USE OF MIXED REALITY TO PROVIDE GAIT REHABILITATION

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Gait disorders are a common issue affecting millions of people worldwide regardless of age. In addition to reducing mobility, gait disorders increase the risk of falling, and can adversely affect the quality of life. Therefore, gait training is an essential aspect of well-being, especially for the elderly population. To address this problem, many systems have been developed. In this study, we present a novel method to provide gait training. We present two portable mixed reality systems designed to aid gait training for individuals with gait disabilities.

The first system uses an avatar to provide visual cues to the patient. It relies on the proteus effect and complexity matching to restore the natural gait. The proteus effect refers to the phenomenon where individuals adopt the characteristics of their virtual avatars. Complexity matching is the tendency to synchronize movements by matching others' complexity. Both theories are backed by credible scientific evidence. Our pilot study showed that this approach is effective in restoring gait patterns. The system is currently undergoing large-scale human trials to evaluate its feasibility further.

A second system provides rhythmic visual cues through a moving bar, and the user must match their foot placement accordingly. As the rhythm changes, users are required to strike with their left heel when the bar reaches the top level and with their right heel when it hits the bottom level. Pilot studies supported by similar research have also shown promising results, and we are currently conducting large-scale human trials to evaluate the system's effectiveness further.

Both systems are designed to help patients with gait disabilities and provide implicit learning. We aim to provide them with cost-effective, self-training methods to restore their gait. The results of this study could have significant implications for the rehabilitation of individuals with gait disabilities.

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1. Introduction

1.1 What is a gait disorder?

The gait of a person is their pattern of walking. Gait is a complex mechanism that involves the coordination of nerves, musculoskeletal, and sensory systems, and many other joints in the human body. When this complex mechanism works in harmony, we identified it as a normal gait cycle. An abnormal gait cycle occurs when this pattern is disturbed. Figure 1.1 shows normal and five other pathological gait disorders.

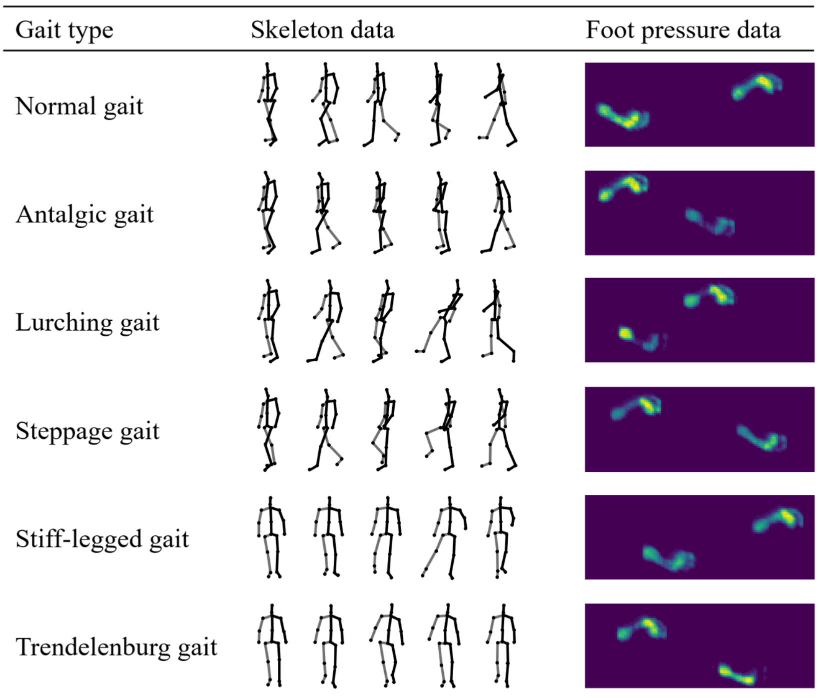


Figure 1.1: Normal vs five pathological gaits [1]

The elderly population is more prone to develop gait-related disorders due to the waning muscle strength, vascular encephalopathy and motor impairments associated with the aging process. [3, 4] Between the ages of 60 and 69 years, the risk of gait disorder increased by around 10%, but over 80 years, the risk increased by more than 60% [5]. However, regardless of age, anyone can develop gait disorders due to many other reasons [6] such as diseases like Huntington's disease [7], Parkinson's disease [8], vestibular balance disorder [9], strokes [10], neurological conditions [11], mental health [12], and severe injuries [13]. For instance, stroke survivors are 90 percent likely to have some form of functional disability, with mobility being the most common problem [14]. Gait disorders increase the chance of frequent falls and can have a fatal impact on the patient's life. Furthermore, it can significantly reduce the quality of the patient's life [5] and independence.

1.2 Gait Rehabilitation

Gait rehabilitation also known as gait training is a type of physical therapy that can improve the patient's walking and balance. Gait training can help patients to strengthen their muscles and joints, improve balance and posture, develop new motor programs or refinement of existing programs (muscle memory), increase mobility, and lower the chance of falling [15–17].

Over the years, many gait training methods were developed to help patients. Among those, there are some conventional methods such as doing simple overground exercises like walking a few meters with a physical therapist, stepping over objects, and other simple activities such as standing up and sitting down. Similarly, treadmill-based gait training is also a popular and proven gait training method in the medical community [18–20].

As technology advanced, many researchers worked on utilizing these new technologies to improve gait training efficiency. New technologies significantly improved the traditional gait training methods. For example, fully mechanized more efficient gait trainers were created to assist patients [21]. Similarly, modern robotics were combined with traditional treadmill-based gait training creating robot-assisted treadmill training. As a result of that exoskeleton systems such as HAL [22] and ALEX [23] was developed to assist patients. In addition, some studies have found new ways to provide gait training, such as by providing rhythmic auditory stimulation [24].

The recent development of extended reality(XR) created another new array of gait training methods. Extended reality is an umbrella term for Virtual Reality(VR), Augmented Reality(AR), and Mixed Reality(MR). The fields of VR, AR, and MR introduced immersive sensory stimuli that can further enhance the efficiency of gait training methods. The XR-based gait training provides a faster learning rate, high acceptability, and motivation and reduces dropout rate and training time [25].

For example, Brütsch et al, coupled virtual reality with robot-assisted gait training and studies its effect on children with varying gait disorders [25]. For this study, 10 patients (mean age = 12.47 years, standard deviation = 1.84 years, 5 males and 5 females) and 14 healthy children (mean age = 11.76 years. standard deviation = 2.75 years, 7 males and 7 females) participated. Four different conditions were randomly assigned to all participants when walking on the Lokomat device. Primary outcomes were derived from biofeedback values calculated during swing phases, and secondary outcomes were derived from a motivation questionnaire. The findings revealed a significant main effect for training conditions among all participants ($p < 0.001$), patients ($p < 0.05$), and healthy controls ($p < 0.01$). The children who used the virtual reality-assisted gait training approach shows a very high level of motivation.

Similarly, Ilona et al carried out a systematic review and meta-analysis of 21 studies that compare VR-based and non-VR-based gait training in patients with stroke-related gait disorders [26]. The mean age of the participants for the VR group is in the range of 45.9-65.9 years while the control group's mean age is in the range of 46.3-65.7 years. 8 of these studies were carried out using the treadmill-based approach while the other 13 studies were carried out with a more traditional over-the-ground approach. The result of the analysis indicates significant improvements in the balance and gait speed of the patients who used the VR-based approach over the patients who used the non-VR-based approach.

In line with the above results, another systemic analysis carried out by Gil et al presents solid evidence of gait improvements as a result of an Augmented Reality based gait training approach [27]. The analysis reviewed the results of 308 patients with varying gait disorders from stroke-related gait disorders to Parkinson related gait disorders. They also found out AR based gait training approach has significant improvements over the traditional approach. The researchers used Berg Balance Scale to measure the balance (standardized mean change 0.473, 95% CI -0.0877 to 1.0338; z=1.65; P=.10) and the Timed Up and Go test to measure the mobility (standardized mean change -1.211, 95% CI -3.2005 to 0.7768; z=-1.194; P=.23). Both of these results are favorable for the AR-based gait training approach. In addition to that, over the years, many studies highlighted the success and immense potential of XR-based gait training [28–31].

1.3 Mixed Reality (MR) and Gait Rehabilitation

1.3.1 What is Mixed Reality?

The term "mixed reality" was introduced in a 1994 paper by Paul Milgram and Fumio Kishino [32]. Mixed reality combines both elements of augmented reality and virtual reality. Therefore, to understand mixed reality one needs to understand both augmented reality and virtual reality. Virtual reality separates you from the real world and brings you to an entirely virtual world. Augmented reality allows you to add virtual elements to the real world. Mixed reality combines both of these and allows you to add virtual elements to the real world in a more interactive and immersive manner. The level of immersion and interactivity is far superior in mixed reality than in augmented and virtual reality. Figure 1.2 shows how mixed reality is different from augmented and virtual reality.

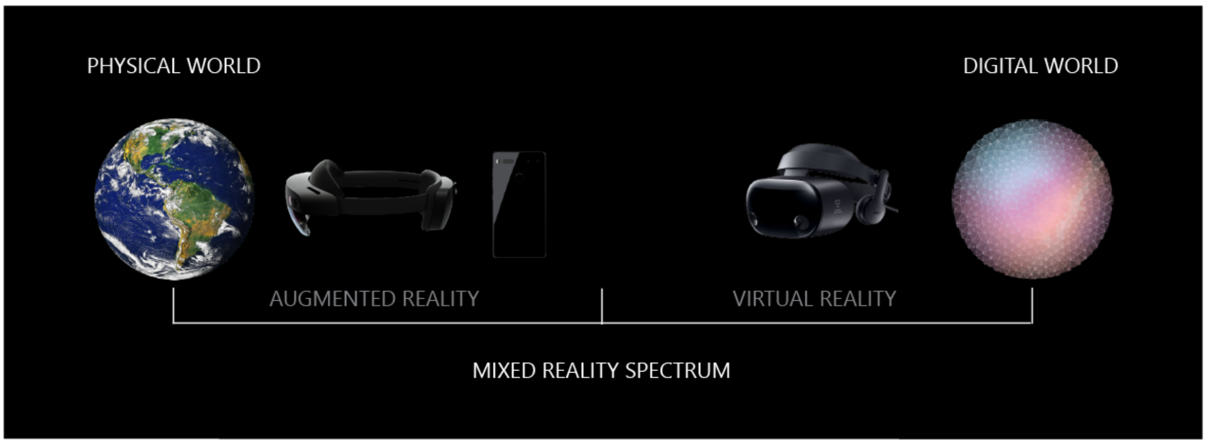


Figure 1.2: Mixed Reality Spectrum [2]

1.3.2 Mixed Reality (MR) Based Gait Rehabilitation

Over the years, many scholars have conducted numerous types of research about virtual elements and their effects on human psychology. For instance, the theory of the Proteus effect suggests that an individual's attitude and behavior can converge and align with the characteristics and features of a virtual avatar [33]. Similarly, Ogawa et al. showed that virtual hand realism affects the user's perception of the object sizes [34]. Ogawa et al. also present evidence showing that realistic full-body avatars create a strong sense of embodiment including body ownership [35]. Highly realistic and immersive virtual avatars can create a stronger effect. Therefore, compared to virtual and augmented reality-based gait trainers, mixed reality-based gait trainer offers more realism and immersion while creating a strong sense of body ownership. This can further enhance the gait training experience in the patients. Therefore, we chose the HoloLens which offers state of an art immersive mixed-reality experience.

1.4 Research Agenda

The purpose of this study is to address the following research question in light of the challenges associated with gait training.

- **RQ1:** Design and develop a portable, mixed-reality, avatar-based gait training system that provides patients with self-assisted gait training.
- **RQ2:** Design and develop a portable, mixed-reality, rhythmic visual cue based gait training system that provides patients with self-assisted gait training.
- **RQ3:** Evaluation of Mixed Reality Based Gait Training System.

1.5 Major Research Contribution

1.5.1 Portable Mixed Reality Avatar Based Gait Training System (RQ1)

Our main goal in this research is to design and develop a portable gait training system that does not require lots of specialized hardware such as treadmills. Many existing gait training systems such as Locomat require expensive specialized hardware and specialized environments. To obtain training from these systems, gait patients must attend multiple sessions and many patients found it to be a difficult task. Furthermore, some studies pointed out that even after a patient's gait function had been sufficiently restored by hospital-based rehabilitation programs, patients are still at risk of falling in their homes [36, 37]. The environmental differences between the training environment and the actual environment are the reason for this. For instance, narrower corridors and a larger number of objects and furniture in the house, may cause an inappropriate allocation of visual attention and increase the risk of falling. Using a portable system, patients can train their gait in any environment they like. Furthermore, such systems offer more degree of freedom by eliminating regular travel to specific environments. Therefore, we designed our system to support any indoor environment instead of a specialized environment. In this version, a humanoid avatar assists the user in retraining their gait pattern by providing visual cues. Furthermore, we designed our system on top of the OpenXR platform which allows our system to run on other devices such as SteamVR, Meta Quest, and Windows Mixed Reality-based headsets apart from HoloLens 2. This allows our system to not to limit to specialized hardware and increases affordability by allowing patients to select from multiple devices.

1.5.2 Portable Mixed Reality Rhythmic Cue Based Gait Training System (RQ2)

This version design is almost similar to our avatar-based gait trainer except for the training modality. Instead of a humanoid avatar, this version provides a rhythmic visual cue through a bar that travels up and down mimicking a frequency of rhythmic noise. The results of existing research indicate that visual rhythmic cues can assist patients in improving their timing, neuromuscular coordination, and balance. Furthermore, it helps patients to establish a regular walking pattern and maintained a steady pace. Therefore, by designing this we are trying to understand how we can leverage the mixed reality to increase the efficiency of the gait training through visual rhythmic cues.

1.5.3 Evaluation of Mixed Reality Based Gait Training System (RQ3)

We evaluate the result of our system in multiple ways. We conducted a literature review of existing researchers about extended reality based gait training and how it can be used to promote motor learning principles. To understand our system performance, we collected system performance data through the windows performance analyzer. By using this method, we are able to benchmark the utilization of CPUs, GPUs, memory, and disks. To understand the effects of gait training, we conducted a pilot test with human subjects and are currently in the process to conduct a more complex study. We discuss our results in Chapter 4.

1.6 Outline

The organization of the rest of the paper is as follows. Chapter two presents the related work in gait training. Chapter two is divided into 3 sections. These sections present related works in augmented reality, virtual reality, and mixed reality based gait training systems. Chapter 3 gives details explanations of our system design, and the challenges we faced. Furthermore, in chapter 3, we present two unique systems and the iterations of these system designs. Chapter 4 outlines how we evaluate our system and discuss the system's limitations. Chapter 5 presents a summary and conclusion including future studies.

2. Related Work

2.1 Background

Gait is responsible for all human movements. Any disruptions to gait affect more than just a patient's legs. Over time, these disruptions can alter the balance and increase the risk of falling, can add strain to multiple parts of the body, and can increase the chance of severe or fatal injuries. Therefore, throughout time, many researchers have been trying to improve the gait of patients with gait disorders. As a result of that, many systems and methods were developed to provide gait training. As a result of that, many systems and methods were developed to provide gait training.

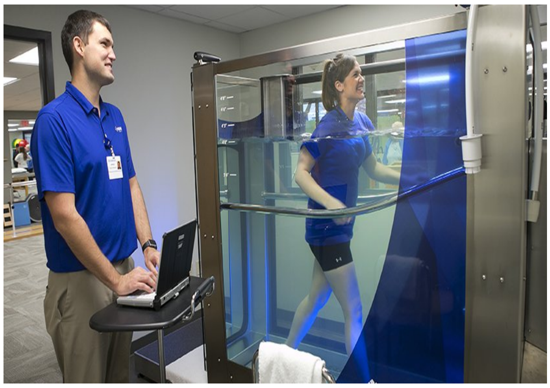
Traditional gait training involves simple but effective exercises done over the ground. In this case, patients are supposed to do exercises such as stepping through a line, standing up and sitting down, stepping over objects, and lifting their legs. In addition to that, some studies suggested dance [38] and yoga [39] can also improve gait and balance. This method has several advantages. For instance, it doesn't require any specialized equipment or environment and costs less than instrumented gait analysis. However, on the downside, it provides less accurate data about gait since it relies on mainly observational gait analysis. Similarly, the effectiveness of such training entirely depends on the physical therapist's expertise.

Many researchers have been concentrating on incorporating technology with traditional gait training in order to improve the efficiency of gait training systems to harness the advantages of the advancements in modern technology. As a result of that many different systems were born as shown in figure 2.1. For example, over the ground, body weight-supported robot-assisted gait training systems such as ZeroG, Robot-assisted treadmill based systems such as Lokomat, Exoskeleton suits that are equipped with wearable sensors such as Atalante, underwater gait training systems such as HydroWorx were developed to improve the accuracy and efficiency of gait training. However, these systems do not have the advantages of traditional gait training since they require specialized hardware as well as being expensive, and require a specialized environment.

(a) ZeroG System

(b) Lokomat System

(c) Atalante System



(d) HydroWorx System

Figure 2.1: Gait Training Systems

Due to the recent breakthroughs and the popularity of Extended Reality (XR), many researchers have been focusing on designing novel extended reality-based gait training systems and incorporating extended reality with current gait training systems. These systems are based on two scientific theories called "Proteus effect" and "Complexity matching". The Proteus effect describes the human tendency to be affected by their virtual avatar representation [33]. For example, Jorge Peña et al. present evidence of how the illusory ownership of different virtual bodies influenced male participants who were playing an exergame [40]. According to their results, participants who were assigned athletic virtual avatars showed more physical activities than the participant who were assigned obese avatars.

The theory of complexity matching describes interacting systems with similar characteristics aiming to maximize information exchange and attune their complexity to improve coordination [41]. Almurad et al present evidence that complexity matching can be used for gait training. In this research, the researchers observed that when older participants walked closely synchronized with younger participants, the older participants managed to inherit the complexity of younger participants after three weeks of trials. Furthermore, this newly restored complexity persisted even after two weeks of the training session [42].

Similarly, extended reality can be successfully incorporated with existing gait training systems to further enhance their efficiency. Many of the existing traditional gait training systems involve lots of repetitive exercises and tasks. This results in waning motivation and boredom for the participants. Many researchers presented credible evidence of gamification of gait exercises and the use of extended reality can the motivation level of the participants [25, 43, 44].

2.2 Augmented Reality Based Gait Training

Augmented reality adds virtual elements to the real world and provides a more realistic user experience. Therefore, augmented reality (AR) can provide a higher degree of body ownership, freedom, and embodiment than virtual reality. This provides a good platform for gait training.

Cheng et al developed an augmented reality exergame system intending to reduce fall risk in the elderly population. The game has three modes that provide fall risk assignments, gait training, and provides training feedback [45].

The risk assignment was done by a self-assessment tool that has 12 questions allocated with 2 points. Every "Yes" will award 2 points and the higher the score, the greater the risk of falling.

The gait training was provided by three games. In the first game, participants had to change their body position to match a unique position in an incoming wall. These shapes were designed to invoke quick thinking and motor dexterity. This exercise aims to increase muscle strength, balance, and attention span. In the seconds game participants had to memorize 3 random fruits displayed in random locations for 5 seconds and then try to capture the correct fruit by moving from side to side. This game was designed to improve short-term memory and balancing ability. In the third game, users had to stomp the rats that are randomly emerging from 9 holes in the ground. participants had to raise the leg to a certain height and stomp the rat by 10 times in order to kill it. This was designed to strengthen the lower limb muscles and stride length. The feedback was determined by the scoring system that awards points for correct behavior and penalizes the users for incorrect behaviors.

To test the system 25 participants (9 females and 16 males mean ± SD age, 71.48 ± 4.09 years) participated. The user experience was evaluated by using a questionnaire. The final results showed that the average scores for each aspect were: pragmatic quality(effectiveness) score (1.652 ± 0.868); hedonic quality score(convenience, motivation, attraction) (1.880 ± 0.962); and the overall score was 1.776 ± 0.819. Compared to the traditional baseline version, all the aspects were scored high by the users, and the users overwhelmingly favored the positive user experience offered by the system.

2.3 Virtual Reality Based Gait Training

It is often noted that the absence of representations of the user's body in a virtual reality environment lessens the spatial sense of presence. However, even with that disadvantage, Many studies have proven that virtual reality can be used as an effective tool to provide gait training.

de Rooij et al present evidence of VR gait training and non-VR-based gait training with 50 patients who suffered motor impairment as a result of a stroke [46]. The patients were selected from between 2 weeks and 6 months after the stroke and then randomly assigned into VR and non-VR groups. After 6 weeks of 12 to 30-minute training sessions, participants' mobility, balance, walking activity, and fall risks were evaluated. The results showed no significant differences between VR vs Non-VR groups and the researchers were unable to find any adverse effects from both groups. However, when measuring user experience, the VR group was overwhelmingly positive about VR-based gait training. The results show that VR-based training is also just as effective and generates more positive experiences for users with stroke-related gait impairments.

Lee et al conducted a study to understand the effects of VR gait training with a non-motorized treadmill on balance and gait improvements in the elderly population [47].

For this study, 56 elderly people participated and were randomly assigned to VR vs Non-VR gait training groups. Both groups trained 50 minutes sessions per day, 5 days a week for 4 weeks. The results showed significant improvements in mobility, stride length, and step length in the VR group compared to the Non-VR group.

Mirelman et al conducted a similar study to evaluate the effects of how VR-based gait training influences the fall risk in the elderly population [48]. The researchers carried out randomized controlled trials in five clinics across 5 European countries (Belgium, Israel, Italy, the Netherlands, and the UK). 282 adults in the age group of 60-90 and who have records of more than 2 falls before the 6 months of the study participated in this trial. The participants were randomly divided into two groups that received VR-based gait training and Non-VR-based gait training. Both groups trained 3 times per week with 45 minutes sessions for 6 weeks. The trials were designed to simulate the real-life challenges that increase the risk of falling such as obstacles, and distractions. After 6 months, the results showed a significant reduction in falls in the VR group compared to the other group. Furthermore, after 6 months of the trials, the rate of falls was significantly lower in the VR group compared to the Non-VR group.

The results from the above studies show that even with less immersion and less spatial sense of presence, VR is a capable tool to provide efficient gait training.

2.4 Mixed Reality Based Gait Training

Compared to virtual and augmented realities, mixed reality offers superior immersion due to its ability to blend the physical world with virtual elements. The mixed reality can retain natural human intuitions, spatial awareness, and presence. Therefore, it can generate a strong proteus effect such as the body ownership, and facilitate the maximum information exchange through complexity matching. This makes mixed reality an ideal platform for gait training software. Naturally, this attracted many gait training researchers' attention. As a result of that, they introduced several unique gait training systems and methods which utilize mixed reality.

Guinet et al explored HoloLen's cutting-edge head-tracking capabilities and introduced a novel algorithm called HoloStep [49]. With only the head pose provided by an augmented reality headset, the algorithm calculates spatiotemporal gait parameters which can be used to identify gait deviations. The researchers included 63 children with cerebral palsy and compared the results of the HoloStep algorithm against the baseline Zeni's reference algorithm. In addition to good performance when applied to most gait patterns, HoloStep also performed well when applied to children with CP who used walking aids. Unlike our system, HoloStep did not employ any avatars or virtual elements which makes this system a unique approach. The results prove that even without holograms, the sensor data streams and Hololen's precision tracing abilities can be useful for gait training and analysis.

In line with our work Guinet et al, presented a serious game Augmented Reality Rehabilitation of Walking-Cerebral Palsy (ARRoW-CP) [50]. The game provides gait training, fun, and motivation for children who has gait disorders related to cerebral palsy. The system was tested with 14 children in the age group 10-18 years with cerebral palsy. They were divided into two groups where one trained with ARRoW-CP and the control group trained with regular treadmill-based gait training. The trials went 4 weeks with three 30-minute sessions per week. In line with other similar studies, the group that used mixed reality training showed improved gait and has higher motivation and fun. The system shows lots of similarities with our system. For instance, both are mixed reality avatar-based gait training systems. However, fundamental design principles are different. For example, our system is primarily designed to reduce the fall risk of the elderly population while ARRoW-CP is primarily designed to improve the gait speed of children. Furthermore, our system uses a rhythmic metronome to provide gait training and is more portable that the ARRoW-CP.

Held et al also presented a similar system that provides gait training for patients who has stroke-related gait impairments [51]. However, it should be noted that trial data is a major limitation of this study since the data is based on only one patient. Despite that limitation, patients showed promising improvements after completing gait training with mixed reality and gave overwhelming positive user ratings about the system. The system was named ARISE (Augmented Reality for gait Impairments after StrokE). It provides a mixed reality parkour course for patients to complete and provide patient-centered performance feedback. Even though ARISE system and our system share some similarities both systems follow unique approaches. For example, our system utilizes a Proteus effect and complexity matching with avatar centric approach with a rhythmic metronome while ARISE uses a parkour course. Furthermore, patients need to wear a bodysuit with motion sensors while using ARISE system. Hence it requires a specialized environment with camera arrays and specialized hardware. Since our system doesn't require a specialized environment and hardware setup it is much more portable than the ARISE and can be run on multiple platforms instead of being limited to HoloLens 2.

In conclusion, the evidence gained from the previous gait training research that uses extended reality shows that AR, VR, and MR is a capable platforms to provide effective gait training to patients.

3. System Design

3.1 Hardware and Software

Many researchers have presented evidence highlighting the importance of realism and immersion. A realistic full-body avatar, for example, creates a strong sense of embodiment, including ownership of the body, according to Ogawa et al [35]. As well, Choi et al demonstrate that avatar head-to-knee visibility improves the naturalness of glide styles [52]. Therefore, for our project, we chose mixed reality over virtual and augmented reality. The mixed reality blends the virtual elements with the real world preserving natural intuition, and spatial awareness and creating a superior immersive experience.

3.1.1 Hardware

To implement our system, we chose Microsoft Hololens, which was the first untethered holographic computing device that offer a mixed-reality immersive experience. The Hololens offers a see-through holographic lens, so the users can clearly see the environment around them and the virtual elements in the environment. In the context of gait training, this allows patients to clearly see the world around them and preserve spatial understanding while following a virtual avatar.

After carefully considering Hololens 1 and 2, we decided to use Hololens 2. The main reason behind this was the field of view. Hololens 1 has a small field of view of 30° compared to Hololens 2 field of view of 52° as shown in figure 3.1. In Hololens 1 users had to often turn their heads left to right in order to see more. Thanks to the increased field of view in Hololens 2, users have much freedom of retraining spatial understanding. Similarly, Hololens 2 has a higher resolution than Hololens 1. For instance, Hololens 2 has a 2K display per eye compared to the 720p per eye resolution in Hololens 1. Therefore, Hololens 2 can offer superior immersion than Hololens 1.

Figure 3.1: Hololens 1 vs Hololens 2 Field of Views

In addition to that, Hololens 2 offers precious head-tracking and eye-tracking capabilities. Previous literature regards to gait analysis showed that this head-tracking ability can be successfully used to calculate spatiotemporal gait parameters [49]. Furthermore, eye tracking functionality allows the system to know where the user is looking and this can be to understand how the user's attention changes throughout time and also used to provide important internal cues. Similarly, Hololens 2 eye-tracking offers calibration functionality that can be used to create a tailored experience for each user. The Hololens use these eye-tracking data and optimised the placement of Holograms creating a unique immersive experience for each user. Finally, Hololens 2's IMU (Inertial Measurement Unit) data such as Accelerometer, Gyroscope, and Magnetometer data streams can be also used to track changes in gait speed, balance, and rotation.

In order to add natural and realistic walking animations, we decided to record walking animations through motion capture. For this task, we used Xsens full body motion capture system and recorded multiple animations with different gait patterns at 60Hz.

3.1.2 Software

There are multiple paths to develop mixed reality software for Hololens 2. For example, Hololens allows development support for existing 3D engines such as Unity and Unreal as well as native engines such as WinRT and OpenXR. We evaluated all of these options to find the best development platform for our system.

3.1.2.1 Native Engine Development

The Windows Mixed Reality platform supports both Universal Windows Platform(UWP) and Win32 mixed reality applications that utilize HolograpicSpace API with DirectX 11 and above or OpenXR API.

DirectX 11 template with HolograpicSpace allows the developers to optimize the performance while exercising more freedom of development. This utilizes C++ and targets the universal windows platform. The development process is complex, time-consuming, and prone to errors. Furthermore, the developers have to write a lot of middleware from scratch to implement even basic functionalities such as animations. Therefore, we eliminated this option. Furthermore, Microsoft considers HolographicSpace as a legacy and no longer supports this. For the new native developments, Microsoft recommends OpenXR API.

OpenXR is a royalty-free API that provides native access to a range of mixed-reality devices. The biggest advantage of this is its support for cross-platform developments which is a core part of our research. Figure 3.2 shows a high-level abstraction of the OpenXR framework. However, developing native applications with OpenXR is also complicated and requires the implementation of a lot of middleware. Since we are using animations and physics we decided to eliminate this option and move on with a game engine that has pre-build support for animations and physics.

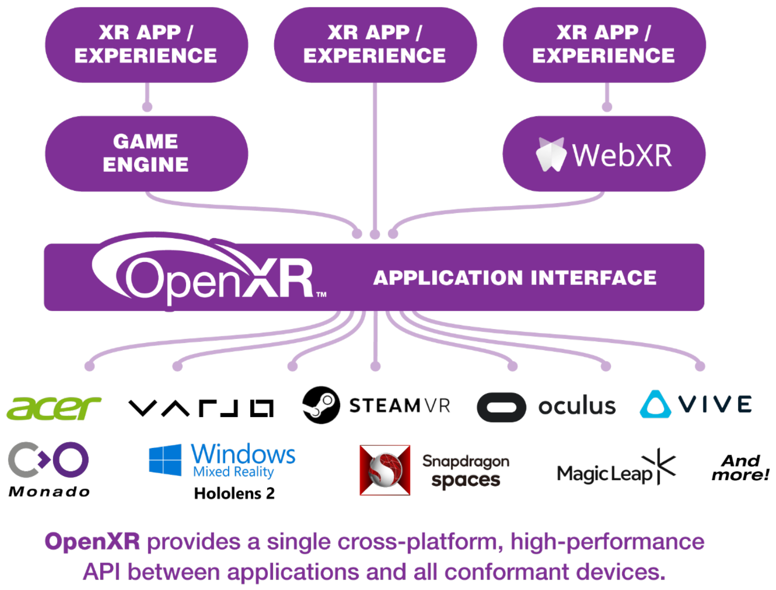


Figure 3.2: Cross platform development overview with OpenXR

3.1.2.2 Game Engine Development

A game engine offers the easiest path for the Hololens 2 development since it already has lots of integrated support for physics, animations, sound, and UI development. When we start developing our project (August 2021) both Unity and Unreal game engines were supported by Microsoft for mixed reality application development. However, at that time, Unity was better supported by Microsoft compared to Unreal. Throughout time, Microsoft managed to close this gap by adding more support to the Unreal engine. However, even today (February 2023), some mixed reality features such as world locking tools, Azure Object Anchors, and Azure Remote Rendering are not supported for Unreal but have support for Unity. Therefore, we chose Unity (version 2021.1.14f1) as our game engine. For the cross-compilation to the universal windows platform and ARM64 architecture, we used windows 10 SDK version 10.0.19041.0 and visual studio 2019 with the UWP toolkit.

3.1.2.3 Other Software

We intend to make this project open source and bring more developers and researchers to further develop it. Therefore, we developed extensive documentation using the Doxygen tool which generates automatic documentation. Figure 3.3 shows an overview of our documentation website. Furthermore, we used GitHub for version control, Git LFS (Large File Storage) to store large assets such as 3D models and animation files since GitHub does not manage assets greater than or equal 100Mb, and Jira to document issues and milestones. We also created a dev journal explaining our development decisions and highlighting issues. For integration and deployment, we used GitHub Actions and Jenkins. For publishing our code documentation as a website, we use GitHub Pages. For artifact management, we used AWS S3 general purpose bucket. To analyze the system behavior and resource consumption we used Windows Performance Analyzer.

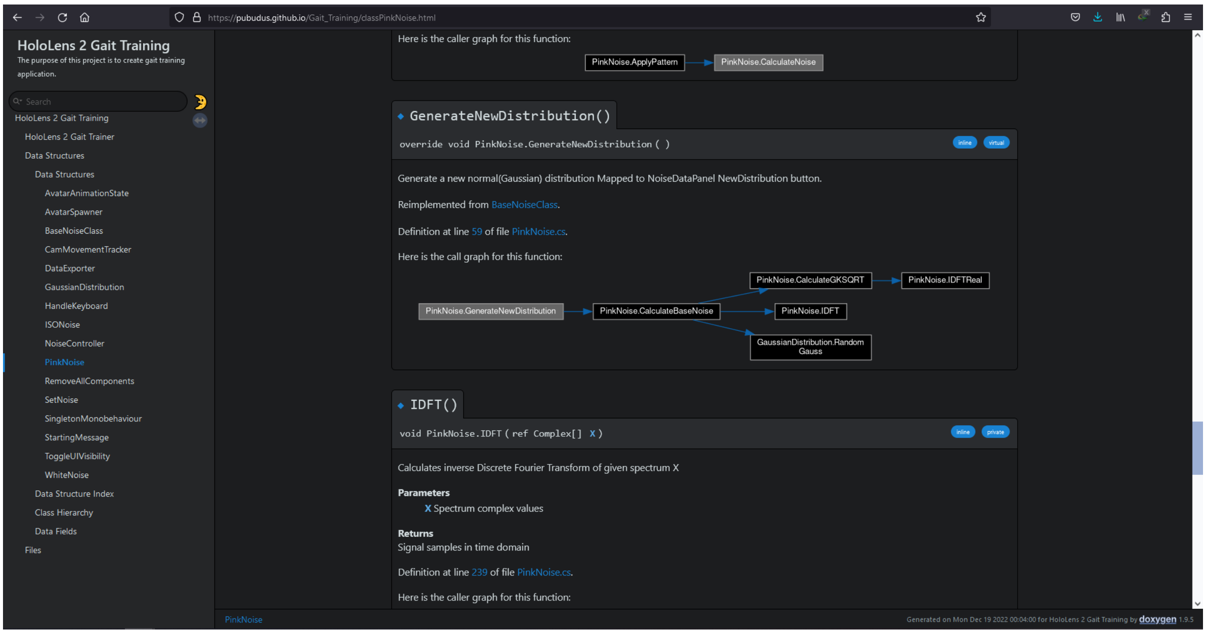


Figure 3.3: Documentation Website Generated by Doxygen

3.1.2.4 *CICD Pipeline*

To enhance our testing capabilities and allow faster deployment of our application to multiple Hololenses, we also developed a CICD pipeline. When the developer pushes new changes to GitHub, it will divide the files and store these in two different locations. This was done because GitHub doesn't allow uploading files large than 100Mb. Therefore, files larger than 100Mb and the files that contain animations, and videos are stored in Git Large File Storage(Git LFS) while code-related files are stored in the GitHub database. Once the upload is finished, GitHub will trigger two triggers in GitHub actions and Jenkins.

GitHub actions will start the Doxygen workflow and generate code documentation website and upload all the artifacts in the gh-pages branch. Once the artifacts are uploaded, the website will be linked with the following domain (`https://pubudus.github.io/Gait_Training/`). This contains all the documentation, caller graphs, and dependencies graphs.

Similarly, after receiving the trigger, Jenkins will use the Unity compiler to compile the project that is compatible with UWP and generates a Visual Studio solution file (.sln). This step compiles C# scripts in Unity to IL2CPP (Intermediate Language To C++) code since Unity uses C# for scripting. After that, Jenkins uses the visual studio compiler and UWP toolkit chain to compile the project to UWP-compatible ARM64 artifacts packed with dependencies, an installer, and a webpage that can be used to download these artifacts. Then, Jenkins will push these to the AWS S3 bucket. The raw link to the index.html page inside the bucket is linked to a QR code. So, by looking at this QR code through the HoloLens users can install the new version in the Hololens. This allows us to rapidly deploy integrate and deploy new changes to multiple Hololenses for rapid testing. Figure 3.4 shows an overview of our CICD pipeline.

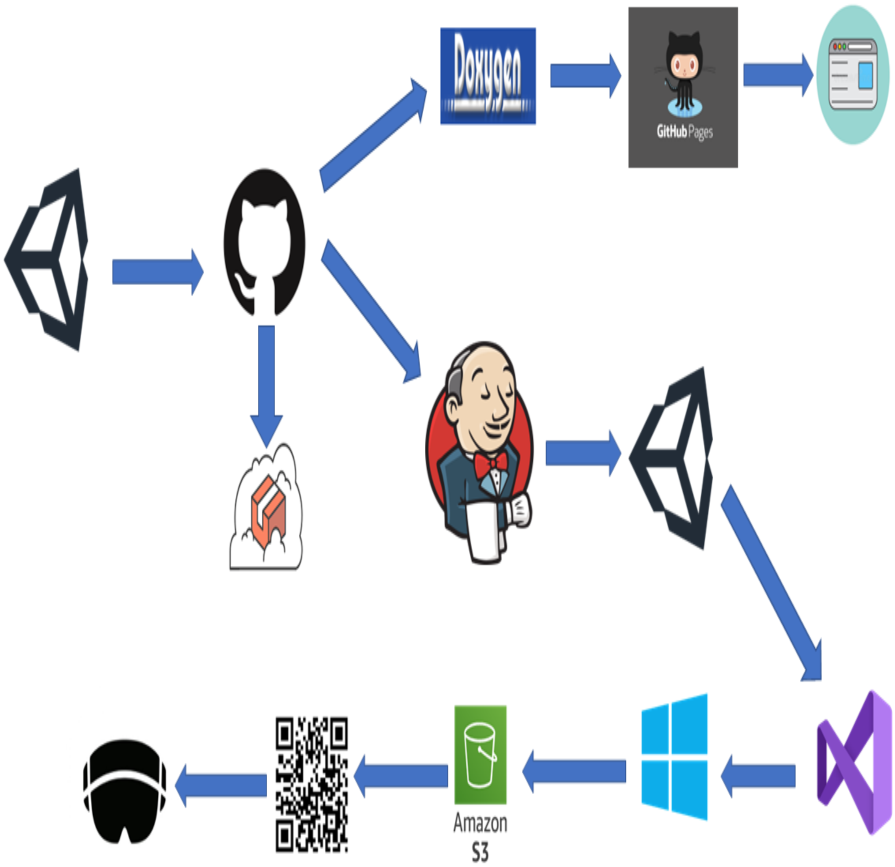


Figure 3.4: CICD Pipeline Process

3.1.2.5 Unit Testing

Unity has a free asset called Unity Test Tools which has many helper utility classes for unit testing. The tool provides an assertion engine that can be used for common errors such as dividing by zero to compare the difference of object state and compare the expected outcome of complex mathematical objects such as quaternions. This tool can be used to cover many unity-specific behaviors such as physics and animation engines.

However, when it comes to the Hololens, we had a hard time coming up with unit tests due to three reasons. The mixed reality is a relatively new concept and Microsoft constantly changes some of the modules. Therefore, it is quite hard to predict expected behavior. Similarly, some functions such as scene understanding heavily rely on multiple factors such as unique shapes in the environment, light conditions, moving objects, etc. These conditions are very hard to cover in test cases and there are so many edge cases which makes it impossible to cover all of these edge cases. Furthermore, Hololens has nontrivial user inputs such as hand gestures, iris recognition, and voice commands. These inputs are also very hard to cover and test edge cases. Therefore, we abandoned the idea of integrating test cases into our CICD pipeline for now. However, with new updates to Hololen's development, we plan to integrate more test cases in the future.

3.1.2.6 The MRTK Framework

The MRTK framework integrates common mixed reality building blocks such as spatial understanding, mesh generation, eye and head tracking, and voice commands to the unity engine. This eases up the development and reduces the development time significantly since the developers don't have to implement complex algorithms from scratch. Since MRTK version 2.7.3 and above, it supports OpenXR. Therefore, it provides a cross-platform input system, and using this a Hololens application can be run on multiple other devices such as OpenVR headsets(HTC Vive / Oculus Rift). This provides a perfect way to use OpenXR without implementing lots of middleware on our own. Therefore, we use MRTK 2.7.3 in our system to increase its platform independence.

3.2 Overview of our avatar based gait training system (RQ1)

Before providing gait training, a gait analysis must be done to identify the variables such as the stride length of the patient. In our system, the gait analysis path is done separately by using existing systems such as the treadmill or motion capture. After recognizing the variables, the patient has to input that into our system and select an appropriate pattern to train. Then our system will generate frequencies for that pattern. After that, the patient can select an avatar they like from a diverse pool of avatars. Once the avatar is spawned, when the patient starts moving avatar will also start walking in

Software	Version	Purpose
Unity	2021.1.14f1	Provides a 3D engine
MRTK	2.7.3	Increase platform independence
Visual Studio	2019	Provide compiler for UWP
Doxygen	1.9.5	Auto generate documents
Git	2.33.1	Version control
JIRA	8.19.0	Project management
GitHub Actions	Auto update to latest	Publishing the website
AWS S3	Auto update to latest	Storing artifacts
Git LFS	3.0.1	Managing large files
Jenkins	2.346.3	Build artifacts
Windows Performance Analyzer	10.0.19041.1	Benchmark

Table 3.1: Software toolkit used for development.

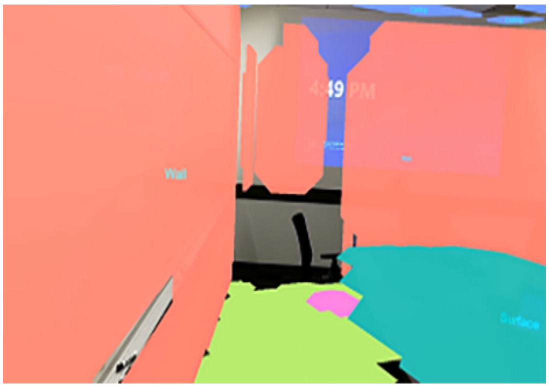
front of the patient mimicking the healthy gait pattern. Each gait cycle (time between the heel strike of one leg and the heel strike of the contralateral leg) will be extended or shrink based on the frequency. For instance, if the frequency is 2.781, a gait cycle will be completed in 2.781 seconds. After walking the desired period of time for the desired time frame of the exercising patient can improve their gait pattern through the proteus effect and complexity matching and reduce the risk of falls.

3.3 Scene Understanding Version with AI Navigation

3.3.1 Overview of Scene Understanding

To design environmentally aware applications and place objects in the environment, Hololens provides two mechanisms spatial mapping and scene understanding. Spatial mapping system has low latency than scene understanding. However, scene understanding is more accurate at the cost of higher latency but allows developers more high-level processing functionalities. Furthermore, scene understanding also includes the spatial mapping mesh as part of its output.

One advantage of scene understanding over spatial mapping is it can be used without scanning the entire environment by enabling inference. When using the meshes obtain through spatial mapping, developers need to write code to post-process the data and identify the unscanned area and fill those areas. The scene understanding can intelligently fill the unscanned areas and invalidate areas that aren't part of the surface. Figure 3.5 shows the difference in auto-filling unscanned areas.



(a) SceneQuads with inference disabled, unscanned areas are not filled

(b) Quads with inference enabled, unscanned areas are filled

Figure 3.5: Scene understanding automatic area filling

Our early iteration of the system used the spatial mapping system due to its lower latency. However, with the new updates to the MRTK framework Microsoft stop supporting spatial mapping API in favor of scene understanding. Therefore, we integrated scene understanding to map the environment.

3.3.1.1 Scene Objects

Hololens 2 constantly learn information about the environment by analyzing data from multiple data streams such as visible light cameras, infrared cameras, and depth cameras. Scene understanding uses this data to generate scenes, which are constructed by using scene objects. The scene object represents a single thing in the environment such as part of a wall, ceiling, or floor. Scene objects are purely geometric and only store the data about their location in the space. When in need of more data such as the logical structure of the object, scene objects can refer to scene components to get these data.

Scene Object	Description
Background	Background refers to objects that are not known to be walls, floors, ceilings, platforms, or worlds.
Wall	A wall in the environment
Floor	Any surfaces on which one can walk.
Ceiling	A ceiling in the environment
Platform	Geometric data agnostic to labels
World	Project management
Unknown	A kind has not been assigned to this scene object

Table 3.2: Scene Objects in Scene Understanding.

3.3.1.2 Scene Components

Scene objects are a composition of scene components. These are basic building blocks in scene understanding such as meshes, quads, and bounding boxes. Each of these scene components can be updated independently and can be referenced by other scene components.

3.3.1.3 Scene Mesh

A SceneMesh is a type of SceneComponent that represents the shape of different objects using a triangle list. It can be used to represent the structure of cells or as the WorldMesh, which represents the unbounded spatial mapping mesh associated with the Scene.

3.3.1.4 Scene Quad

A SceneQuad is a scene component that represents 2d surfaces that occupy the 3D world. They can be used to place a hologram. An example would be to scan a room and extract a platform quad that matches the hologram's area, then place it on top.

3.3.2 Unity NavMesh

NavMesh component in the Unity engine allows developers to label walkable and unwalkable areas. The NavMesh has an AI component called NavMesh Agent which can utilize this map of the walkable area to calculate the most efficient path while avoiding obstacles. Figure 3.6 shows a navmesh baked into a floor area.

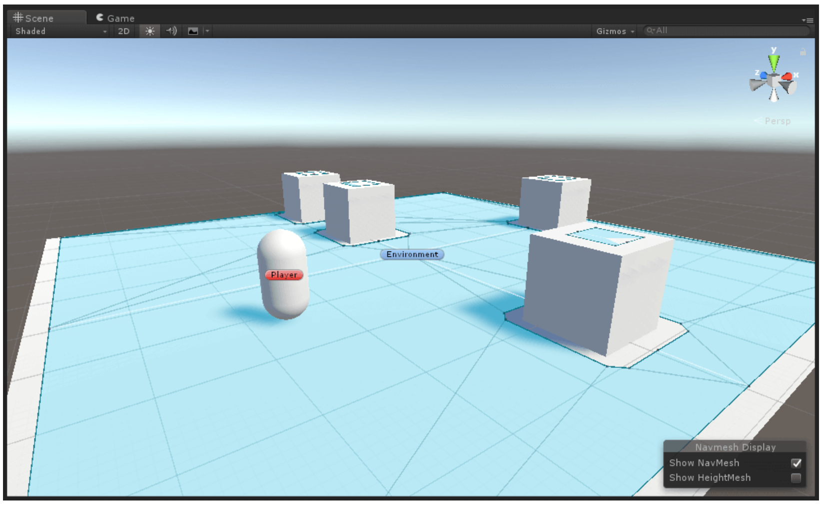


Figure 3.6: A NavMesh baked into the floor area

3.3.3 Scene Understanding Version Design

In this version of our system, we combined the scene understanding with NavMesh. Through scene understanding, we obtain the scene objects of floor, wall, and the areas of other objects occupying the floor area. Then we baked NavMesh to the scene quads of these objects. Walls and objects that occupy the floor area were marked as unwalkable and the floor area that remains free of obstacles was marked as a walkable area. Then using the NavMesh agent we code our avatar to avoid occupied areas and calculated the most efficient path for walking considering the user's body rotation. When the user starts moving avatar will also walk 2 meters in front of the user and it also matches the user's rotation. For example, if the user turns right, the avatar will also turn right. Using this method, the avatar can avoid any obstacles in the environment and simulate natural walking.

We also considered sudden environmental changes such as people moving around the environment. To avoid the avatar colliding with moving people other than the user, we baked NavMesh dynamically. For example, each time something new happened in the environment, our algorithm created a new NavMesh marking the walkable and unwalkable areas. So, the AI agent is aware of the new changes and can calculate the new path. For example, if another person comes toward the avatar, it will recognize that and calculate a new path avoiding that person instead of going through the person. The scene understanding system worked as intended but we found several challenges. Figure 3.7 shows what the user sees when using our application version with scene understanding. Appendix A.1 includes links to source code and documentation of all the versions. Appendix A.3 includes a link to a video demonstration of this version as well as other versions.

(a) Female avatar standing on top of walkable area

(b) Male avatar standing on top of walkable area

Figure 3.7: Scene understanding view of the environment. The colored area is just to visualize scene objects. In our actual system user's can see the real environment without these colored areas

3.3.4 Problems in Scene Understanding Version

The process of analyzing and processing multiple raw data streams from sensors and converting that into a scene is a very expensive operation. Microsoft realized this problem and integrated a custom multiprocessor called Holographic Processing Unit (HPU) in Hololens 2. The HPU is responsible for processing all the sensor data such as depth sensors, visible light and infrared cameras, and inertial measurement unit (IMU).

In this way, the HPU takes out the burden of this data processing from the Hololens CPU and allows it to focus on other things.

However, even with the HPU, converting raw data into a scene can take a few seconds to a few minutes depending on multiple factors. The size of the room can increase this latency. For example, when we test this version, we tested in multiple rooms. For a medium space such as 10x10 meters, it takes a few seconds, for 50x50 meters it takes time closer to a minute. For the patient testing, we used 3 lanes 1/8 miles (201 meters) of indoor track. The ceiling height of this ranges from 3.6 - 5.0 meters. In this environment, the lagging increased significantly.

To fix that problem, we limited the scene understanding to recognizing only floor, wall, and background elements in the environment. This reduces the lagging but not by a significant amount. Therefore, we altered our algorithm to cache the static scenes so the system does not have to recalculate that. However, due to the large size of the environment, it occupied the large size of available memory and slow down our application significantly, and increased the occasional crashes. Furthermore, when the room has lots of static objects or moving objects the processing time also increases. In an environment with lots of movement, our algorithm baked a new NavMesh each time it detects a new movement to keep track of moving objects' position, rotation, and scale. This further increased the processing time.

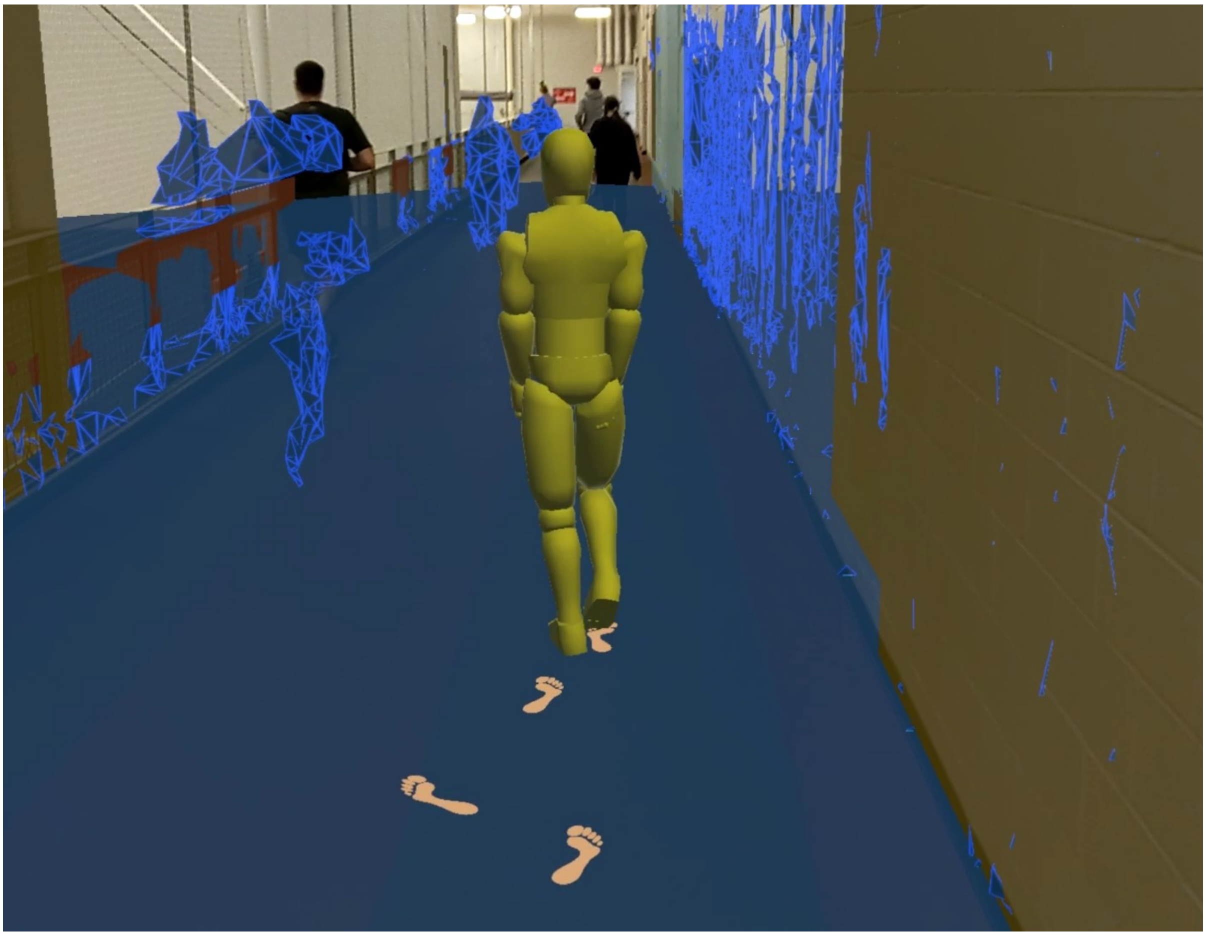


Figure 3.8: Ghost meshes left behind by joggers

As a result of this latency, ghost meshes also became a problem. Whenever someone is moving in front of the user, our system covered the area with a mesh to alert the avatar to void the collisions. Due to the increased latency of processing time, these meshes updated very slowly. In other words, even if the person in front of the user has walked away, the previous mesh will still show an obstacle that does not actually exist. Figure 3.8 shows ghost meshes left by joggers.

Furthermore, scene understanding is a Hololens-specific feature. One of our key goals for this application is to make it platform-independent as much as possible. Therefore, we develop it on top of OpenXR to allow it to run on multiple devices. However, since scene understanding is a device-specific feature, if we use that it will effectively eliminate the platform-independent nature of our application. Because of these problems, we decided not to move forward with this approach and focus on a new approach.

3.4 Way Points Version Design

In our next iteration of the project, we removed the scene understanding and NavMesh components from our system. To understand the environment, we switched back to a spatial mapping system due to its lower latency, but at the expense of accuracy. This version involves a calibration period where users need to define the path each time they open the application. We created a UI to allow users to place waypoints to define the path. After that, the avatar will move from waypoint to waypoint until the user reaches the destination and then reset, allowing the user to continue exercising. Figure 3.9 shows what the user sees in our waypoint version.

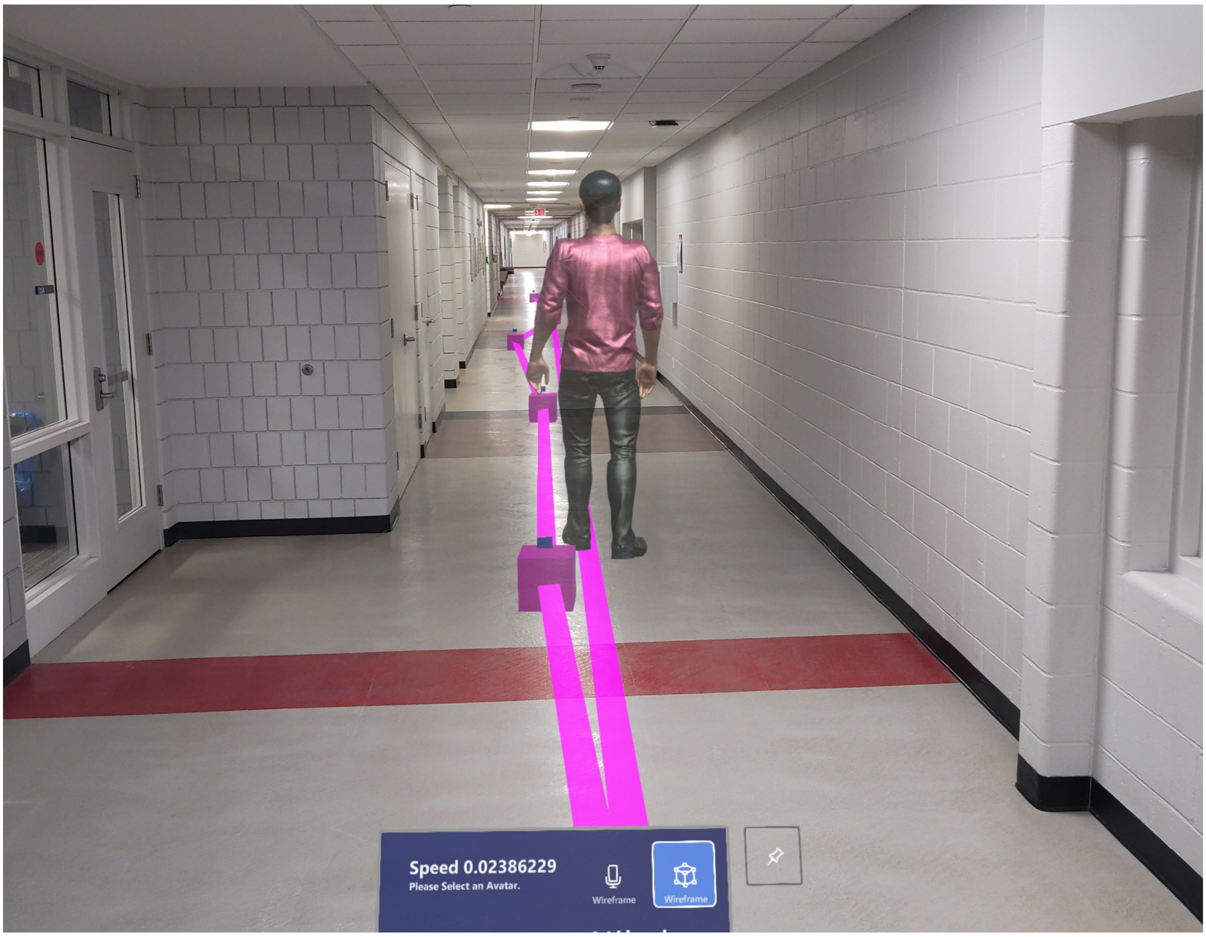


Figure 3.9: Way point system

3.4.1 Problems in Waypoints Version

When testing this version, we noted that waypoints often drifted around the intended positions. Most of the time, this happened due to three reasons. When Hololens starts collecting data about the world, it actually estimates distances between Holograms. The more data is analyzed Hololens adjust these estimations to actual distance. For example, when the application when places a waypoint, it might estimate that the distance between the waypoint and the nearest wall is 0.3 meters. When it learns more about the environment, however, it may update the initial estimate to an actual number, such as 0.4 meters. When that happened Hololens pushes the waypoint 0.1 meters away from the wall to match the actual distance.

The second reason this may have happened is because of different lighting conditions, which we will discuss in more detail in the limitation section. When there are different light conditions such as brightness differences, and natural vs artificial light combinations, can confuse the Hololens tracking system. For example, if you are entering from a well-lit area to a dark corner, Hololens might get incorrect information about the position and rotation of objects. Thirdly, when the holograms are placed outside a 5-meter diameter from the device, it struggles to track and maintain the positions of these holograms.

To fix this problem, Microsoft introduced spatial anchors. A spatial anchor preserves the coordination of a point in the world that the system tracks over time and stores in a cloud. We didn't use this method due to two reasons. One it makes our system depend on an internet connection. Two, Microsoft advised against creating a grid of spatial anchors because it involves more management for the application [53]. Therefore, we decided to move forward with another solution.

3.5 Follow Me Version Design

To render highly dynamic holograms such as our moving avatar, Microsoft recommends using the stationary frame of reference instead of a spatial anchor [53]. In a stationary frame of reference, the coordinate system maintains the position of objects near the user as accurately as possible while respecting changes in the user's head position within a 5-meter diameter around the device.

Holograms in a stationary frame of reference might experience drift when the user is far beyond the 5-meter diameter of the hologram. We fixed this by making our avatar locked to 1.5 meters in front of the user. The avatar will always spawn and stay within this boundary preventing any drifting issues. When the user starts moving forward avatar will also move forward and stop when the user stops moving while respecting the 1.5-meter boundary. Furthermore, the avatar matches the user's head rotation. So, if the user turns left or right, the avatar mimics the same movement. Figure 3.10 shows what the user sees in our follow me version.

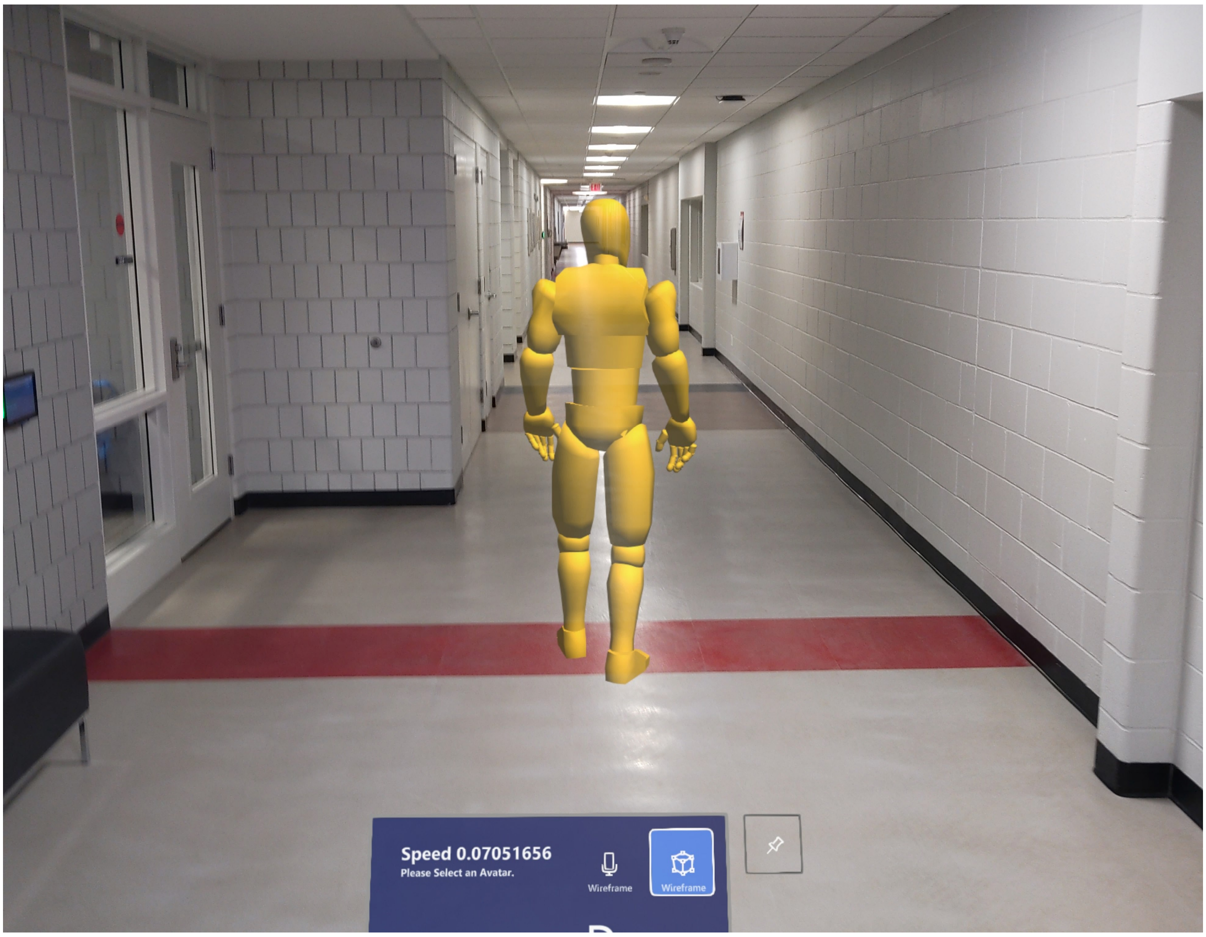


Figure 3.10: Follow me system

Compared to the other versions, this version is more simple to implement but offers a high-performing system with low latency. Since we only scan the 5-meter diameter, the application does not need to scan the entire room and the users do not have to place waypoints to define the path. The user can simply wear the headset to start the exercise immediately without any lagging or slowing down the system. This also decreased the batter consumption significantly because of low processing stress. Therefore we ended up using this version.

3.6 Design and Implementation of colored noise

The colored noise algorithms were initially designed by the Bio-Mechanics department of the University of Nebraska at Omaha. The scripts were written in MatLab. Since Hololens doesn't run Matlab scripts, we needed to find a way to port this to the Hololens. We found 3 ways to do that. Since Hololens operating system is Windows 10, The Microsoft Component Object Model (COM) which allows integrating reusable binaries into applications. However, to do this a Matlab instance need to be running on the Hololens. Since Matlab does not run on Hololens we eliminated this method. The second option is to compile Matlab assembly code to .NET assembly codes and integrate that into our application. Performance wise this is an expensive process. Therefore we eliminated that option too. The other option is to compile Matlab code into the C/C++ library and then use that in the C# class using P/Invoke. This is also very expensive performance-wise. Therefore we decided to implement core Matlab functions in native C# and implement the same algorithms. This allows us to optimize these algorithms in the native C# level.

3.6.1 White Noise

The white noise function is nothing more than a normally distributed random number. In Matlab, there is a dedicated function randn() that generates normally distributed random number sequences. However, in Unity C#, the random number generation returns uniformly distributed random numbers. Therefore, we implemented a new class in C# that uses the Box-Muller transformation to generate the normally distributed random number sequence. This transformation takes two uniformly distributed deviates within the unit circle and transforms them into two independently distributed normal deviates. Our implementation returns a similar result compared to Matlab.

$$y = \mu + \sigma * (\sqrt{-2\lg(X_1)}\cos(2\pi X_2)) \tag{3.1}$$

where $\mu = 0$, $\sigma = 1$, and X_1, X_2 are two uniformly distributed deviates within the unit circle. Figure 3.11 shows the statistical characteristic of the white noise signal. The result of the C# implementation and the native Matlab implementation is shown in figure 3.12.

As we age the structure in our physiologies breaks down and we tend to exhibit more of a white noise signature in things like heartbeat and stride intervals. White noise maintains equal power across all of its frequencies resulting in a static rhythm. White noise promotes a random hard to predict pattern. In our experiment, we use this to see how it affects young healthy participants.

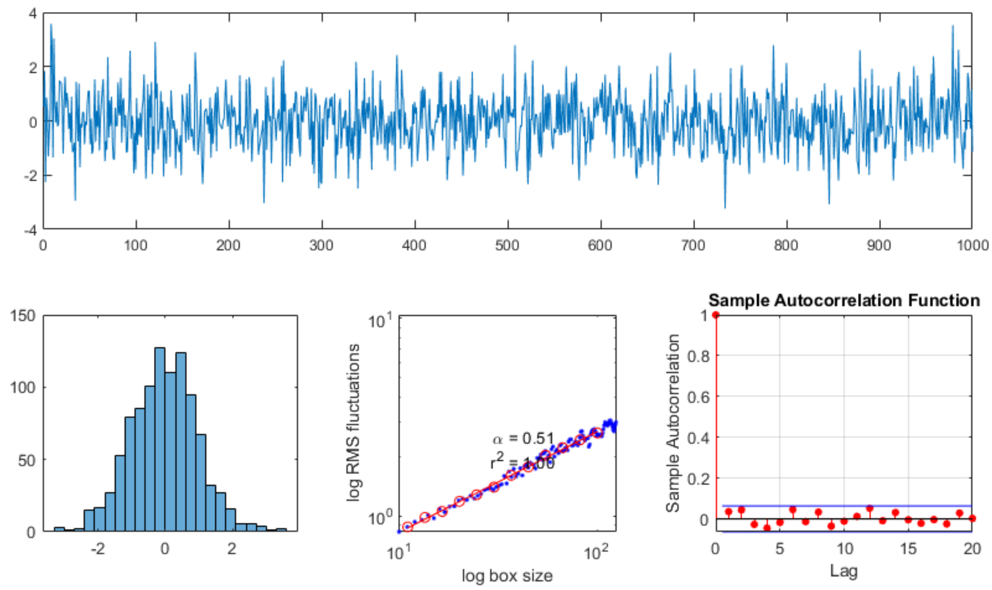


Figure 3.11: White Noise

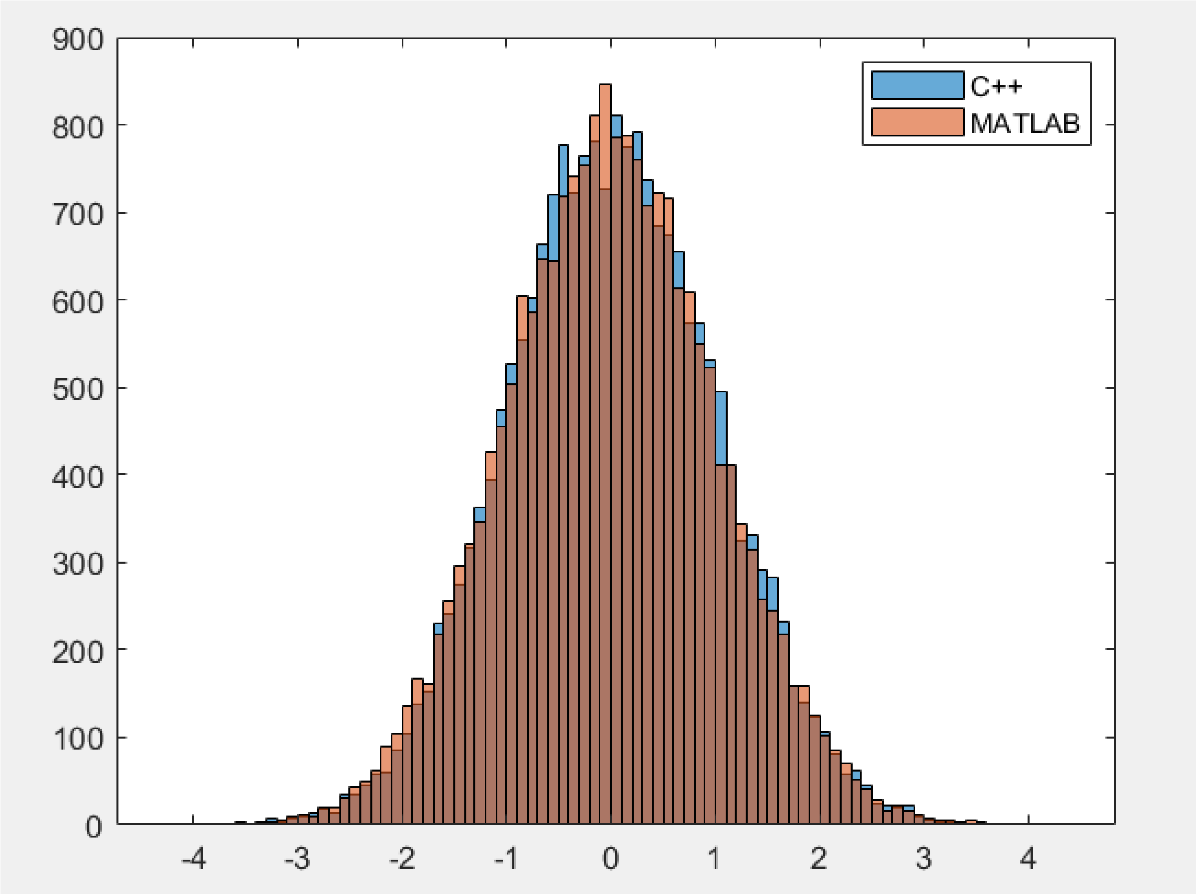


Figure 3.12: Comparison between Matlab vs C# normal distribution

3.6.2 Pink Noise

A few decades ago, people became interested in studying how different events or values in a series of data are related to each other over a large time scale. This was important for medical sciences, economics, and many other scientific fields. At first, researchers were concerned about short-term dependencies which means the current value has dependencies with the previous value or a few consecutive previous values. In time, however, researchers have learned that, in many cases, the value of the current value in a series is not just based on the value immediately before it, but also on the value from further back in time. This pattern can repeat at different time scales, like hours, days, weeks, or years. This means that the current value remembers the values that came before it, and this is called long-term memory, long-range dependence, fractal process, or 1/f noise.

Throughout time, researchers discovered that 1/f noise emerged in many complex systems and situations. For example, Kobayashi et al discuss how 1/f noise has been found in the heartbeat series [54]. Similarly, Hausdorff et al show how 1/f noise emerges in stride time series [55]. Gilden et al also presented credible evidence of how 1/f noise is associated with cognitive processes [56]. Furthermore, Diniz et al presented a solid analysis of 1/f noise and how it relates to motor control [57]. The interest in 1/f noise peaked upon the discovery of its relationship with health. The 1/f noise can be used as a key indicator of health, and is generally present in young, healthy systems performing easy tasks and tends to disappear with aging or disease [58].

We design the Pink noise according to this principle. It is a signal with a power spectral density inversely proportional to the frequency. Figure 3.13 shows the statistical characteristic of the pink noise signal. Using the data we gathered during gait analysis, we generate a personalized pink noise pattern for each user. Then we apply the noise to the avatar animation so that when the avatar walks each gait cycle will simulate different speeds. The change in speed is directly related to the standard deviation of stride times obtained from the first self-paced trial. That is, the speed does not exceed the range of speeds observed from the participant's self-selected cadence. In line with our study, Hunt et al provide credible evidence that shows young and healthy adults who walked with pink noise cues exhibited a stride-to-stride time interval variability that resembled that of un-paced natural walking [59]. Therefore, this module was created with the aim of facilitating implicit learning through the use of the proteus effect and complexity matching techniques, in order to train users to restore their natural gait by adopting the pink noise characteristics.

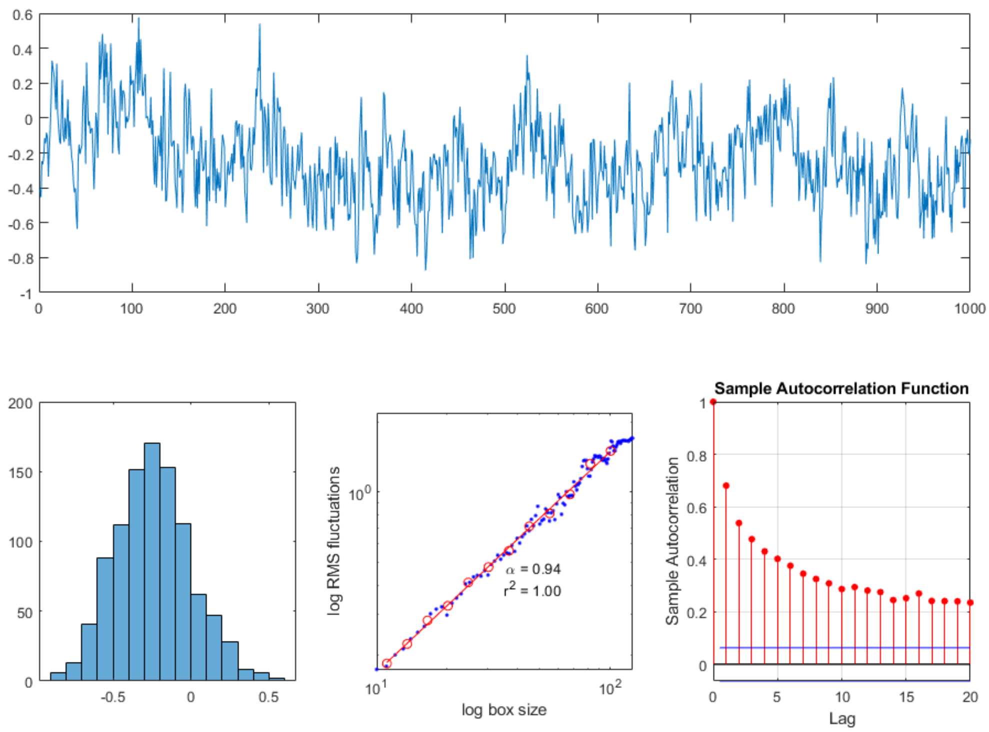


Figure 3.13: Pink Noise

3.6.3 ISO (Isochronous) Noise

Isochronous noise is the simplest noise in our system. It is a constant value without any variations. Isochronous noise introduces a stable and predictable rhythm that can help patients with gait disorders to synchronize their steps and maintain a steady gait pattern. Spaulding et al presented credible evidence that isochronous noise can be particularly effective in improving gait speed and stride length in individuals with Parkinson's disease, stroke, and other movement disorders [60]. Furthermore, isochronous noise can help individuals to overcome the freezing of gait, improve their balance, and reduce the risk of falls.

In our system, this is implemented as nothing more than a constant variable. At the start of the app, the user needs to enter a value and throughout the lifetime of the system, this value is maintained as a constant.

3.6.4 Design of the Noise Module

We design the colored noise algorithm with portability. We achieved portability by abstraction. We developed an abstract base noise class that has all the necessary Matlab functions to generate colored noises. Through this base class, Pink, White, and ISO color noises can be derived and extended in their functionality as shown in figure 3.14. Similarly, if we need more colored noises in the future such as Brown noise, we can simply derive it from the base class without implementing all the core functionalities.

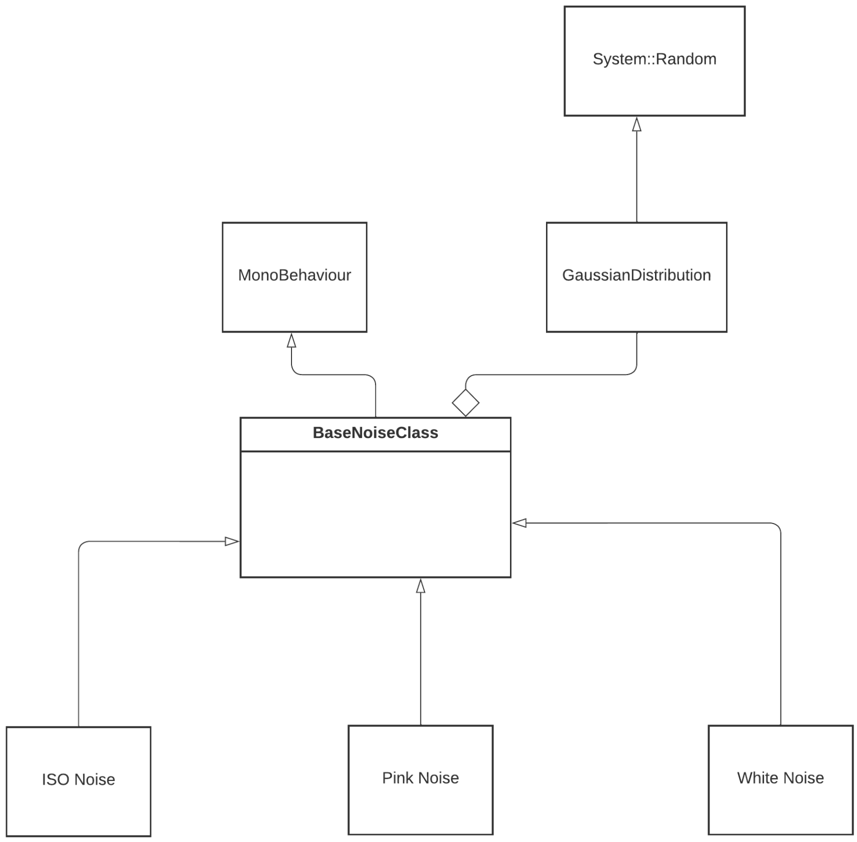


Figure 3.14: Noise module designing

3.7 Coupling Noise with Animations

The next challenge we faced was how to alter our animation with the frequency of the selected noise. We need to apply the relevant frequency to each gait cycle (time between the heel strike of one leg and the heel strike of the contralateral leg). For example, if we have frequencies like 1.15, 2.28, etc, the first gait cycle must be completed within 1.15 seconds and the second gait cycle must be completed within 2.28 seconds, and so on. This was challenging because unity's traditional animations are predefined and hard to alter without breaking them.

To solve this problem, we started to experiment with procedural animations. Unlike traditional animations, procedural animations are not predefined. Procedural animations are driven by code and can be generated procedurally. Thus, we can generate each gait cycle that is completed within the given frequency procedurally and apply it to our avatar. Even though the idea behind it looks promising, procedural animations have a steep learning curve that involves complex mathematics and physics. We did manage to create a prototype that alter each gait cycle. However, the walking pattern was too mechanical and did not feel natural. Since the efficiency of the Proteus effect and complexity matching relies on realism, we had to abandon this idea.

In order to add realistic walking motions, we decided to use traditional animations. To capture the realistic animations, we used an Xsens motion capture body suit and software kit. A researcher wore the suit and walked on over the ground simulating a specific noise for 40 minutes and the motions were recorded at 60Hz. We recorded three animations each lasting 40 minutes for all three noises. Then these animations were processed to clear any anomalies and then converted to .fbx format to use in unity.

We did not find a way to alter each gait cycle in the entire 40 minute long animations. We developed another way to work around this problem. Instead of using a long animation, we sliced a single gait cycle with a length of 1.18 seconds. Then using the unity animator speed component we manipulate the playback speed of the gait cycle. This method allows us to expand and shrink the gait cycle according to the frequency. This worked well while preserving the natural order of the walking motion, unlike procedural animation. Furthermore, code is more readable, simple, and easy to maintain than procedural animation. Figure 3.15 shows the function that changes the gait cycles.

```
float animationLength = 0.0f;
bool isValidAnimLength = m_OriginalAnimationLength.TryGetValue(m_NoisePatternLbl, out animationLength);

if( isValidAnimLength && noiseValue != 0 )
{
    desiredSpeed = ( animationLength / noiseValue );
}

m_IsAnimationLocked = true;
m_Animator.speed = desiredSpeed;
m_NoiseDataPanelTitle.text = m_NoisePatternLbl + " Noise = " + noiseValue;
```

Figure 3.15: Function that changes gait cycle

3.8 Gait Metronome Design (RQ2)

We also designed another application that provides gait training using another method. In this version, instead of following an avatar, the user has to observe visual cues from a rhythmic metronome. In this version, the metronome was designed as a rectangle cube that moves between upper and lower cubes. A full cycle (A time between leaving from the lower platform to return to the same platform) is completed with a relevant noise frequency. In this version, we asked patients to do a right heel strike when the bar reaches the top bar and a left heel strike when it reaches the bottom bar. Most of the UI design, noise calculation module, and altering of the animation module is the same as our avatar version. The only difference between these two versions is the modality of providing the visual cues, avatar vs rhythmic visual pattern. Figure 3.16 shows the user's view of our rhythmic gait metronome.

Figure 3.16: The design of our rhythmic MR-based gait metronome running on Hololens 2. The right heel strike should happen when the moving bar reaches the top bar and the left heel strike should happen when it reaches the bottom bar.

Previous research was also conducted to study how rhythm can affect the gait patterns of patients. For example, Thaut et al looked at how patients with Huntington's disease (HD) are able to control their walking speed without external cues, and how they respond to rhythmic cues from a metronome and music [61]. First, the researchers recorded 27 patients' normal gait patterns without providing cues in normal, slower, and faster self-paced walking. Then they delivered 10% slower and 10-20% faster musical beat patterns with a metronome while patients are walking. After that, patients were retested without rhythm at normal gait speed. researchers found that patients with HD had slower walking speeds than normal, but were still able to modulate their walking speed in response to both self-paced walking and rhythmic cues. However, patients had more difficulty with the rhythm of music than a metronome, and their ability to synchronize with a rhythm deteriorated as the disease progressed. Overall, the study suggests that patients with HD can modulate their walking speed with rhythm cues, but may have difficulty with rhythm and synchronization as the disease advances.

Similarly, Ghai et al carried out a systematic review and meta-analysis on 50 studies that involves 1892 patients [62]. The researchers analyzed the effects of different auditory feedbacks on gait and postural performance in Parkinson's disease patients.

According to the study, rhythmic auditory cueing improved gait velocity and stride length, but negatively affected cadence. As an adjunct to medication, cueing is also discussed, as well as the underlying neurophysiological mechanisms. The study suggests that the use of auditory cueing can be used as a rehabilitation approach to enhance motor performance and quality of life in the Parkinson's disease community.

In line with our work, Zhao et al also experimented with how both visual and auditory rhythmic cues affect patients with Parkinson's disease [63]. For their experiment, they use google smart glass and created a custom application. For the trials, 12 participants participated and the researchers analyzed a few key gait parameters such as walking speed, cadence, stride length, and stride length variability. The established baseline condition is walking without any visual or auditory cues. For the other trials, participants had to complete several walking tasks with different complexities, and their motion was captured by 7 sensors attached to their legs. The user experience was also evaluated through semi-open interviews. The results showed stable gait patterns emerged with cues, especially on complicated walking courses. However, this didn't affect the freezing of gait significantly. They also noted that more effective than rhythmic visual cues and was preferred by the participants. Furthermore, participants were positive about their overall experience and expressed willingness to use this technology at home. Therefore, researchers highlighted the effectiveness of smart glasses to provide personalized mobile cueing to prove gait training. The above researches show that using rhythmic cues for gait training is a viable option.

4. Evaluation and Discussion

4.1 Mixed Reality and Motor Learning Principles

4.1.1 Focus of Attention

In traditional gait training, patients often receive explicit instruction from the physical therapist. According to motor learning literature, this instruction promotes internal focus. This diverts the patient's attention to the movement and promotes deliberate and conscious movements which go against the natural movement resulting from automatic motor control. For example, Johnson et al conclude that instructions that promote internal focus reduce automaticity and hinder learning and retention [64]. Contrary to the traditional systems, our system uses complexity matching and the proteus effect which promotes external focus. This allows patients to walk naturally without reducing automaticity.

4.1.2 Implicit Learning

The traditional way of teaching new motor skills is by giving explicit instructions. However, this may interfere with automatic processes and lead to worse performance, especially under pressure. There is evidence that implicit learning, which is not necessarily conscious of what is being learned, may be more effective in gait training [65–67]. Implicit learning can be promoted through an external focus of attention, concurrent cognitive tasks, or by providing variations in the task at hand. Both versions of our system promote implicit learning and external focus of attention. Therefore, we argue that it provides a unique opportunity to increase the efficiency of gait training.

4.1.3 Training Intensity

The training frequency of gait exercises has an important role in gait training. To maximize the efficiency of gait restoration, high-intensity training is often required [68]. However, gait training often involves repetitive tasks which can quickly become boring and reduce motivation, especially in pediatric gait training. Our system can provide a solution to this problem. Since our system has superior mobility compared to the cumbersome gait training systems, it can be deployed in different environments which simulate different gait training challenges. Furthermore, since we have implemented multiple noises and a way to customize these noises based on the need, the system can easily provide different walking patterns. Additionally, patients can use this system in their homes or more comfortable environments without the need to travel to a specialized environment. Based on these, our system can increase the training intensity and maintain high morale throughout the exercise time.

4.2 System Performance

We evaluated our system performance using the Windows Performance Toolkit which is a part of the Windows Assessment and Deployment Kit. The Windows Performance Toolkit has a powerful recording tool called Windows Performance Recorder (WPR), which can be used to record in-depth performance data about resource consumption and system and application behaviors. It also provides a helper tool called Windows Performance Analyzer (WPA) which can be used to analyze and visualize the performance data recorded by WPR. These tools can be used to perform detailed event tracing and visualize system performance on Windows devices running Windows 8 or later operating systems with .NET 4.5 or later versions. However, in order to record a specific scenario, the user must create a custom profile using XML schemas and specify what data WPR should collect. Therefore, we created a custom profile to pull and record HoloLens 2 system performance data. Using this profile, we recorded multiple system trace data logs.

After generating an ETL trace file, a user can perform basic analysis and visualization using the Windows Performance Analyzer tool or using the command line. However, this option is not suitable to analyze multiple trace files and their recurring patterns. Therefore, we created a helper program using Java and wpaexporter, which can iterate over multiple ETL files and convert the data into CSV files. Then using python, we created scripts to go through these data logs and graph the performance data for better visualization. The links to our helper tool and the ETL records are also provided in the Appendix A.2 section. Figure 4.1 shows the GUI of our ETL to CSV converter tool.

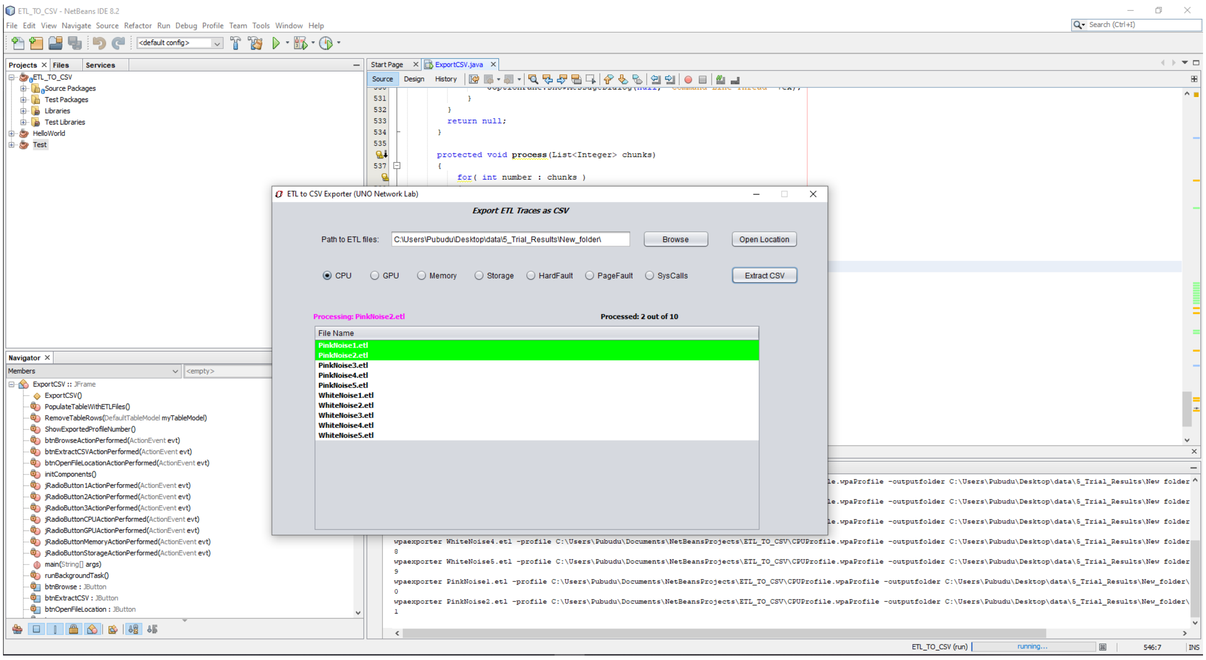


Figure 4.1: ETL to CSV converter

4.2.1 Benchmark Data

For the purpose of the benchmark, we collected 5 traces of pink noise and 5 traces of white noise. Since ISO noise is nothing more than a constant value, we ignore ISO noise. After starting the application, we generated 5000 samples of noise, applied them to the avatar, and walked with the avatar for five minutes while capturing the ETL traces. After capturing the ETL file, we restarted the entire device before capturing the next trace in order to flush the cached data from the memory. After gathering the traces, we export them into CSV files and then explore the CPU, GPU, and memory. Both ETL traces and CSV files are available in Appendix A.2.

Hololens 2 has three processors that are responsible for handling the computations. In addition to the traditional CPU and GPU, Hololens 2 has a custom chip named Holographic Processing Unit (HPU). The HPU is responsible for handling all the sensor data, processing images, and tracking user movements. For Hololens 2, Microsoft has integrated an additional AI coprocessor to analyze data using deep neural networks. During our data collection, we did not find a way to record the HPU performance using WPR. Since this is a new custom processor, the WPR was unable to recognize it and collect the data from it. Therefore, our current dataset does not have HPU performance data.

4.2.1.1 CPU Performance

The Hololens 2 CPU is mainly responsible for processing input, animations, physics, and other app logic. Figure 4.2a shows the CPU performance of our application. Even though pink noise generation involves more mathematical operations than white noise, our results demonstrate that white noise consumes slightly more amount of CPU power. The cause of this can be attributed to two main factors. When generating pink noise, it blocks other threads for a few seconds (3-4 seconds). This might be the reason behind the differences. We tried to address this using coroutines in Unity. The basic idea was to spread the calculations over several frames instead of one frame. Additionally, we attempted to make the function asynchronous. Both attempts complicated the code and also introduce some unpredictabilities like occasional crashing. Therefore, we decided not to use these and leave them as it is for the current version. After initial patient testing is over, we plan to use the Unity Job function to run the calculations in a separate parallel thread. A second reason might be the randomness of white noise. In comparison to pink noise animation, white noise animation tends to move faster and slower in a totally random manner. Since the CPU handles the animation engine and animation state transitions, this might consume more CPU resources.

4.2.1.2 GPU Performance

The Hololens 2 GPU is responsible for handling the graphic pipeline. Our results as illustrated in figure 4.2b shows that pink noise consumes slightly more GPU power than white noise. It handles various tasks such as pixel manipulation, handling draw calls, and converting data into 2D and 3D shapes. Even though our results show that pink noise consumes more GPU power than white noise, the consumption of GPU resources depends on many external factors. For example, our system matches the user's movements and rotation to the avatar. This means if the user rotates too much or walks too fast, the GPU needs to redraw the UI elements and avatar to match the position and rotation. Furthermore, environmental factors also can affect the rendering of the virtual elements. In the case of an avatar that is behind a table or covered by a ghost mesh, the GPU will not render the part of the avatar that is covered by the object. As a result, the GPU may receive fewer draw calls, which may result in fewer calculations being performed on the GPU.

4.2.1.3 Memory Performance

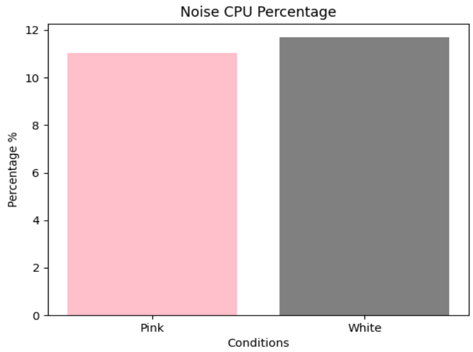
Figure 4.2c shows that both pink and white noise consumes an equal amount of memory. There are two reasons behind this. When Hololens OS detects free available memory, it uses this available memory to maximize efficiency. For example, in this kind of situation, Hololens cache more data in the memory in order to reduce the overhead of reading these data from storage. This means when memory is freely available, Hololens uses more memory than necessary to increase the speed and efficiency. The second reason is when developing our application we used object pooling to reduce the cost of continuous memory allocation and deallocation. As an example, if the user generates multiple noises with the same sample size, the list will be reused instead of allocating new memory every time. To conserve resources, many elements such as UIs and objects are reused throughout the program's lifetime. Furthermore, we used the Singleton design pattern for all the controllers. This prevents controllers from having more than one object throughout the lifespan of the program.

4.3 Patient Trials

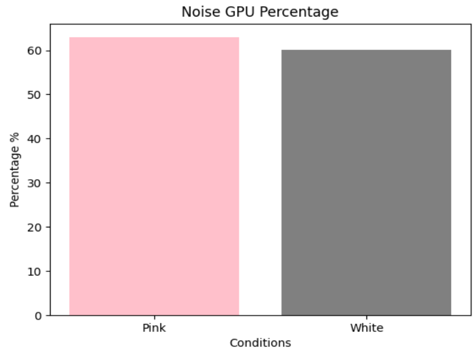
We are still conducting patient trials. The results of our patient trials will be shared with the research community as soon as they are completed.

4.3.1 Gait Analysis

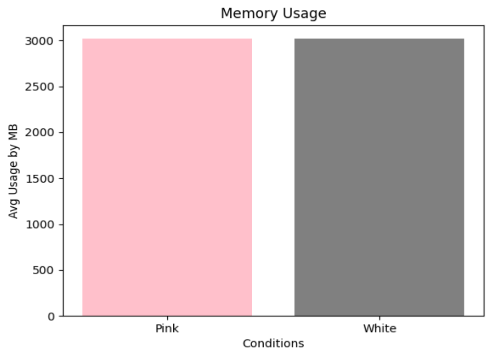
During the first phase of the experiment, we will run a gait analysis of each patient. The goal of this is to identify and collect the unique variables such as stride time and



(a) CPU Performance



(b) GPU Performance



(c) Memory Performance

Figure 4.2: System Performance Data

stride intervals of the patients. Before collecting data we got the IRB approval from the medical center of the University of Nebraska at Omaha (approval numbers #0697-21-FB and #0009-22-EP). Furthermore, all the patients were informed about the data collection and data usage beforehand and we collected their consent. The entirety of the data conforms to the regulations stipulated by the U.S. Health Insurance Portability and Accountability Act (HIPAA). The figure 4.3 shows a sample of gait analysis data of an imaginary patient.

Noraxon MyoMotion Bilateral Gait Side Overlay Report

1

NORAXON™
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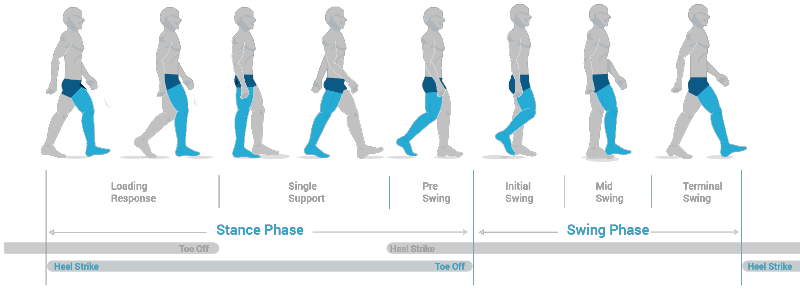
Patient		**Record**	
Project	Gaitprint	Name	HoloLens
First Name	t	Date Measured	12/1/2021 18:50
Last Name	w	Number of periods	384
Sex	Male		

myo MOTION™

Gait Phases



Gait Phase Parameters

Stance Phase, %	**Left**	**61.7±2.2**
	Right	**60.5±2.6**
	Diff, %	**-1.8**
Load Response, %	**Left**	**11.6±1.5**
	Right	**10.5±2.0**
	Diff, %	**-8.9**
Single Support, %	**Left**	**39.5±2.7**
	Right	**38.4±2.5**
	Diff, %	**-3.0**
Pre-swing, %	**Left**	**10.6±2.0**
	Right	**11.6±1.8**
	Diff, %	**10.1**
Swing Phase, %	**Left**	**38.3±2.2**
	Right	**39.5±2.6**
	Diff, %	**2.9**
Double Stance, %		**22.1±2.8**

Gait Spatial Parameters

Foot Rotation, deg	**Left**	
	Right	
Step Length, cm	**Left**	**-6±154**
	Right	**2±179**
	Diff, %	**-130.9**
Stride Length, cm		**-10±334**
Step Width, cm		
Velocity, km/h		**-0.5±10.9**

Attention: for insole recordings. the spatial parameters are calculated assuming a fixed travel distance (as entered in report setup step two period definition)

Gait Time Parameters

Step Time, ms	**Left**	**537±36**
	Right	**567±144**
	Diff, %	**5.4**
Stride Time, ms		**1104±155**
Cadence, step/min		**110±7**

Figure 4.3: Sample gait analysis data of an imaginary patient.

4.3.2 Experimental Design

The study design is a (2 age groups) x (2 modalities) x (3 patterns) experimental design with age being a between subjects variable (young, old) and pattern (self-pace, pink noise, isochronous) and modality (metronome, avatar) being within subjects variables.

4.3.2.1 Modality

The modality manipulation will consist of alternating between either a visual rhythmic metronome or an avatar-based pacing signal. Participants will be randomly assigned to either modality based on the subject number (eg. subjects with even numbers will be assigned to the metronome modality) to ensure the same number of participants are in each group.

The visual metronome condition will consist of two horizontal bars, one at the top of the visual field and one at the bottom. A horizontal timing bar will move between them cueing the participant to perform a right heel strike as the bar hit the upper stationary bar. The left heel strike should happen when the bar reaches the lower stationary bar.

During conditions involving the avatar, participants will be asked to follow the avatar around the 1/8th mile indoor track while walking. The avatar will be programmed to walk at a set distance (e.g. 2 meters) in front of the participant and change speeds which the participants will need to react to in order to keep the predefined distance constant. The change in speed is directly related to the standard deviation of stride times obtained from the gait analysis trials. That is, the speed does not exceed the range of speeds observed from the participant's self-selected cadence. The visual feedback will be given during this task in the form of a color gradient line with red being too close/far and green being the appropriate distance from the avatar.

4.3.2.2 Patterns

There will be two different movement patterns that participants will follow. The first, isochronous, will involve the moving bar going up and down at a constant rate. In this condition, the avatar will also move forward at a constant speed. In the pink noise condition, however, there will be irregularity in the time intervals between when the horizontal bar turns red to indicate a heel strike and the speed at which the avatar moves.

The experimental protocol will be very similar for each modality with the only difference being whether the subject will time their strides based on the moving bar or the avatar's speed. This experiment will be divided into 5 trials for each participant. Each participant will be told during informed consent how many trials they will need to complete. In order to account for the possibility of carryover effects between trials, all conditions (patterns) will be counter-balanced between participants. Each trial has the same basic structure and procedural instructions with only the stimulus pattern changing in each trial. The only exception is the first trial which will always be a self-paced trial so we can use the participant's own preferred walking cadence to personalize the rest of the conditions to them. Each walking trial will be approximately 15 minutes long with at least a 5-minute break between each. This trial length considers the suggested 600 data points by Damouras et al [69] in order to provide greater accuracy of the detrended fluctuation analysis (DFA) scaling exponent, the principal variable in this study.

4.4 System Limitations

Even though both versions of our systems returned satisfactory results in preliminary trials, both versions have some limitations. In our current version, to provide gait training, gait analysis must be done before in a separate phase using existing methods. As part of the gait analysis process, we identify the variables that are specific to each individual, including stride length, which is then transferred to our system, which then generates personalized training patterns based on these variables. This dependency is one of the major limitations of our current system. Furthermore, our results are based on a trial of 10 patients. This sample size is too small and we need to have more trials with a bigger sample size to fully understand the system behaviors and identify the edge cases.

Similarly, even though Hololens 2 is a cutting-edge device with powerful tracking ability, it should be noted that mixed reality is still an emerging field with many uncharted areas and the device itself has many limitations. The tracking ability of the device is heavily influenced by the environment the user is in. To understand the environment and how the user is located in that environment, Hololens fused many environmental variables together. Each of these variables can be considered a limitation of the overall system [70].

4.4.1 Light

The Hololens process the environmental information using visual light cameras. When the environment is too dark or saturated with too much bright lights, the cameras are struggling to pick up information and nothing might be seen. In this kind of situation, the device might not be able to display the holograms relative to the correct user position.

Furthermore, areas that have unstable lights such as flashing lights can also cause problems. In this kind of scenario, the device might get confused and think changes of light equal to the change in location and try to move holograms to match the new location. This might create drifting issues. Similarly, uneven light can also affect this problem. For example, overall dim areas with a point of bright lights can also confuse the device and create drifting issues and return incorrect tracking data. The indoor track we used to test our application has large windows and indoor lights. We noted some anomalies such as drifting when we walked through the areas that combined natural light coming from the windows and indoor lights. In addition to that, a narrow corridor we used to test our application has yellow and white lights. When we step from an area with a white light to an area with yellow light we also noted some drifting issues. Additionally, it is also possible for outdoor lighting to cause instability in the tracker, as the sun's position over time may change considerably. For instance, tracking in the same space in the summer versus winter can produce drastically different results due to the different levels of second-hand light outside. In order to give the best performance, the environment needs to have sufficient and even light.

4.4.2 AC Frequency

AC frequency can also influence Hololen's tracking abilities. Many countries use a 50 Hz frequency. This means current pulses 50 times per second and a light bulb will blink 50 times per second. Even though this is indistinguishable for the human eyes, Hololens visible light cameras can see these changes. The cameras operate at a 30-frame rate per second. This means some frames are well-lit and others are dark or saturated with light. When it comes to fluorescent lighting, can also cause issues. However, in US and Canada, this might not cause a problem because both countries use 60Hz and it aligns with Hololens 30 fps.

4.4.3 Items in Space

To define the location of the user, Hololens also analyze the unique shapes in the environment. This means if we have two identical rooms Hololens might think it is in the same room. Similarly, if the environment has the same repeating shapes such as the same statue in multiple places, the device may return inaccurate tracking information. This problem, however, can be easily solved by adding unique shapes to the environment. For example, adding a circular photo frame on one wall and a rectangular photo frame on another wall can help the device identify two locations.

4.4.4 Dynamic Environments

A rapidly changing environment such as an environment filled with lots of moving people or objects might also present a significant challenge to the device. This is one of the main reasons we eliminated using scene understanding in our application. In the presence of many moving objects, Hololens is unable to locate a stable feature. If the area is frequently scanned and has even visible light, the device can adapt to these changes. However, if these conditions did not meet, the device can lag behind reality and create ghost meshes such as in figure 3.8.

4.4.5 Other Factors

The proximity between the lenses and the objects also has a major impact on tracking. If the objects are too close to the cameras, the device will struggle to analyze the objects. The device will have major tracking issues if the device is not clearly visible for both left and right lenses. Microsoft recommends that the object and the lenses must have at least a 15cm distance between them.

Shiny highly reflective surfaces can also confuse the signal because of the reflection of light. The device may misinterpret this reflection as a change of environment.

Hololens also consider wifi fingerprints to track objects even if you are not connected to the network. The device might misinterpret a drastic change in wifi signal strength as a change of environment. It is also possible that environmental recognition will be slower if there is no wifi fingerprint in the area.

5. SUMMARY AND CONCLUSIONS

5.1 Summary

We present two portable mixed reality systems to provide gait training. The first system uses an avatar to provide visual cues to the gait patients and uses the proteus effect (the tendency to be influenced by virtual avatars) and complexity matching (the tendency to synchronize movements by matching others' complexity). Our pilot results show that this can use to influence changing gait patterns. The system is currently undergoing large-scale human trials in order to gain a better understanding of its feasibility.

The second system used a different modality compared to our first system. Instead of a virtual avatar, it provides rhythmic visual cues to the user using a moving bar. As the rhythm changes, the users have to match their foot placement. When the bar reaches the top level, users are required to strike with their left heel and when the bar hits the bottom level, they should strike with their right heel. Pilot studies backed by similar research have also shown promising results, and we are currently conducting large-scale human trials to evaluate the system. We hope both of these systems can help patients with gait disabilities restore their natural gait. Furthermore, we hope to share our results with the scientific community in order to further develop these systems.

5.2 Further Study

Our initial patient trials involve 10 patients. Even though the initial results look promising much larger, an in-depth study is needed to fully evaluate the system. So, in the next phase, we are planning to expand the number of patients and do the trials. Similarly, we intend to conduct multiple trials to identify edge cases and anomalies, and then try to fix them. Based on our current and future trial results we plan to share our results with the scientific community by publishing multiple papers in the area of biomechanics, metaverse, and system design. Furthermore, we plan to continue enhancing our system by making it fully open-source and bringing a diverse body of talented developers and scientists.

In our current system design, gait analysis, and gait training are done in two separate phases. For example, before using our system, we need to identify several variables that are unique to the patient like stride length. We do plan to develop a module that provides gait analysis and is integrated with our system by combining these two phases. Currently, we have two ideas to achieve this. The first idea is coupling a motion-capture body suit with the Unity engine to capture the limb movements. In this scenario, the patient wears the body suit and performs some simple gait exercises and then the system gathered the data analyze them, stores them, and directly applies them to create a training exercise. The second idea is to use Hololen's powerful sensors and tracking ability to analyze gait patterns. For example, Guinet et al already explored the feasibility of this idea and developed the HoloStep algorithm, and proved the validity of the idea [49]. We do plan to continue their work further.

Another possible idea for improvement is the gamification of the experience. Gait training often involves very repetitive tasks and many patients' motivation levels tend to get low after some time. Especially in pediatric gait rehabilitation, motivation and willingness to participate in the exercises are vital to successful gait restoration. Many researchers highlighted that gamification can increase the motivation and willingness to participate in the exercises [25, 43, 50]. Therefore, we plan to introduce different game modes to reduce repetitiveness and add a score function, scoreboard, milestone, and achievement system to increase motivation and fun.

Another element we plan to add is multiple modalities of cues. For example, in the next phase of this project, we plan to experiment with visual, auditory, and haptic cues, and based on the result we plan to integrate these cues. For example, when the user gets too close or too far from the appropriate following distance, we can show a red indicator alerting the user, or a beeping noise or hepatic feedback.

Furthermore, one of our key goals when designing the application is to make it platform-independent as much as possible. This will allow patients a variety of options to choose an affordable device. Our current version was built on top of OpenXR and it supports the following devices. Windows Mixed Reality (eg: HP Reverb, Samsung Odyssey), Oculus Quest & Quest 2, Pimax 5K & 8KX, Varjo Aero & VR-3, Valve Index, HTC Vive, HTC Vive Cosmos, Pico Neo 3 & 4. However, we did not test these due to time constraints. Therefore, proper in-depth testing on these devices is needed and we need to improve the experience and further enhance the platform independence.

5.3 Conclusion

Gait disorders are a prevalent problem for a large number of the population. Gait disorders caused reduced mobility, increased risk of falling and fall-related injuries, and adversely affect their quality of life. However, some gait disorders can be treated by retraining the body to restore its natural gait.

In this study, we present two unique gait training systems that utilize the emerging field of mixed reality. Even though many different gait training systems exist, our systems are unique in many ways. Both systems are highly portable, cost-effective, and provide an opportunity to self-train. Furthermore, one of its major advantages is that it provides implicit gait learning opportunities, which is consistent with the way gait is naturally learned. Our systems can also be used in any environment where the user feels comfortable due to their high portability, saving the user time by eliminating the need to travel to a specific location.

The first system uses an avatar to provide visual cues, while the second system provides rhythmic visual cues through a moving bar. Both systems are based on scientific theories that are supported by credible science, the proteus effect, and complexity matching. Our pilot studies have shown promising results that align with similar research. Currently, we are conducting large-scale human trials to assess their effectiveness further. If successful, these systems could have significant implications for the rehabilitation of individuals with gait disabilities, providing cost-effective and implicit self-training methods to restore their gait.

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APPENDIX A

First Appendix

A.1 Git Repository and Documentation

MatLab rand() function C# implementation: https://github.com/PubuduS/Gait_Training/blob/dev_followme/Assets/_HoloLens_Avatar/Scripts/Runtime/ColoredNoise/GaussianDistribution.cs

Colored Noise Implementation: https://github.com/PubuduS/Gait_Training/tree/dev_followme/Assets/_HoloLens_Avatar/Scripts/Runtime/ColoredNoise

Link to the repository of the gait avatar version: https://github.com/PubuduS/Gait_Training/tree/dev_followme

Link to the documentation of the gait avatar version: https://pubudus.github.io/Gait_Training/

Link to the repository of the gait metronome version: https://github.com/PubuduS/Gait_Metronome

Link to the documentation of the gait metronome version: https://pubudus.github.io/Gait_Metronome/

A.2 ETL Trace Repository

Link to ETL trace file repository used for benchmark: https://unomail-my.sharepoint.com/:f:/g/personal/pwijesooriya_unomaha_edu/Ei1wbCWGOdBAl Vk9kQTHrzg?e=RuZQjZ

Link to .wprp Profile we used to record system data: https://github.com/PubuduS/Trace_Profile

Link to the Java tool to export ETL performance data in CSV format. https://github.com/PubuduS/ETL_TO_CSV_Exporter.git

A.3 Video demos of the different versions

Scene Understanding Demo: `https://youtu.be/t9CPMqp_rRg`

Waypoints Version Demo: `https://youtu.be/mRH1bqFAF7A`

FollowMe Version Demo: `https://youtu.be/tRFuAZiyt8U`

Moving Bar Metronome Demo: `https://youtu.be/aIg3G_k2_ZI`