to report them at the end of the trial. To validate and score participants' response, the numbers in the 5 sentences will be recorded in logs.

4.5 Assessment mode and analytics mode

As mentioned before, the analytics mode will provides an in-situ visualization for the user to view the motion replay in VR as an observer. The analytics mode is only for viewing the visualizations of trials, not for conducting experiments. In the analytics mode, the VR user (who can be the participant themselves or the experimenter) is an observer who can view the visualizations of the metrics, and watch the motion replay of the head, waist, and feet in the VR replay. The analytics mode has full control of the VR playback, including play and stop, pause and resume and frame slider.

Differently than the analytics mode that utilizes a replay module which loads the data recording and playback the attributes, the assessment mode utilizes a record module that handles the attributes recording during trials. The participant has the first-person perspective for the tasks in the assessment trials. In the assessment mode, the rendering of the head and waist are disabled otherwise the participant would feel it is a third-person view. During the trials, the participant can see the embodied foot models because the system provides visual feedback for the collision between their feet and virtual obstacles. To have a flexible record and replay that can support arbitrary body segments, the record/replay modules utilize a Manager-Handler architecture. In the system, there is only one record manager that manages the start and stop for all recording, and one replay manager that manages the start and stop for all playbacks. Each object to be recorded/replayed needs to have a record/replay handler attached to it. The record/replay handlers inherit BaseRecord/BaseReplay, and implements the serialization/ deserialization of the attributes to be recorded/replayed. For the head and feet, the attributes we track are their transforms including position and orientation.

4.6 Motion capture and equipment selection

According to R1, tracking requirements should cover the head, waist, and feet. The Optitrack, a marker-based motion capture system is the the gold standard of motion tracking and could be used to track these segments [15, 25]. Compared to the HTC Vive Pro and Vive Trackers, Optitrack has a full-body tracking capacity and is less susceptible to tracking failures. However, it does not fulfill requirement R2, namely, it is costly, the full-body tracking requires extra equipment such as a motion capture suit, the setup is not portable and requires specific professional skills. In comparison, the HTC Vive Pro is one of the most popular commercially available VR platforms, employing a room-scale tracking technology called Lighthouse. Lighthouse tracking is an Infrared-diode-based tracking solution. Four base stations support up to 11 Vive trackers which equip infrared diodes to receive signals. The solution is low cost, has high precision, and its portability makes it a simpler solution for researchers and an easy fit for clinicians. Our goal (R2) is to track the most critical body parts for gait performance, so in addition to the head tracking reported by the HMD, we integrated 3 Vive trackers in the current version of the system to track the waist, left foot, and right foot. As mentioned in Section 4.1, participants' feet are represented by human foot graphic models in VR.

4.7 Foot tracking, calibration, and collision detection

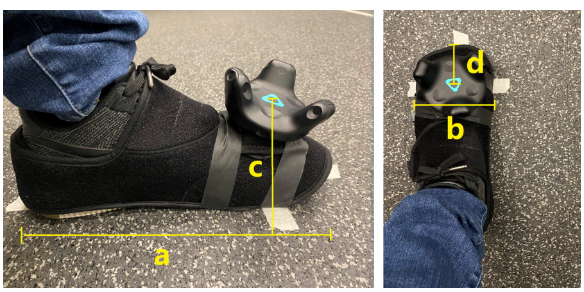

Figure 2: Vive tracker setup on the top of the foot. Four parameters to measure for foot calibration: a. foot length; b. foot width; c. height from the ground to the center of the Vive tracker; d. horizontal distance from the tip of the toe to the Vive tracker.

Foot tracking is of utmost importance for a walking analytical system. It obtains the foot kinematics for data analysis, and allows the graphic foot's embodiment which plays a vital role as visual feedback in the obstacle crossing. Wang et al. [51] designed a system with Vive trackers mounted on the ankles, but that setup was not ideal for a couple of reasons: 1. The foot model was not scalable to match participants' foot size; 2. A Vive tracker on the ankle cannot truly reflect the foot position, and is not optimal to detect obstacle clearance.

We mounted Vive trackers on the forefoot and designed a foot calibration method to align the graphic foot models with participants' feet (see Figure 2) so that participants can control the virtual feet as if they are their actual feet. We measure foot dimension and relative location of the Vive tracker when the participant is standing hips-width on the ground with both feet parallel and facing forward. During calibration, we obtaine the following parameters: the foot length, foot width, the vertical distance from the tracker to the ground, the horizontal distance from the tracker to the tip of the toe. The foot calibration module scales the graphic foot model to the foot dimension, and calibrates its relative transform based on the tracker.

Collision detection for the foot models helps us detect the distance between the participant's feet and the virtual obstacles. The collision is computed as the intersection of the meshes. In the assessment mode, collisions are recorded as events in logs, but not highlighted visually in real-time, because such feedback would cause participants to excessively look at their feet when crossing obstacles. In the playback mode, the segment involved in collision will be highlighted.

4.8 Outcome measures

The system has a measurement module which calculates a number of metrics during runtime. The system measures the following metrics:

(1) Walking velocity from headset, to analyze walking speed;
(2) Gait parameters from Vive trackers: step length and step width;
(3) Success/failure rate of obstacle crossing: based on clearance of the obstacles

On analytics mode, experimenters and participants can see the graphs on top of the left controller in VR. The outcome measures are displayed in VR and/or on screen.

4.9 Trial comparison

Overlapping the VR playback of the two trials and replaying them side-by-side simultaneously can make it easier to detect between-trials differences, such as which trial has a lower foot clearance, longer step length, shorter step width, etc. Therefore, we implement the trial comparison module to load two trials' playback data and replay them in the same time frame and the same place (see Figure 3). The purposes of this function are to:

(1) Compare intra-participant performance over time by loading and visualizing two trials under different experimental conditions (e.g. single/dual task)
(2) Compare intra-participant performance by loading and visualizing two trials under different experimental conditions (e.g. single/dual task)
(3) Compare inter-participant performance by loading and visualizing two trials under the same experimental condition.

Experimenters have full control over the display of the two trials. The two trials have different color coding for their motion trajectories. The second selected trial's graphic body parts and trajectories are displayed in a semi-transparent rendering to visually discern the two trials. Experimenters can replay the trials from the beginning to the end simultaneously, or jump to a specific frame. For each trial, there is a corresponding frame slider for users to pick any frame and align the starting point of the trial with the other trial. For example, users can use the frame sliders to align the trials based on the moment of their second stride of the left/right foot, and replay the trials simultaneously from that moment.

Figure 3 shows two trials, the normal avatar is from a single-task trial with obstacle crossing, the semi-transparent avatar is from a dual-task trial with obstacle crossing and cognitive load. We can obtain important information from the foot comparison, such as the single task avatar is slightly faster than the dual task, but which segments of the trial the speed differences occurred; whether the participant has the same strategy for each obstacle crossing and turning; whether/how the collisions differ in different trials/crossings.

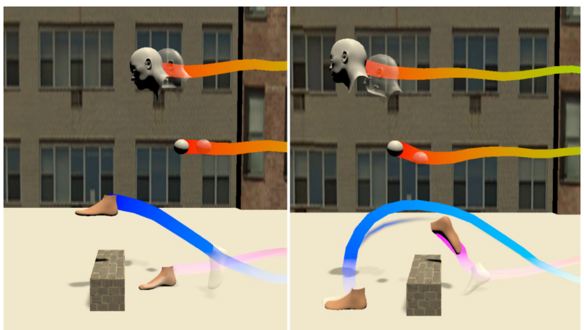

Figure 3: A trial comparision between a single-task trial (shown as the avatar with normal rendering) and a dual-task trial (shown as the avatar with semi-transparent rendering)

4.10 Motion trajectory visualization

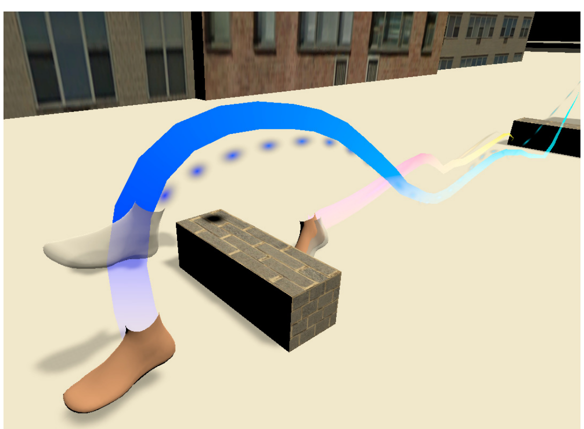

Figure 4: The motion trajectory visualization for a two-trial comparison with different foot clearances. The solid trajectory representing the single-task trial shows a higher foot clearance than the segmented trajectory which represents the dual-task trial.

Motion trajectory visualization creates a trajectory behind the moving segment. It helps visualize the trajectory of the movement and could be useful for better visual tracking and interpretation.

The trajectory visualization module utilizes Unity's trail renderer to visualize objects' trajectories for a certain duration. Experimenters can set trajectory's color coding or textures to differentiate between trajectories from different body parts, and can set duration of the trajectories all the way from 0 (no trajectory) to the full duration of the trial (keep movement trajectory during the whole trial). This feature gives experimenters and participants intuitive visual feedback regarding each body parts' behavior as well as overall participants' performance . Motion trajectory can also help understand obstacle crossing strategy such as foot clearance. In Figure 4, we can see two blue motion trajectories in the trial comparison. The segmented trajectory curve is the left foot's trajectory in the dual-task trial, which has a lower height than in the single-task trial.

4.11 Differences between VR and real-world gait assessment

The experience in VR is not a 1:1 replication of the physical world. Some deviation from reality is inevitable based on the current state of technology. However, we still believe VR is the right technology for gait assessment for 3 reasons:

(1) Context: Ideal simulation approach to provide immersion, controllable multisensory stimuli. It is typically not feasible to test and train patients in all real environments, however VR can provide the necessary contexts.
(2) Transfer: Studies [26, 28] showed that locomotor skills and obstacle crossing practice transferred to the real world. Performance measures in each environment were strongly correlated with retention performance in the same real world environment.
(3) Comparison: Some bias is inevitable when using VR for gait assessment (e.g. exaggerating movement in VR) however this bias should be consistent between all trials. Therefore, the effect caused by experimental conditions should remain valid.

5 PILOT STUDY

We first tested the feasibility of the system internally with team members, and then we conducted a pilot study to test the procedures, collect feedback and establish the system's feasibility with external participants. Implementation studies typically employ mixed quantitative-qualitative designs, identifying factors that impact clinical translation across multiple levels, including patients, clinicians and the overall facility[36]. This study was a first-step user study aiming to collect evaluations of clinician stakeholders regarding whether the system can be used in clinics and whether it can help researchers conduct their experiments.

5.1 Participants

The pilot study enrolled 7 participants who have professional PT background: 2 PT students (P1, P2), 2 PT (P6, P7), and the last 3 were both Physical Therapist and PT researcher (P3, P4, P5). The participants' age range was between 24-39.

5.2 Procedures

Each session was about 90 minutes long. During the experiment, two experimenters E1, E2 worked simultaneously on different aspects, as detailed below. The pilot study included the following phases:

5.2.1 Phase 1: Screening and system setup (15 minutes). E1 evaluated participant's sensory systems, mobility, and cognitive function. In the meantime, E2 turned on all the devices, paired the untethered VR headset, and calibrated the play area of the VR system.

5.2.2 Phase 2: Vive tracker setup (10-15 minutes). After Phase 1, E2 helped the participant to wear the HMD, while E1 mounted Vive trackers to the participant's mid lumbar and the top of each foot, measured the dimension of the participant's foot, and measured the relative position of the trackers to the feet.

5.2.3 Phase 3: Explanation and Experiments (30 minutes). When the Vive tracker setup was completed, E1 explained the general experiment tasks (motor and cognitive tasks), and guarded the participants during the experiment. Each participant had at least 2 practice trials until the participant could successfully cross all obstacles in a single trial. E2 controlled the system and set the experimental conditions for each trial.

5.2.4 Phase 4: Questionnaire and Interview (20-30 minutes). At the end of the session, an open-ended interview and a close-ended questionnaire was administrated by E2 to investigate participants' opinions about usefulness of the system and difficulties of the tasks. The questionnaire consisted of 7-point Likert scale questions with the following rating: 1-strongly disagree, 2-disagree, 3-somewhat disagree, 4-neutral, 5-somewhat agree, 6-agree, and 7-strongly agree. The open-ended interview allowed for participants to elaborate on their feedback, and to give further details regarding how participants would use this VR system in their clinical programs.

5.3 Results

5.3.1 Equipment accessibility. All participants agreed that the system setup is relatively low cost, and not as complicated as optical motion capture (mocap) systems that are marker-based.

P1, a PT student, mentioned: "For a typical force plate, they could cost a few thousand, and not to mention the whole set of motion capture system in addition to the floor sensors, the whole system would cost hundreds of thousands of dollars. The mocap systems that I've seen are much more invasive."

P5, a PT and researcher who has experience in PT research with optical marker-based motion capture systems, commented: "I realize that your study setup was pretty fast. Because I did not have too many sensors, and it was not uncomfortable. I have done the mocap on myself, and I felt it was a little uncomfortable for me because there were too many markers, and the markers kept falling. And sometimes you have to attach the markers and start the process from the top. So that's a little inconvenient for me. For your setup, you don't need too many markers."

P1 thinks the system would be a great solution from a business perspective because it costs less than $3000 plus a VR-ready computer. "It's not that expensive. I think from a business perspective, it's great... If you're a personal practitioner, a contract or non-contract PT, that's just what you need... This is a setup that you can have at home or in your own office/clinic. So I think accessibility-wise, it's great."

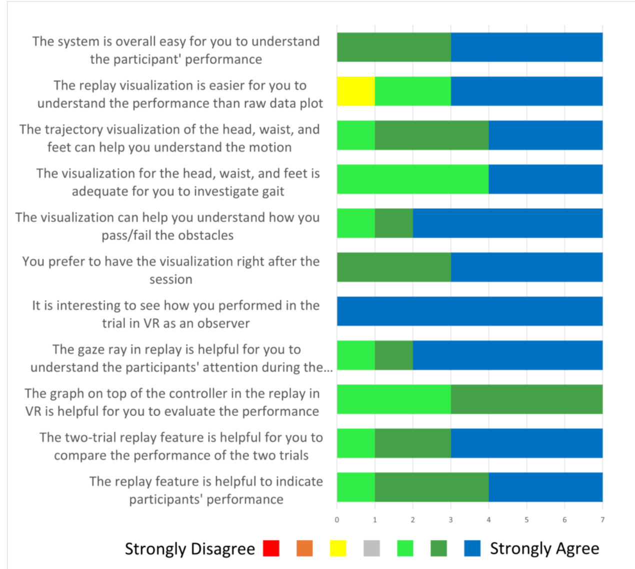

Figure 5: Questionnaire responses

5.3.2 Participant's evaluation of the metrics. For the statement: "The visualization for the head, waist, and feet is adequate for you to investigate gait." 4/7 somewhat agreed, 3/7 strongly agreed.

One PT researcher noted, "I think I would add ground reaction force for gait analysis."

Another PT stated: P1, "I think one thing that would be nice is to see from a midline how far participants are swaying left to right with their center of mass or their head." and "The height of the foot crossing an obstacle is a really important metric. Another important metric should be how high participants lift up their foot from baseline."

5.3.3 VR playback. All participants strongly agreed that it was interesting to watch their own VR playback as an observer. They were excited that the VR playback could allow them to choose perspectives and positions to observe their trials' simulation.

Regarding the VR playback, P2 mentioned "That's really helpful for patients. Because there are a lot of patients that don't understand what they're doing wrong, and then you can show this is what you're doing. For me as a student or as a future clinician, I was trained to look at the graphs and the charts afterward, so that's easier for me to obtain and digest the data on the graphs while watching the replay."

P7 thinks that VR playback can give them more details than simple observer feedback: "This is so much better. I couldn't understand much If you told me in general "you did a little bit better on this". But when I could see it with my own eyes through the visualization, I could tell myself to try to walk or cross obstacles differently, and then watch how I controlled it. I think that's really effective."

1/7 somewhat disagree, 2 somewhat agree, and 4/7 strongly agree that the VR playback was easier to understand the performance than the data charts. According to the interview results, when asked to compare the importance of the VR playback to the graphs/charts, researchers preferred the graphs/charts.

As P3 mentioned, "I would like to have the replay, but I still need the graphs..."

And P5 said, "I always see the graphs first for anything..."

5.3.4 Trial comparison. Each participant watched the comparison of their own two trials. The trials were a single-task trial and a dual-task trial. The single-task trial was an obstacle crossing task with no cognitive load. The dual-task trial was obstacle crossing with cognitive load. Often in the dual-task trial the avatar was lagging behind the single-task avatar.

P2 mentioned: "I really liked the two overlapping, because you could actually see that the pacing or my gait while clearing the obstacles was the same until I messed up on something or there was something that must have distracted me, and then you could see I lagged behind a little bit on one of them. I think it is helpful for the understanding of the cost of mental task of remembering something or saying something on walking performance. Data analysis is another tool to use for gait analysis, but I think the feature of having the ability to overlap it is really important."

P4 thought that the trials comparison can help insurance company know the insured's progress over time. "It would be great if you can turn the progress in VR into an actual way of demonstrating to insurance: a person is progressing, this is where they work from, and this is where they are now. You want to intuitively see the difference between each other...a big part of PT is insurance reimbursement."

5.3.5 Immediate spatial visualization or offline report? All participants reported that they preferred to observe the spatial visualizations immediately after their trials. (3/7 participants chose agree, 4/7 chose strongly agree). Note that their choice between the immediate spatial visualization and offline reports appeared to depend on their professional training level.

P6 and P7, who are Physical Therapists, strongly favored the immediate spatial visualization over offline reports.

P6, "I can get all of the metrics I want from the instant spatial visualization, and I do not need the offline report... From a clinician POV, if I'm telling a patient to do it again, I have the results immediately so I don't have to wait... I think it is 100% good if we have instantaneous results."

P3, P4 and P5, who are both PT and researchers, think the immediate visualization is a feature they want to have, but they think offline reports are still essential.

P3 suggested that the immediate visualization would be helpful for studies that require participants to learn and perform better, "The immediate visualization is helpful for people to understand how they failed and you as a researcher want them to learn and try again. Nevertheless, I think offline reports are more important."

The immediate visualization could also be a good indicator for technical errors during the experiment as P5 suggested: "I think the immediate visualization is much better because many times it happens that you collect the whole data, you process it and you realize, this is a big mistake and you need to do it again. It would be a big mess. So I think this is very convenient as a physical therapist and a researcher. If I don't get it immediately, I will not understand what's going on. And even if I'm getting it after some time, I will forget what I had done."

5.3.6 Gait Parameter Analysis. The system can get foot kinematics from the Vive trackers mounted on the foot; and get gait parameters, including step length and width (see Figure 6), by calculating the positions of both feet when they are both on the ground. Our preliminary exploratory analysis for the step length and step width in obstacle crossing show that step length decreased while the step width increased under high cognitive load conditions compared to no cognitive load. Figure 6 shows a visual comparison between step length and step width from participan P4 between no cognitive load vs. high cognitive load when the trials have obstacle crossing conditions. Figures 7 & 8 show a difference between the mean step length and mean step width of all the participants while crossing obstacles with and without cognitive load. These result are in agreement with previous studies [34, 43, 44]] where healthy young adults demonstrated a shorter step length and a wider step width when walking and performing another cognitive task. This is often referred to as the "dual task cost". When two tasks are performed together, the performance of either or both will deteriorate as a result of our limited information processing i.e., our limited attentional capacity. As shown in these boxplots, changes in walking performance occurred when adding a cognitive task to the walking task. These changes in walking are believed to help stabilize the walk, since a shorter step length minimize the time spent on single support (standing on one leg; the unstable part of walking) and a wider step width provides a wider base of support. Such careful walking strategy can help reduce the risk of tripping. However, given that our study focused on the system's feasibility; these results are preliminary and should be extended to a larger, diverse sample.

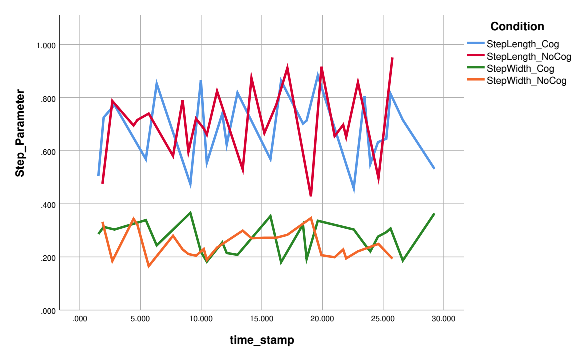

Figure 6: Step length and step width from participant P4 in the obstacle-crossing trials with and without cognitive load.

6 DISCUSSION AND FUTURE WORK

The system was found to be feasible for gait assessment, and all participants appreciated its clinical and research potential. All participants indicated the importance of instant feedback and real-time analysis of performance for clinical implications. All indicated that

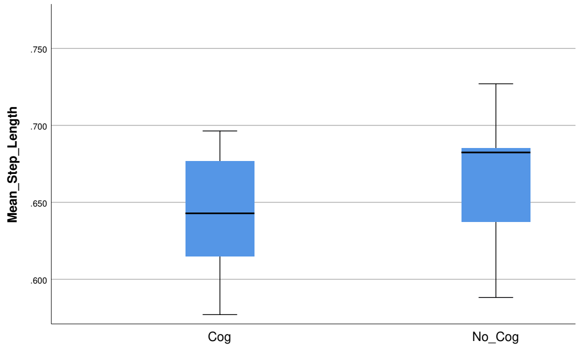

Figure 7: Mean step length (N = 7) in the obstacle-crossing trials with and without cognitive load.

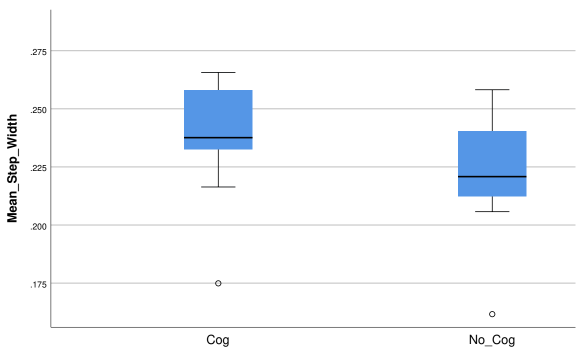

Figure 8: Mean step width (N = 7) in the obstacle-crossing trials with and without cognitive load.

the spatial visualization features could be effective for performance interpretation. We will take several future steps including in-clinic usability studies where the clinicians themselves run the system; comparative studies to investigate different patient populations; and intervention studies to test sensitivity to change.

Several limitations of the VR setup should be discussed. First, individuals tend to overestimate height in VR and therefore tend to exaggerate their foot clearance. Visualizing virtual feet helped decrease this over-estimation but the implication of this exaggerated movement to real-life performance needs to be further investigated.

Second, given the immersive nature of VR, a researcher must walk close to the participants to assure their safety. This could potentially block the Vive lighthouses and may interfere with the quality of tracking. We found that up to 6 meters could be tracked accurately with 4 light-houses if the researcher is aware of the surrounding light houses and walks accordingly.

Note that 6 meters are translated into a relatively short straight line walking distance which may limit the ability to analyze gait. However, according to a recent review [9], while the largest possible number of gait cycles is recommended for gait analysis, as little as 3 consecutive gait cycles could suffice. In addition, 5 to 10 meter distances are more clinically feasible than longer walkways. Indeed, our priority has been the potential of clinical translation. We believe that up to 4 light houses would be feasible in a small clinic. Indeed, we have set up the system in a clinic which is a hospital-based outpatient clinic in a metropolitan area, and its space is constrained and is comparable to similar clinics (hospitals may have clinics with larger shared gym space but not all outpatient or private practice would have that). The length of the setup area was 7m x 5m (7m x 7m is the maximum capacity of the system due to HTC Vive Tracker's tracking capability). When designing the system, we balanced the need for at least 5 meters of straight-line walking (to have sufficient consecutive steps between obstacles) with space constraints in most clinics.

This study was limited to a small cohesive group of stakeholders. The usability of the setup needs to be further validated with different stakeholder of various perspectives (e.g., clinical directors, insurers etc.) as well as diverse patient populations and clinicians.

Our next steps include: 1. implementing more metrics, such as sway, and foot clearance. The motion trajectory was designed for users to understand the sway and foot clearance by viewing the visualization. Based on the interview sessions, the PT researchers seem to prefer numeric data over descriptive visual playback. Therefore, we plan to implement these metrics in the next version. 2. wiring up timeframes of the VR playback and the graphs, so that users can move the seek slider to view the VR playback and values at each moment. If the dataset is much larger, it could take more effort to find the right value from the visualization of all the values plotted on the graphs. 3. In addition, we plan to test the effectiveness of the spatial visualizations with diversified populations who typically present with balance and gait impairments, such as people with Parkinson Disease, post-concussion, etc.

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