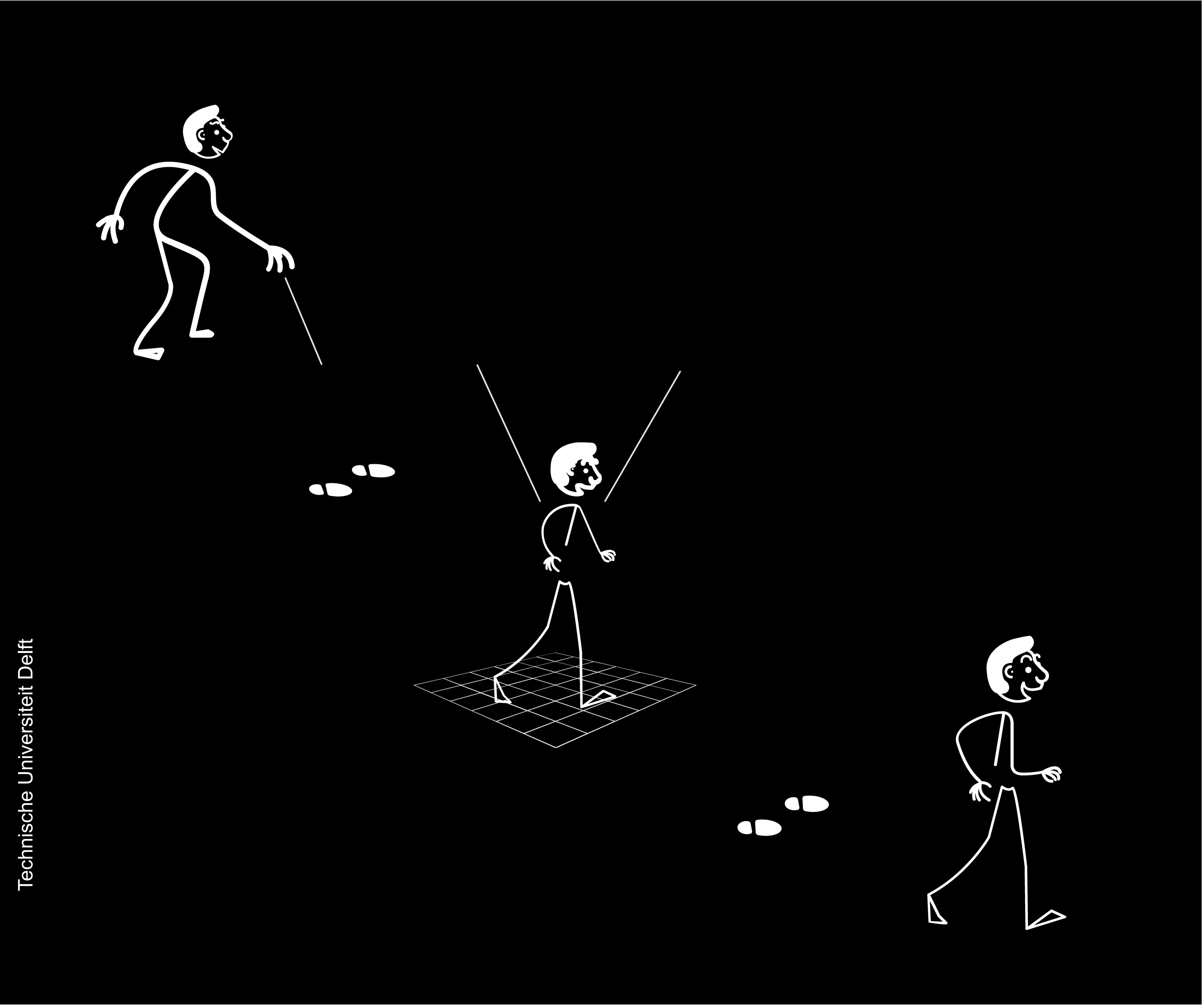

Adaptive Generation of Movement Challenges for Gait Rehabilitation

Silong Lyu

TU Delft

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by

Silong Lyu

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Thesis committee:	Prof. dr. Elmar Eisemann,	TU Delft, chair
	Dr. ir. Rafael Bidarra,	TU Delft, supervisor
	Dr. Valentijn Visch,	TU Delft
	Coen de Weerd,	Motek Medical B.V.

TU Delft

Abstract

Gait impairments negatively affect patients' walking ability, without which they tend to suffer from a higher risk of falling and a lower quality of life. Repetitious training is necessary for patients to regain and maintain this ability. Compared with the conventional rehabilitation process, gamified rehabilitation has the potential to provide patients with a more engaging experience with helpful feedback. Extensive research has focused on the game design and rehabilitation technologies, however, less attention is paid to the personalization and adaptation within the game.

In this thesis, we propose a generic adaptation scheme to support physiotherapists in conducting gait training. The scheme features the parameterized generation of the levels which can be steered dynamically based on the player model and therapists' intervention. Two difficulty adjustment methods are adopted to provide patients with a personalized rehabilitation experience, which are (i) parameters-progression schemes manipulating multiple parameters in two systematic ways for creating levels with appropriate difficulty, and (ii) meaningful integration of separate rehabilitation exercises for providing variety in difficulty transition. Our goal is to assess how adaptive steering of a procedural game level generator can support a physiotherapist in achieving the desired rehabilitation goals. We implemented our design in a standalone prototype for conducting gait training in a three-dimensional overground body weight support system RYSEN. A set of mini-games was first developed through a mapping from therapy goals to the movement challenges in the gameplay. The difficulty adjustment methods were adopted in these games. Apart from the automatic game system, the prototype provides a real-time interface for therapists, which ensures their control of the rehabilitation session. Nine physiotherapists took part in the evaluation with their focus on the difficulty adjustment. The results show that our approach can assist physiotherapists in providing (i) helpful diversity for patients in everyday gait training, (ii) adequate challenge levels for a wider group of patients in various gait exercises, (iii) useful game controls to tailor the level of challenges for patients when necessary.

Preface

This thesis presents the results of my final master project at the Delft University of Technology. Looking back on this journey, I see myself striving in the ups and downs, and 'shining' people who are always with me. I am proud of myself and deeply grateful to those people who are instrumental in my completion of the degree.

First of all, I would like to express my heartfelt gratitude to my supervisor Rafael Bidarra. Collaborating with external resources in such a special circumstance undoubtedly brought tremendous difficulty to us. Every time the project deviated from course, his efforts are significant and unforgettable. He is a magician who encourages me when I am frustrated, inspires me when I am at a loss, and, most importantly, motivates me when I am on my way. I treasure our insightful weekly discussions, through which I not only improved my academic ability, but also acquired better communication and problem-solving skills in everyday life.

I would also express many thanks to the members of Motek, the company we cooperated with. I want to thank Coen de Weerd and Selma Papegaaij for providing detailed information on the RYSEN, sharing the clinical experience with us, and conducting the evaluation for us. I also appreciate Tim Hoogenkamp's help in game development. The project would not have gone this far without your help.

Finally, I am deeply indebted to my family for their unconditional love and support. It is they who help me cultivate a positive attitude to life and teach me how to be an upright person. My friends are the precious wealth of my life. Thank Jiayao, Yuhao, Haozhou for their company and encouragement in this difficult time. I also thank Huinan, Zehao, Zhoufan, and Danfeng for their suggestions in my thesis. These thanks should be extended to every friend I met in Sweden and Netherlands.

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Contents

1 Introduction

1.1. Context

Gait impairments are serious motor symptoms caused by prevalent neurological disorders such as stroke and Parkinson's disease. Patients suffering from these impairments tend to have the limitation of walking functions and experience a lower quality of life [1]. To make it worse, such impairments can lead to a higher risk of falling [2] in their daily life. Gait rehabilitation is then necessary to help patients overcome such long-term impairments, which consists of a series of physical exercises conducted under physiotherapists' supervision. According to neuroplasticity literature [3], performing one recovery exercise hundreds to thousands of times is required for patients to regain and maintain their motor functions.

Nevertheless, it has never been a trivial task to optimize the recovery process and outcomes in conventional rehabilitation. The results of one study [4] shows that less than one-third of 300 stroke survivors met the exercise intensity recommended by physicians. The first reason lies in the nature of rehabilitation, which requires repetitive movement to achieve lasting motor functions. Performing monotonous tasks day by day makes patients less motivated to adhere to the therapy schedule, especially considering the fact that they need to overcome the pain and physical limitations at the same time. Besides, the lack of timely and accurate feedback is also an issue hindering better motor performance. Informing patients of their current performance gives them a clearer idea to improve skills in the coming exercise. However, patients acquire feedback, in most cases, only from their vision, perception, and limited reflective advice from therapists. Moreover, motor learning is supposed to be implicit learning [5]. A common scenario in a hospital or a rehabilitation center is that therapists explicitly instruct patients how and to which extent they should move their bodies. However, seldom are we aware of which parts of our body we are controlling when performing daily motor tasks. Hence, giving implicit instructions has more potential to improve functionalities.

As far back as 1952, Piaget [6] proposed that the make-believe gameplay is able to offer players the chance to experience real life while reducing the negative feelings. This can partly explain the potentials for hiding the learning components in video games, namely serious games. Like gaining knowledge with enjoyment from games in our childhood, accomplishing therapy exercises in a gamified environment can be both joyful and meaningful. Besides rehabilitation and health promotion, serious games can be utilized in various fields including cultural training, education, etc. Unlike leisure games designed for pure entertainment, or computer-intervention systems aiming for assistance in the serious domain, serious games seek to bring *learn* and *play* together and balance them [7]. In rehabilitation background, the learning components refer to motor and cognitive learning, i.e. the improvement of a set of motor and cognitive skills.

Gamification in gait rehabilitation is emerging as a promising tool since it is suitable to solve current rehabilitation problems. Gamified elements are able to give external guidance during the training, such as a sequence of patterns to step on and regularly moving objects to bypass. This avoids conventional instructions that focus on explaining the movement of specific body parts like ”let your toes of the back-foot touch the heel of the front-foot”. Inadequate feedback also becomes less of an issue in serious games. First, the patient-related data during training sessions can be tracked for detailed feedback and analysis. Second, with recent advances in augmented reality and virtual reality technology [8], biofeedback is made accessible to patients and thus improves efficiency [9] and engagement [10]. These inspiring features not only attract the wide application of serious games in rehabilitation but also encourage more researchers to optimize the rehabilitation progress and outcomes with gamified rehabilitation.

1.2. Motivation

Health conditions and rehabilitation progress can differ between individuals. In order to be adopted as an applicable therapeutic vehicle for motor learning, one essential feature that a serious game should possess is player-centered adaptivity. Adaptivity can happen before each level starts. Based on personalized therapeutic goals, pre-defined training constraints, as well as the player's previous performance, the content of the game is customized accordingly. It is essential to challenge players properly because it can both motivate them to ensure sufficient training intensity and keep them from being frustrated. On-line adaptivity highlights itself in adapting challenging levels to fit player's abilities in the real-time, which is referred to as dynamic difficulty adjustment (DDA) [11].

A player model is usually built to steer the adaptivity. It takes the player-centric data as input, measures the current skills of the player, and predicts the right challenge in the upcoming level. Several player modeling techniques in recent adaptive games are rather *ad-hoc*, which are made for a specific context and thus hinder their re-usability. A generic and concise player model to capture player's skills and progress in gait rehabilitation context is then useful to support various adaptive methods in a more general setting. Apart from player modeling, adaptation mechanism is the other main aspect of an adaptive game [12]. Based on the prediction from the player model, the in-game interventions will then adjust the difficulty level correspondingly. It either increases the difficulty to challenge the player when he/she shows good proficiency in the current skill or lowers the difficulty to engage the player when he/she relapses. Several aspects should be taken into consideration in the difficulty adjustment. On one hand, the differences between difficulty levels should not be negligible in order to give players a sense of progression and encourage them to exert themselves. On the other hand, the differences in level difficulty should take account of the smoothness in order to avoid exhausting them. One limitation in current works is that they ignore the importance of diversity in difficulty transition, making their difficulty transitions rather monotonous. Mostly, only one parameter is adjusted in each game during the whole rehabilitation process.

Procedural content generation (PCG) [13] is a powerful technique for adaptation mechanisms. PCG is a term for methods that generate the game world automatically through algorithms based on predefined rules and restrictions. By adding variations to the games under certain constraints, the game is able to generate different 2D/3D visual scenes for rehabilitation based on different pattern arrangements, quasi-random object spawning, texture selections, etc. Compared to pre-scripted and manually designed games, PCG-based games advantage themselves in providing unlimited content which offers a new experience every time the player enters the level, thus preventing simply learning the game through route. As a result, not only can PCG-based games make the rehabilitation process less predictable and more appealing to the player, but they can also enhance the robustness of skill acquisition in motor learning. Finally, the involvement of physiotherapists in the configuration of player-related settings and decision on difficulty-related parameters should be implemented. Being one of the cornerstones of the therapy, experts and physiotherapists are supposed to have control over the game to achieve their desired therapeutic goals for each patient before or even during the game. Some semi-automatic approaches [14], [15] are adopted in previous works aiming at achieving manual intervention. However, the exposure of too many game parameters during whole rehabilitation process can be overwhelming especially considering the number of exercises a patient has to perform and the number of patients the therapists need to take care of. Besides, most adaptive game systems are designed for home-based rehabilitation. In this circumstance, the configuration and intervention from therapists usually take place at the beginning or end of each training session. Whether a real-time intervention from the therapists to the automatic game system in a clinical context is beneficial and how to provide helpful control options are worth researching.

1.3. Proposed solution

We propose a generic method to adaptively steer the level generator for gait rehabilitation in a clinical environment (e.g. hospitals, rehabilitation centers). A player model is first created which takes performance-related data as input and evaluates the skills based on performance-related metrics. Together with the player's past performance, the model predicts if there is a necessity to adjust the current difficulty and how should the difficulty be adapted. Multiple parameters can be utilized to characterize the difficulty of each game. To seek a systematic means to influence the challenges of each exercise, first, parameters are configured respectively including their starting and end value for the easiest and hardest scenario and meaningful increments. Two general progression schemes are then adopted to affect the difficulty by manipulating these parameters. The first straight-forward solution is increasing/decreasing each parameter simultaneously while the second one is to increase/decrease parameters in an alternate sequence. By providing these two methods, we aim at providing an appropriate challenge level to a larger group of patients at different conditions, which does not need to know how much each parameter contributes to the overall difficulty in each gait exercise.

The derived values of parameters are then applied to steer the level generator. In addition to adding variations in the gameplay, the procedural content generator makes it possible to integrate two (or more) exercises into one game scene in real-time. We capitalize on it to create a new layer of difficulty. Specifically, when a patient consistently shows proficiency in current skills, the system can advise therapists to integrate the current exercise with an easier exercise. Together with the aforementioned parameter-progression schemes, they constitute the difficulty adjustment strategies in our work.

To evaluate the usefulness of the adaptation scheme, we implement our adaptation mechanism in a standalone prototype for gait recovery in a three-dimensional overground body weight support system RYSEN. A proper type of immersion and game scenario is first selected. After that, a mapping between therapy goals and the features of typical movement challenges required to achieve those goals is elaborated. Together with therapists, we developed four games for improving gait adaptability and overcoming motor-cognitive dual-task interference. In a game designed for the exercise which requires asymmetry efforts for lower limbs, the parameter-progression schemes further separate the difficulty for each limb. A real-time interface is also implemented as a layer between the automatic system and therapists. Following the same ideas in building a player model, both accuracy and efficiency information is utilized to describe the performance of the patient. To minimize the efforts, only logical and essential operations will be displayed to therapists.

The proposed solution raises our main research questions:

> *How can adaptive steering of a procedural game level generator support a physiotherapist in achieving the desired gait rehabilitation goals?*

To answer this, we focus on the following questions:

1. How can generated levels effectively support therapists in each therapy goal?
2. How to realize an effective difficulty adaptation to assist therapists in gait rehabilitation?
3. How to give therapists control on what the game system is going to automatically generate?

1.4. Thesis structure

To answer the research questions, the dissertation is organized in the following manner. Chapter 2 identifies the possibilities and direction for further research in gamified gait rehabilitation through reviewing the serious game domain and analysis of current works in gait rehabilitation. Chapter 3 proposes an adaptation scheme based on a generic player model. Two difficulty adjustment strategies are introduced, which also allow the therapist's control of the automatic system. Chapter 4 implements the design in a standalone game prototype made for gait rehabilitation. The game content is procedurally generated and is controlled by our adaptation scheme. The real-time intervention is also realized for the therapist through a user interface. Chapter 5 tests how helpful our design is and analyzes the collected feedback. At last, chapter 6 draws conclusions based on our research results and proposes recommendations accordingly.

2
Related Work

This chapter studies the adaptation in the context of gait rehabilitation. First, serious games in the rehabilitation field are briefly introduced, the advantages and attractive features of which are discussed respectively. With a general idea of game interventions in the rehabilitation domain, the review goes deeper with its focus on gait rehabilitation in a virtual environment. To further optimize the rehabilitation, the method of difficulty adaptation is researched followed by how the content is steered in games.

2.1. Gamified rehabilitation

In recent work, a study [16] systematically analyzed over 60 works on serious games in motor rehabilitation context and showed the effectiveness of serious games on improving movement and balance functions compared with conventional rehabilitation. One obvious benefit of adopting gamified technologies in rehabilitation is the improvement of patients' motivation. Rand et al. [17] quantitatively studied patients' engagement in gamified extremity rehabilitation. It assessed the initiative of patients' movement based on accelerometer measurements and the experience of occupational therapists. The results demonstrated 5 times more purposeful repetitions when performing the movement in a gamified environment compared with conventional therapy. The engaging rehabilitation progress thus guarantees a satisfactory quality of rehabilitation. Jung et al. [18] compared the gait functions after a 6-week rehabilitation session between training with video games and conventional methods. The outcome measurements revealed that patients in the game-based training group acquired significantly faster gait velocity, greater balance, and longer stride length than the conventional therapy group. Furthermore, Hertz et al. [19] tested how long patients could maintain their progress from a gamified rehabilitation. Results showed that even a relatively short-term (four-week) therapy with video games can lead to a continued (one month) improvement, including gait functions and quality of life.

Serious games are being adopted as a promising tool in the rehabilitation domain for several advantages, including fun and entertainment [20], feedback [9], interactivity [21], and adaptivity [22]. State-of-the-art studies are seeking to speedup the gamified rehabilitation process based on these features. Goršič et al. [23] sought to bring more fun into rehabilitation process by developing competitive and cooperative arm rehabilitation games. The idea was to encourage patients to accomplish exercise with their unimpaired friends, relatives or even therapists. Despite the unbalanced capacity issue, these games demonstrated great promise for offering patients more incentive to perform more movement by introducing a new role of opponent or companion into gameplay. Interestingly, more patients are found to prefer their friends and relatives to therapists as their co-players in competitions. Although such competitive or cooperative game forms may not be suitable for all therapy exercises or appeal to all types of patients, they do provide more choices to suit various patients in the different rehabilitation phases. Labruyère et al. [24] put emphasis on the design of meaningful gameplay as well as elaborate graphical design. The level design implicitly mapped therapeutic goals into the gameplay, where patients were required to properly modulate their leg muscles to pick up more flowers on the planet (i.e. to get a higher score in the game). Besides, the graphical representations of the avatar varied at different activity levels, which informed the patients of current activity intensity and added diversification to the game. Tannous et al.[25] designed a system for gamified lower-limb rehabilitation, which highlighted itself in bringing patients and therapists (experts) together through an interface for feedback. It kept track of patient's progress and kinematic data and visualized them. Based on these, experts can assign a proper exercise to each patient and help them correct bad movements during the consultation session. The interactive methods between patients and game elements can vary a lot depending on rehabilitation purposes, which usually involves hands [23], feet [26], and even voice [27] in a virtual reality or augmented reality environment. Together with adaptation techniques, they will be elaborated in the next section with a main focus on gait rehabilitation.

2.2. Gait rehabilitation technologies

Gamified gait rehabilitation nowadays often immerses patients in virtual reality (VR) environment, which aims at providing them with sensory input and/or various real-life situations to speed up knowledge transfer [28]. We can distinguish two main categories in terms of game technologies for gait rehabilitation, which are commercial solutions and specific solutions. Commercial solutions refer to adopting existing gaming systems such as Nintendo Wii and Microsoft Xbox Kinect for patients to perform active movements. By contrast, specific solutions are more goal-oriented and better at incorporating motor learning principles, which include task specificity, training variability, biofeedback, etc.

2.2.1. Commercial solutions

The birth of commercial solutions (Wii in 2007 and Kinect in 2010) brought vigour and vitality into research on gamified rehabilitation. Thanks to the low cost and good usability, commercial solutions became popular worldwide. According to a meta-analysis conducted by Bonnechère [29], the year 2011 witnessed a surge of publications that utilized virtual reality, including non-immersive, semi-immersive, and fully-immersive VR, in gait rehabilitation.Among these, the application of commercial technologies made up a large proportion.

Gamified gait exercise with Nintendo Wii console requires the Wii Balance Board, which keeps track of the center of pressure of patients when they are performing exercise on it. Usually, therapists select suitable games and intensity for each patient through Wii's game system, and patients are required to shift the bodyweight between feet to interact with the game [30], [31]. One drawback of Wii rehabilitation is the limited detection area for patients, thus constraining their lower-limb movement. Gait rehabilitation with Microsoft Kinect tackles the issue to a certain extent. Based on the provided Software Development Kit (SDK) for Kinect, gait parameters can be obtained with Kinect's motion-registration system. Without further needs to wear markers or standing on a small workspace, patients can interact freely with Kinect-based games such as Kinect Sport [32] and Kinect Adventure [33]. Nonetheless, few of these commercial games are made specifically for patients with deficits in lower or upper extremities. This means these technologies are only used in a home-based environment to motivate patients to move their lower or upper limbs actively. Collaborating with therapists, Alankus et al. [34] identified three significant attributes for rehabilitation games, which focused on the motion type and cognitive challenge for patients and also take the patient's social context into the game design. However, the interaction between patients and most commercial game systems was still through a monitor, which limited the potential for a more immersive game experience. Moreover, few effective measures are applied to prevent patients from falling during training, which poses potential risks during home-based rehabilitation.

2.2.2. Specific solutions

The prosperity of commercial games in turn stimulated the research on specific rehabilitation game solutions. Specific solutions develop their own game systems for particular rehabilitation purposes such as gait adaptability, steady-state gait, motor-cognitive dual tasking, etc. These solutions usually take advantage of current technological advances to provide better protection, a natural gait experience, as well as a more immersive experience for patients. The forms of specific technologies for gait rehabilitation are various and mostly focus on two aspects: to better support patients' gait exercise and provide more immersive interaction.

Robot-assisted therapy is the commonly adopted method to support patients with lower-limb disabilities in gait training while minimizing therapists' physical strain. Jezernik et al. [35] proposed an automated treadmill training system with Lokomat [35] to increase the strength of muscles and the range of motion. When training with the robotic orthosis, patients are enforced to follow the movement of Lokomat to build correct motion for the impaired leg. Despite the sophisticated motion control algorithm, it has not been proven to be as effective as traditional therapy. One explanation for this is excessive intervention from Lokomat, which hindered the patients' initiative to perform leg movements. This is because giving patients the chance to make movement themselves, even making mistakes during gait exercise, can better speed up the skill acquisition [36]. Further gait rehabilitation with automated treadmill systems thus offered more freedom for patients. Body weight support (BWS) systems were integrated into such systems [37], which could lift patients up to reduce their weight and provide necessary fall protection during training. One advantage of gait training with a treadmill is that both physiotherapists and gait analysis cameras are relatively static with the patients when they perform gait exercises on treadmills. This is beneficial for ensuring precise gait pattern capture and reliving the physical labor of therapists. However, the relatively small space on the treadmill does not allow patients to perform natural movements such as turning, sidewards walking, etc. Besides, Hollman et al. [38] found that walking on a treadmill could lead to invariant gait patterns compared with overground walking, thus having a negative effect on transferring the skills to real-life walking. In order to provide a more genuine and natural gait rehabilitation experience, Plooij et al. [39] introduced a novel three-dimensional BWS system for gait rehabilitation named RYSEN. Apart from providing overground weight lifting and protection for patients in a larger workspace, it also advantaged itself for energy efficiency.

Common immersion technologies for overground gait rehabilitation mainly include semi-immersive virtual reality and fully-immersive virtual reality. Head mounted displays (HMDs) are commonly adopted to let patients perform exercise within fully immersive virtual surroundings. The advantage of this method is that patients are able to enjoy a 360-degree field of regard, meaning they will always see a corresponding visual image if they look in any direction. However, the motion sickness and dizziness caused by HMDs restrict their widespread use. Moreover, wearing an additional device on the head puts a burden on the patient's cervical spine and movement. Despite that recent technology solved the aforementioned problems to a certain extent (e.g. the oculus rift headset [40] reduced the weight of the headset and relieved the dizziness issues), walking in such a virtual reality environment can still cause slight modification of gait [41] and the effectiveness of utilizing this technology alone in improving gait abilities was not clearly proved [42]. Another promising interaction method is to display game objects on the ground to ensure the direct positioning of the foot relative to the gamified element. Although being semi-immersive, it provides natural overground walking with minimum perturbations. Delden et al. [26] displayed their games on an eight by one meter LED floor equipped with pressure sensors. Patients interact with the game by stepping onto the objects displayed on the walking surface. While LED screen can provide good illumination and resolution, its high cost and poor scalability keep potential users away. Leo et al. [43] proposed a semi-immersive system using a mobile floor projector, which was driven by motor to follow the player. The optical infra-red cameras then capture the motion and position of the patient so that he/she can interact with the system.

To sum up, the specific solutions for gait rehabilitation are diverse in form but with a clear aim to better assist and motivate patients to accomplish rehabilitation training in a clinical environment. As can be concluded from the comparison, it is by no means an easy task to achieve a perfect balance between immersive rehabilitation, cost, and natural walking experience. More solutions are worthy of exploring in this area.

2.3. Adaptivity in rehabilitation

So far, what has been discussed mostly concentrated on the usability of serious games in gait rehabilitation. Another critical aspect of rehabilitation games is sustainability, meaning the capability to continuously improve the gait function of patients over a long recovery period. To achieve this, serious games need to adopt a player-centric strategy which adapts to the player's needs and skills before and during a game.

2.3.1. Off-line adaptivity

Off-line adaptivity denotes the ability to make adaptation based on player-centric data prior to the start of each game session. It can be regarded as an inherent advantage of games as they are able to customize themselves to suit various players.

Several factors can be adjusted in an off-line adaptation. Difficulty-related parameters can be one example. In a game designed for gait adaptability training [44], the therapists, based on the recorded performance of each patient, adjusted the values of each difficulty-related parameter at the beginning of each game. For instance, the irregularity of the stepping targets, the size of obstacles, and the acceleration of a target area can be adjusted to affect the difficulty of visually-guided stepping task, obstacle avoidance task, and speeding-up task respectively. Playing modes can also be modified by therapists depending on the gait skills of each patient. Michaud et al. [45] encode each walking pattern with different functions in a runner game designed for gait rehabilitation with Lokomat. For patients with severe gait disabilities, even a passive movement could have a chance for the avatar to step over an obstacle in the game. By contrast, if the patient is very capable of making lower-limb movements, they have to perform a proactive movement in Lokomat to pass the obstacles. Game metrics can also be adjusted in order to further provide a personalized game experience. In a gait rehabilitation game systems developed by Delden et al. [26], the input data concerning gait information of each patient decided the game metrics. The patients' stride length, track width, and asymmetry leg disorders data would be translated to the recommended values for therapists to decide, such as distance between game objects and the size of objects in the game, etc. With the involvement of physiotherapists in off-line adaptation, a solid foundation is built to provide a personalized experience and satisfying rehabilitation outcomes.

One drawback of relying solely on these methods is the excessive need for therapists' intervention. These methods tend to expose numerous parameters, the values of which are not identical for each patient. To make it worse, most of them are required to be updated with the improvement of patients' performance and day-to-day health conditions. Such complexity might be beneficial for advanced therapists, but most of the time, it costs too much effort for therapists and limits the number of patients they can supervise at the same time.

2.3.2. On-line adaptivity

On-line adaptivity, also known as in-game adaptivity, refers to the ability to make an automatic adjustment based on gameplay-specific data in real-time. One psychological theory that has been widely applied in on-line adaptation techniques is *flow* proposed by Csikszentmihalyi [46]. That is, to offer an optimal gaming experience, the challenges should balance the player's abilities. Dynamic difficulty adjustment (DDA), is the most utilized method to automatically create adequate challenge levels for players [47].

In entertainment games, DDA is designed to enhance the enjoyment of players. Xue et al. [11] quantified the engagement objective using a probabilistic method in level-based mobile games developed by Electronic Arts, Inc. They modeled the player's progression as a probabilistic graph with different states and maximized the number of transitions between states with dynamic programming. Tan et al. [48] addressed DDA with evolutionary computation and reinforcement learning in a car racing game. They measured entertainment based on mean score differences as well as winning percentage differences and proposed two adaptive algorithms to change game AI's proficiency according to different opponents' profiles during the gameplay. In both works, the adaptive strategies were proved to be helpful in increasing the enjoyment of players and catering to a wider range of audiences.

The *flow* theory also makes perfect sense in serious games for rehabilitation, as it will give the patient a sense of exhilaration when his/her body is stretched to a limit and accomplishes a worthwhile task. Different from entertainment games, the purposes of DDA in a clinical context are to enhance patients' motivation and maximize their physical effort to overcome physical barriers. Pirovano et al. [49] applied Quest Bayesian adaptive method [50] to fit each patient's performance in posture and balance rehabilitation. For each mini-game, the therapist first identified one game parameter that affects the task difficulty and then set the initial value and constraints. The Quest is then applied to adapt this parameter after each trial based on the performance of the patient and the pre-set success rate (e.g. 90%). Nevertheless, the determination of parameters in this probabilistic player model was based on healthy people. To achieve better estimation, a larger population is required. Pinto et al. [51] developed a state machine for adaptation in their games for upper-limb rehabilitation. Not only was the state machine responsible for assessing the performance of the patient, but it also predicted the next suitable states for him/her: easy, medium, or hard. Briefly, the parameter that determines the difficulty level of each mini-game will increase when the player is measured to be proficient, and vice versa. The increase or decrease value is determined by the therapist for each patient. The state will remain unchanged if constant performance is measured. Based on the therapist's experience, they set the proper value of parameters for each patient per game. One limitation of the above is that, only one parameter was changed during the adaptation, despite the fact that more than one parameter had an effect on the difficulty in their game design. Such a one-parameter adaptation process may make patients feel bored and stressed if it lasts for the whole rehabilitation.

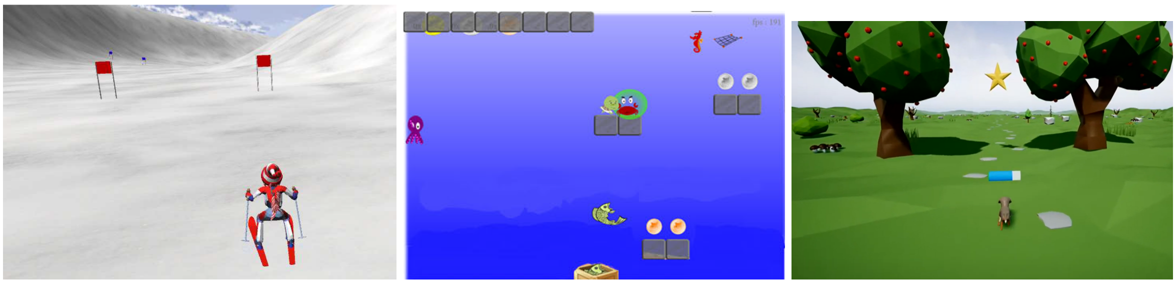
More work aims to add diversity in difficulty adjustment. Cameirão et al. [52] designed a personalized training module adjusting task difficulty in their game Spheroids for stroke patients. In this game, patients were required to move their upper-limbs to intercept the sphere in a virtual environment. Four parameters are characterized to describe the difficulty of this task, i.e. the size, moving, and dispersion range of spheres as well as the time interval between the appearance of two consecutive spheres. The success rate of sphere interception was measured and compared with a pre-defined value to decide if the difficulty should go up or go down. One focus of their work is to determine the contribution of each parameter to the overall difficulty, where they applied a quadratic model and fitted the formula with experimental data. Understanding the difficulty weight of each parameter can bring more variety into gamified training. Even at the same difficulty level, the different combinations of parameters could still offer different game experiences and thus avoid monotony. However, such a way of defining the difficulty greatly increases the development cycle. Considering the smaller group of target players and short lifecycle of a rehabilitation game [53], it lowers the efficiency greatly. Hocine et al. [22] avoided the manipulation of difficulty-related parameters in a platform game PRehab, which is made for patients to reach targets. Instead, they built an ability model of the player by computing his/her ability zone matrix [54] through an assessment exercise, which was then updated during the rehabilitation progress. Such a model directly maps the difficulty to each area in a two-dimensional workspace. Based on this, the game can tailor the difficulty for each patient. However, the ability zone matrix can be large (30×30 in their experiment), making it intricate for the therapist to make adjustments to control the difficulty without concise visualization and interaction. Moreover, such an ability zone only works when the related difficulty can be defined in a two-dimensional space, restricting its usage in more complicated game designs.

In conclusion, most adaptation approaches take a player's performance as the input. The player modeling is critical in these methods, however, most models are game-specific and/or require large empirical data, which prevents them from being generic. When adjusting difficulty levels, a lot of methods focused only on the progression of one single parameter. Although some approaches sought to manipulate multiple parameters diversely, they are lacking in efficiency and reusability.

2.4. Procedural content generation

Procedural content generation (PCG) generates game content automatically with algorithms and various types of input. Depending on different purposes and techniques, game elements such as urban environment, virtual world, road network, terrain, and stories can be diversified at a low-cost [55]. In the clinical context, PCG is considered as a good support for adaptation to create a personalized and manifold gait rehabilitation experience.

Dimovska et al. [13] first applied the idea of PCG in rehabilitation and made a game ReSkii for balance and persistence improvement. Prior to the start of gameplay, the snow mountain terrain is generated with a zig-zag pattern based on Catmull-Rom Splines. As illustrated in Figure 2.1(a) gates are procedurally placed on the right and left sides for the 'skiing' patient to reach. The performance will then affect the distance between gates in the coming level sections. Hocine et al. [22] procedurally placed the points for the player to reach in their game PRehab. Figure 2.1(b) shows a sequence of points that constitute the level. The Monte Carlo tree search algorithm was used to find out a gate layout that exhibits the desired difficulty. PCG in rehabilitation is also used to create a virtual environment. Kern et al. [56] applied PCG to assist in creating an inhabited green forest which aimed to encourage patients to walk using a reward system. The application procedurally placed the vegetation models and reward elements as in Figure 2.1(c). Diversity was achieved through rotation, scaling, and density of these game elements.



(a) (b) (c)

Figure 2.1: (a) Procedurally generated terrain and gates in game ReSkii [13]; (b) Procedurally generated points in game PRehab [22]; (c) An inhabited green forest where vegetation models are placed procedurally [56]

PCG is being adopted in rehabilitation which generates diverse game content, including virtual environment, game objects, game levels, etc. Compared with the hand-crafted level, its flexibility and diversity make it suitable for rehabilitation context. Its promise is fully realized when it is steered by a well-designed adaptation mechanism. One possible improvement for PCG in the rehabilitation context, which is tightly related to the adaptation scheme, could be its interactivity between the game and the therapist. In PCG-based games, most levels are divided into sections. At the end of each section, the game dynamically generates the content for the coming section based on the updated player model. Goršič et al. [57] showed that there is no clear preference between manual and automatic adaptation in an arm rehabilitation game. Since physiotherapists are one of the cornerstones of physical rehabilitation, whether it is beneficial to provide necessary real-time interaction for them to control the adaptation and content generation is worth investigating.

2.5. Conclusion

To sum up, gamified rehabilitation has been proved to be beneficial to gait rehabilitants as a result of its various advantages. It is getting widespread use thanks to some popular commercial solutions in the gait rehabilitation domain. Adaptivity is being regarded as one critical feature in rehabilitation games. However, very few works have concentrated on the adaptation in gait rehabilitation. Besides, adaptation approaches in current rehabilitation games are lacking in either reusability or interactivity, restricting their further application. PCG method in game development for rehabilitation advantages itself for providing manifold game content, its promise in gait rehabilitation when integrated with adaptation schemes is worth discovering.

3

Adaptation scheme

This chapter introduces a generic adaptation scheme of game level content for gait rehabilitation in a clinical environment. As in serious games, adapting to specific skills is of higher priority to the global difficulty [7], the targeted rehabilitation exercises of the proposed adaptation scheme are task-specific gait movements. In order to provide a personalized rehabilitation experience, the procedural generator is adaptively steered based on player model and therapists' input.

3.1. Adaptation overview

The general idea of the proposed adaptation scheme is illustrated in Figure 3.1, which consists of off-line adaptation as well as online adaptation.

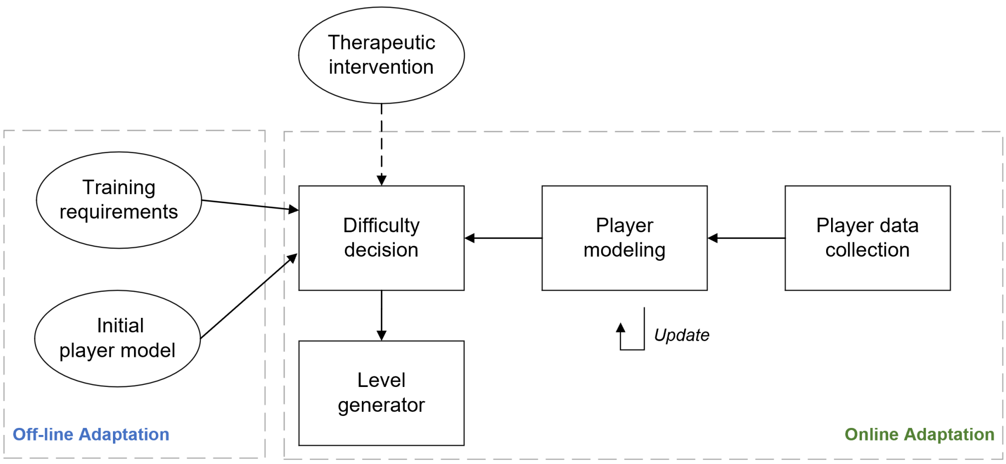


Figure 3.1: Adaptation loop for each task training in gait rehabilitation

Basically, the off-line adaptation is based on training requirements and the initial player model. The training requirements comprise which task the therapist wants the patient to accomplish and how long will this task lasts. Together with the therapist's decision for the starting difficulty level, the procedural generator can provide personalized game content for the patient accordingly. The online adaptation, on the other hand, is responsible for dynamically adjusting the challenges for the patient in real-time. It comprises player skills prediction as well as challenge level intervention. The difficulty decision model manipulates the difficulty-related parameters based on the player model and the therapist's input. What the player modeling module mainly does is to provide a prediction of the patient's current skills through evaluation of his/her performances in the last rounds. Theoretically, the game system is capable of running autonomously based on pre-defined rules and restrictions. However, as the player model is only an abstraction of the player's skills and is not able to capture all possibilities during the rehabilitation progress. Under such circumstances, offering therapists the opportunities to adjust the difficulty level in real-time could be beneficial considering. Apart from manipulating the difficulty-related parameters for each task, the difficulty decision model can also influence the difficulty in another way, that is, combining more than one task at the same level if therapists desire to. All of these difficulty-related designs are realized with the procedural level generator, which divides each task into several level segments for real-time adjustment and intervention.

3.2. Player modeling

One question that needs answering in the adaptation is when to adjust the difficulty level. The assessment of players' performance and prediction of their current skills are critical to answer it.

As discussed in the previous chapter, difficulty in the rehabilitation domain mostly describes the physical effort to achieve a specific goal, which can include the amplitude, velocity, as well as precision of a movement. Following a similar manner, the proposed player model is based on two aspects to measure the player's performance: accuracy and efficiency. **Accuracy** indicates how many mistakes that one player commits during one level segment, while **efficiency** further depicting the amount of extra time consumed by a player in order to accomplish each task. For each therapeutic task, there are several factors describing the player's performance that can be categorized into accuracy and efficiency. Supposing a training task requires a patient to perform a certain gait movement on a walking surface with limited area, for example, performing sidewards walking on a narrow road, there could be at least three factors describing the performance of the patient in each level segment:

- F: Off-zone times, refers to the *frequency* that the patient walk out of the pre-defined area;
- U: Clinically undesirable movement counts, stand for the *number* the patient fails to stretch his/her body to a right extend;
- V: Average moving speed, denotes the mean *velocity* during current level.

The factors F and U represent how accurate the performance is at the current level, and the factor V describes how efficiently the patient finishes this level. Essentially, the idea of the proposed player model is to compare the player's status data with a collection of reference values set by physiotherapists based on accuracy and efficiency aspects. Equation 3.1 quantitatively describes the impact of each factor on a player's current performance. The collected player-related data is represented with subscripted ***measure*** and reference values at current level are highlighted with subscripted ***currentRef***. W_A and W_E represent the weights of accuracy and efficiency respectively.

$$currentScore = 2W_A \cdot (H\,(F_{\text{currentRef}} - F_{\text{measure}}) \cdot H\,(U_{\text{currentRef}} - U_{\text{measure}}) - 0.5) + 2W_E \cdot H\,(F_{\text{currentRef}} - F_{\text{measure}}) \cdot H\,(U_{\text{currentRef}} - U_{\text{measure}}) \cdot (H\,(V_{\text{measure}} - V_{\text{currentRef}}) - 0.5) \quad (3.1)$$

The terms $F_{\text{currentRef}} - F_{\text{measure}}$, $U_{\text{currentRef}} - U_{\text{measure}}$, $V_{\text{measure}} - V_{\text{currentRef}}$ compare the measured data with reference value respectively. The returned values are then used as input of Heaviside step function $H(x)$, which returns 1 when $x \geq 0$ and return 0 when $x < 0$. The results based on the same aspect are then multiplied with each other, indicating that the accuracy or efficiency is only satisfied when all related factors are measured to be qualified when compared with their reference values. To normalize the output score between -1 and 1, the results are first shifted along the y-axis by -0.5 and then multiplied by their weights and 2 before being adding together. As performing gait movements in a correct way is a necessary condition in each therapy goal, the score of efficiency is multiplied by accuracy-related results, which are $H\,(F_{\text{currentRef}} - F_{\text{measure}}) \cdot H\,(U_{\text{currentRef}} - U_{\text{measure}})$.

The values of weights W_A and W_E depend on the type of exercise. For training tasks that require precise control of lower-limb muscles, the accuracy weight W_A can be emphasized. By contrast, if the therapy task is meant to encourage the patient to stretch his/her lower-limb muscles at a higher pace, the efficiency weight W_E should be paid more attention. The benefit of introducing both accuracy and efficiency weights for each exercise is to achieve better therapy outcomes. On one hand, ensuring patients performing accurately regardless of the type of training tasks can always guide patients to stretch their bodies in an acceptable range to help them avoid getting injured. On the other hand, when the patient is correctly performing a task that is less speed-related (e.g. sideward walking or backward walking) but at a slow rate, the supervising therapist tends to urge the patient to move faster. This is because increasing the movement speed is viewed as a cost-free strategy [58], which is able to increase the training intensity and thus speed up the motor learning process.

It is worth mentioning that the equation 3.1 does not make the player's ***currentScore*** proportional to the differences between the measured values and expected reference values. The main reason is that the difficulty level is increased/decreased gradually based on the player's performance. In other words, the condition for the patient to enter level X is that he/she has proven to be capable of handling the challenges in level $X - 1$. In this case, it would make less sense to decrease the difficulty directly to level $X - 2$ or even level $X - 3$ when a player shows an unsatisfactory performance at level X. Also, as the game is designed for patients with lower-limb impairment, it is less clinically desirable to increase the difficulty level in a steep way such as directly from level X to level $X + 2$ or even level $X + 3$ in a short time. Besides, the score in efficiency aspect only makes contributions to ***currentScore*** when the accuracy requirement is satisfied. Such a design aims to offer more chances to patients to adapt themselves to a new difficulty level.

Last thing to make this player model a more comprehensive tool for performance evaluation is considering the impact of difficulty level on the predefined reference values. As the difficulty levels proceeds, the reference values set at initial levels are likely to be out of reach for some patients in some exercises. For instance, the increasingly complex game scenes make it difficult for patients to achieve the same average walking speed as the initial simple levels, thus frustrating them. One practical solution is to assign another set of reference values at the most difficult level and fitting these values into a mathematics model. Take the average speed V as an example, a linear model is applied to calculate reference values at different difficulty levels as:

$$V_{\text{currentRef}} = V_{\text{initalRef}} + (currLevel - 1) \cdot \frac{V_{\text{endRef}} - V_{\text{initalRef}}}{\text{endLevel} - 1} \quad (3.2)$$

It takes *currLevel* as an argument, seeking a relationship between the current reference value and reference values at initial level $V_{\text{initalRef}}$ and last level V_{endRef}. As depicted in Figure 3.2, with the difficulty level proceeding to the last level (i.e. *endLevel* = 7), the reference value used to evaluate the average walking speed drops from 0.7 m/s (i.e. $V_{\text{initalRef}}$ = 0.7) to 0.6 m/s (i.e. V_{endRef} = 0.6) to suit the patient's condition.

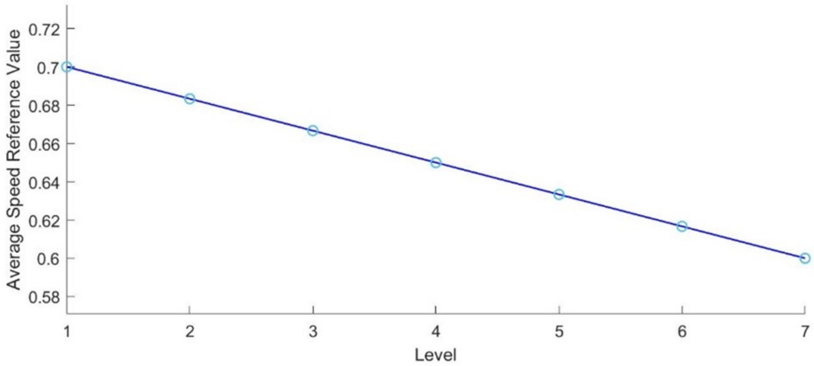


Figure 3.2: Linear model to calculate reference value at different difficulty levels (take average speed value as an example)

The score of the patient in each task is then accumulated over several level segments to predict the skill of the patient as expressed in equation 3.3.

$$accumScore = \sum_{i=1} s \cdot currentScore_i \quad (3.3)$$

The result ***accumScore*** is re-evaluated every level segment. When ***accumScore*** changes its integer value by either 1 or -1, the patient's skills are measured to be progressive or getting worse. Correspondingly, the player model is suggesting either increasing or decreasing the difficulty level to later modules. As the $currentScore_i \in [-1, 1]$, the coefficient s represent the value of evaluation cycle, i.e. the speed of difficulty adjustment. The ways to determine the coefficient s can be flexible. Specifically, it can be either experience-based or duration-based. The experience-based method is expressed in equation 3.4

$$s = \frac{1}{r} \quad (3.4)$$

where r stands for the minimum number of level segment before the model proposes changing the difficulty level. The value r can be decided based on experience from therapists and fine tuned during the game. Another solution, namely duration-based method, is to let the coefficient s can be dependent on duration for today's task training. It is shown in equation 3.5

$$s = k \cdot \frac{Q_{\text{mean}}}{Q_{\text{total}}} \quad (3.5)$$

where Q_{total} is the total training duration for today's task and Q_{mean} denotes the average time the patient takes to go through each level segment, which can be recorded in the player model. Hence, the parameter k refers to the maximum number of difficulty level that can be adjusted in today's training task given a predefined training duration.

3.3. Difficulty adjustment

Next question in adaptation is how to adjust the difficulty levels accordingly. For each gait task, a set of parameters can be characterized to satisfy clinical needs. The reasonable difficulty design for individual gait rehabilitation task then becomes the study of the treatment of each parameter's value and their combination. In addition, as the main goal of gait rehabilitation is to help patients regain their gait abilities to handle various walking scenes in real-life, it can be clinically beneficial to integrate separate tasks in a meaningful way.

3.3.1. Parameter-progression schemes

Knowing the explicit relationship between each parameter and the overall difficulty could be a solution to the difficulty design. However, it can be less cost-effective to find a correlation. For one thing, it takes extensive clinical design and experiment to derive such a relationship. For another, even the same parameter can have different effects on different individuals. Thus, designing difficulty level in this way is not conducive to a personalized or generic method. Although it is not feasible to clearly figure out how each parameter contributes to the task difficulty, we do know which levels are more difficult if the parameters change in a regular way. Specifically, we view the difficulty manipulation from a *transition* perspective, where the 'regular' means all parameters are increased (or decreased) either in parallel or in sequence (i.e. alternate). In the following text, for simplicity, an increasing trend in difficulty is applied to describe the transition. It is conceivable that as the difficulty decreases, the corresponding transition will follow the same pattern but in the opposite direction.

- ***Parallel progression scheme***: parameters can be increased simultaneously.
- ***Sequence progression scheme***: parameters are increased alternately - one and only one parameter can be increased each time.

Assuming there are two parameters m and n defining the difficulty level. The relationship between the two is listed in Table 3.1.

Parameters	m	n
Tiers	$1, 2, 3, ..., M$	$1, 2, 3, ..., N$
Steps	$M - 1$	$N - 1$
Condition	$N \geq M$	

Table 3.1: Parameter assumptions, a two-parameter condition

Tier means the difficulty levels for specific parameters. For **parallel progression**, the total level number T is:

$$T = N \tag{3.6}$$

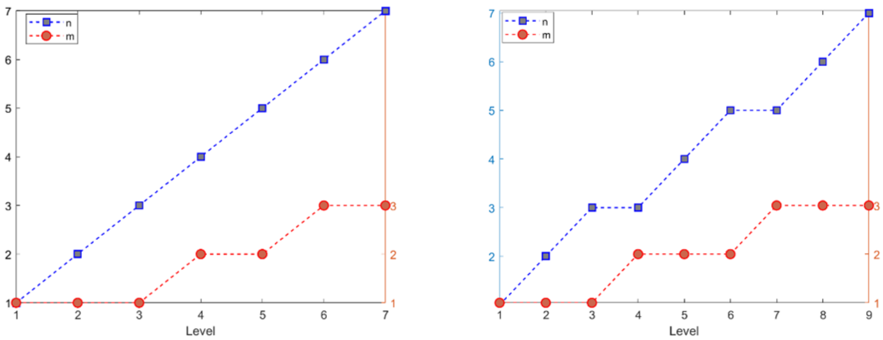
Taking the current level ($currLevel$) as an argument, then parameter n is:

$$n = currLevel \tag{3.7}$$

As for parameter m, the number of tiers is smaller than that of n. To make sure the growth of m is evenly distributed over the N levels, the parameter m grows at a slower pace, i.e. M/N, than n.

$$m = \left\lfloor 1 + (currLevel - 1) \cdot \frac{M}{N} \right\rfloor \tag{3.8}$$

Figure 3.3 (a) shows a progression example of two parameters with the parallel growth of difficulty level. The parameter n goes all the way up to its highest tier. Similarly, parameter m rises at a slower pace due to less number of tiers. As the difficulty level proceeds from level 3 to level 4 and from level 5 to level 6, both parameters are increased simultaneously.



(a) (b)

Figure 3.3: Comparison between two progression schemes (a) Parameter trend example when level difficulty progresses in parallel (M = 3, N = 7, T = 7); (b) Parameter trend example as level progresses in sequence (M = 3, N = 7, T = 7)

For **sequence progression**, the number of total levels is:

$$T = N + M - 1 \tag{3.9}$$

The progression of parameter m is designed to be distributed throughout the whole process. First, i stores the following value:

$$i = \left\lceil \frac{T}{M} \right\rceil \tag{3.10}$$

For parameter m, its value at first level (i.e. $Lv.1$) and end level (i.e. $Lv.T$) is 1 and M respectively. In between, the value of m is derived as:

$$m = \begin{cases} \dfrac{currLevel}{i}, & currLevel\%i = 0 \\ \left\lceil \dfrac{currLevel}{i} \right\rceil, & \text{others} \end{cases} \tag{3.11}$$

As only one parameter can be increased each time, when parameter m is decided n can be then calculated accordingly:

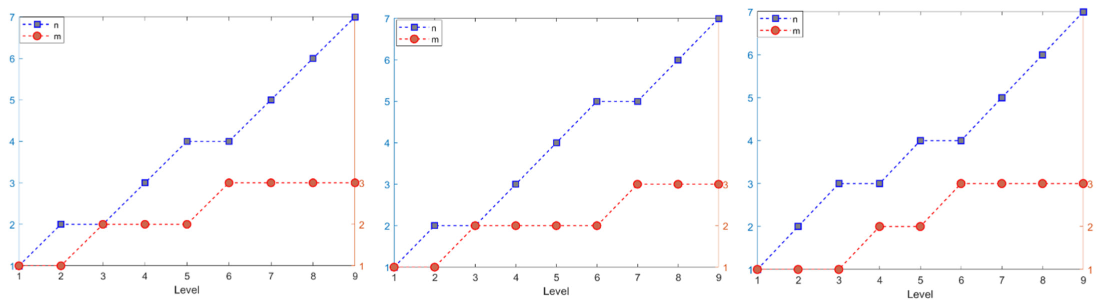
$$n = currLevel + 1 - m(currLevel) \tag{3.12}$$

Figure 3.3 (b) shows one example of two parameters with the sequence progression. Compared with parallel progression, the parameters are increased at a slower rate because only one parameter can be increased each time. Based on this, having the choice of the two progression scheme helps to suit more patients when performing different tasks.

One advantage that can be gained from the sequence progression scheme is randomness. It can happen when both parameters are eligible for an increase, that is $currLevel\%i = 0$ in current assumption:

$$m = \frac{currLevel}{i} + 1 \tag{3.13}$$

Figure 3.4 shows another three possible progressions after applying the randomness. By incorporating the randomness, the game has the potential to provide more variation and diversity for patients.



(a) (b) (c)

Figure 3.4: Three parameter-progression examples when level difficulty randomly progresses in sequence (M = 3, N = 7, T = 7)

Besides, both parameters either increase by 1 or keep their tiers each time and no parameter decreases its tier during whole difficulty progression to avoid difficulty overlap, which we call it progression uniformity. Not only can this scheme help attract patients but also it prevents them from learning from the game routine.

The concise representation of difficulty level with the proposed progression scheme is also helpful. By encapsulating two or more parameters and represent them with one integer ***currLevel*** for each gait rehabilitation task, it makes therapists understand the challenge level and adjust the difficulty with a minimum cognition effort. As the number of parameters increases to three, a similar relationship can be derived given the assumption in table 3.2.

Parameters	l	m	n
Tiers	$1, 2, 3, ..., L$	$1, 2, 3, ..., M$	$1, 2, 3, ..., N$
Steps	$L - 1$	$M - 1$	$N - 1$
Condition	$N \geq M \geq L$		

Table 3.2: Parameter assumptions, a triple-parameter condition

When three parameters are increased in sequence, the total level number T is derived as:

$$T = N + M + L - 2 \tag{3.14}$$

To ensure uniformity, first, one parameter should be set as the main variable. Here, parameter m is selected, which can choose to either increase its difficulty or keep the current tier.

$$m = \begin{cases} \frac{currLevel}{i} \text{ or } \frac{currLevel}{i} + 1, & currLevel\%i = 0 \\ \left\lceil \frac{currLevel}{i} \right\rceil, & \text{others} \end{cases} \tag{3.15}$$

Based on parameter m, the tier of parameter n and l can be calculated correspondingly:

$$n = \begin{cases} 1, & currLevel = 1 \\ n(currLevel - 1), & currLevel\%i \neq 1, currLevel\%j = 0 \\ currLevel - m(currLevel) - l(currLevel) + 2, & \text{others} \end{cases} \tag{3.16}$$

$$l = \begin{cases} currLevel - m(currLevel) - n(currLevel) + 2, & currLevel\%i \neq 1, currLevel\%j = 0 \\ l(currLevel - 1) & currLevel\%i = 1, currLevel\%j \neq 1 \\ \left\lceil \dfrac{currLevel}{j} \right\rceil, & \text{others} \end{cases} \tag{3.17}$$

Figure 3.5 shows a part of possibilities when parameters are increased in sequence. It can be noticed that one and only one parameter increases its tier each time. Besides, for all the three parameters, the increment is distributed over the whole progression.

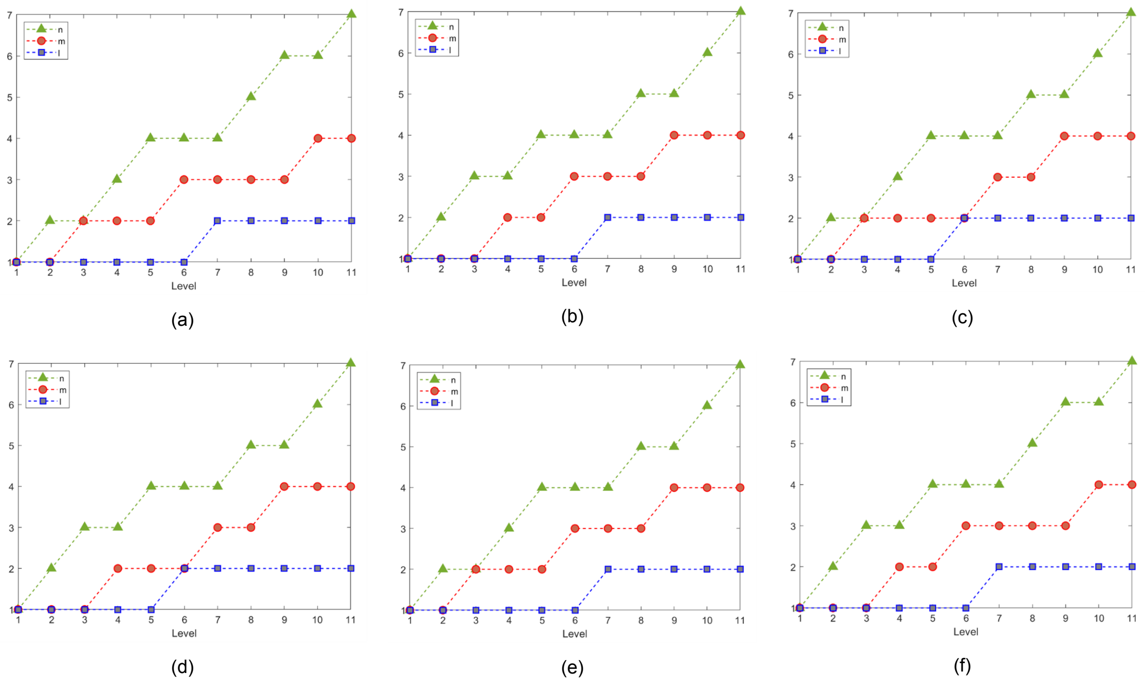


Figure 3.5: Six examples when there are three parameters defining a training task and progressing in sequence (N=7, M=4, L =2)

During the gameplay, the difficulty decision module updates the corresponding value of each parameter based on the calculated tiers when there is a change in the current difficulty level.

3.3.2. Task integration

Integrating different gait exercises into the same game level to improve the difficulty is an auxiliary method to the above two progression schemes. Adjusting the difficulty in the form of clinical tasks integration is to encourage patients to devote more physical (even cognition) effort in a new game scene. Several design principles are proposed in order to make the integrated levels balanced and appropriate.

The first principle is that task integration should be single-skill oriented. Despite the integrated levels that can call for more comprehensive gait ability to accomplish, it should have an emphasis on the single skill. To achieve this, first, the integration is supposed to take place only after the patients show a consistent improvement in the current training task. It is also advisable to let therapists decide when and how to integrate different tasks into the current level. The difficulty adjustment for the integrated task(s) can also be less sophisticated, which can be kept at the level where the patient is proficient. In addition, the incorporated task(s) should have an overall lower challenge level based on clinical experience. This will not only prevents patients from exhaustion by doing some actions that are far beyond their current ability, but also give them a chance to review and consolidate basic gait movements. Last but not least, the integrated tasks should not conflict with the main task. In VR games for gait rehabilitation, the area of walking surface as well as the visual information are rather limited. In this case, every effort should be made to ensure that the content of the original level is not affected by the introduced game elements.

The second principle is to make a meaningful combination. In serious games, the motor learning component outweighs entertainment. One of the main goals of gait rehabilitation is to assist patients in regaining their gait abilities to handle different situations in real-life. To promote motor knowledge transfer, the combination of separate gait task is desirably to resemble the life challenges to a larger extent. Possible interesting and natural task combinations are also able to attract patients under the condition that the whole level design is meaningful in real-life. A concrete implementation of this will be mentioned in the next chapter.

3.4. Procedural level generator

To achieve adaptivity, game elements are supposed to be generated in real-time so that adjustment can take effect when necessary. Procedural content generation (PCG) is therefore regarded as a helpful tool for adaptation. To make PCG support the adaptation scheme in a desirable way, the following factors need to be considered. First, a level generator is required to provide clinically effective game content. A serious game prioritizes its primary goal in its game design. When it comes to the context of gait rehabilitation context, the primary goal generally refers to help patients restore their gait functions after stroke and Parkinson's disease. It varies depending on the patients' conditions and gait rehabilitation phase, which includes muscle strength improving, steady-state gait, gait adaptability, dual-tasking, etc. Usually, each goal encompasses several related sub-goals as concrete tasks for patients to accomplish. To provide a targeted rehabilitation, these tasks are then mapped into the movement challenges in the game, which are responsible to guide and encourage patients to stretch their bodies. The way of delivering the game content determines how it is generated. When performing gait training with semi-immersive VR, the procedural generation is focused on the placement and combination of level elements to provide a reasonable difficulty level. Training with a fully immersive VR, the level generator also focuses on the modeling of 3D objects and the generation of game environments.

Next is the choice of the game settings and the game art where gamified elements should be displayed. Game settings describes in which kind of game scenarios the patients is playing in. There are many factors that affect the choice of game settings, which include culture, patient's personality, age, personal preference, etc, as researched by Pinto et al. [51] and Taut et al. [59]. In the former survey, most patients' preferences for the rehabilitation virtual environment are nature and sports. The latter survey, on the other hand, discovered the fantasy scenario to have the greatest impact on rehabilitation. In the practical design, all these settings can be competitive candidates depending on the targeted patients. The choice of game art in rehabilitation, by comparison, is more flexible. Through reviewing recent games for gait rehabilitation, common art styles include pixel art [26], hand-drawn art [24], as well as vector art [49]. The choice of game art form affects the way the game is presented, the complexity of the scene, etc.

Dividing a long-term rehabilitation process into small pieces of achievements is a good way to motivate patients to make progress. The length of each level segment is also a prominent property of the level generator. The length can be either restricted by physical conditions or set by therapists. For example, walking from one end of the rectangular workspace to the other can naturally divide the level into several segments with a fixed distance. The game could also involve walking in an immersive endless world with a VR device. The duration for each level segment is then set by therapists based on their experience and endurance of each patient.

The last focus on the generator is the variation it brings to the game. As mentioned before, there are several parameters describing the challenge levels for each task. These parameters should also be well-preserved when mapped from physical movements into gameplay action. Thus, the same parameter sets should represent levels with the same difficulty. One advantage of PCG is to provide less predictable game content by using a random or pseudo-random process. Such randomness can be utilized to affect in-game parameters that are not directly related with difficulty level. While bringing diversity to the game, the randomness may also have a negative impact on the difficulty level. Hence, the randomness of PCG needs careful design.

3.5. Conclusion

This chapter proposes an adaptation scheme to steer the procedurally generated levels for gait rehabilitation. The generic player modeling method categorizes the performance-related metrics in gait training into accuracy and efficiency aspects. To provide patients with adequate and diversified challenge levels, the difficulty adjustment strategies consisting of parameters-progression schemes and therapy goal integration methods are designed respectively.

4

Prototype implementation

This chapter describes an implementation of a standalone prototype which makes use of the aforementioned adaptation scheme to provide a personalized gait rehabilitation experience. It first introduces its rehabilitation context and gives an overview of the prototype components. The chapter then focuses on how to generate game content to stimulate the clinically desirable movements as well as how to appropriately steer that generation. To better encourage patients as well as support the therapists in the rehabilitation exercise, the evaluation of the patient's performance is recorded and visualized through a graphical user interface.

4.1. Prototype overview

To begin with, the clinical requirements are specified to describe the context and purpose of this prototype. It is followed by the illustration of the system composition, which describes the composition of the prototype and how they interact with each other.

4.1.1. Clinical objectives

The choice of rehabilitation technologies can vary depending on different gait rehabilitation phases, which subsequently affects the selection of interaction method and game design. One possible rehabilitation example after a stroke or Parkinson's disease [60] is illustrated in Figure 4.1, which consists of therapy goals at different recovery phases. The y-axis depicts the significance and relevance of each therapy goal at a given time. While these therapy goals cover upper-limb, gait as well as balance tasks, the focus of the following analysis remains on gait rehabilitation. At an early phase of rehabilitation, patients are usually in an acute condition and they are required to perform some relatively basic lower extremity training to restore basic movement skills. When entering half of the rehabilitation phase, therapy goals typically focus on step initiation, muscle strength as well as standing balance.

The target population of the proposed prototype is patients at the late phases of gait rehabilitation, and the purpose is to help them tackle walking challenges in daily life. According to neural science and human kinetics, training tasks are supposed to be similar to desired learning outcome, which is also referred to as task specificity or practice specificity [61]. Merely being able to put one foot in front of the

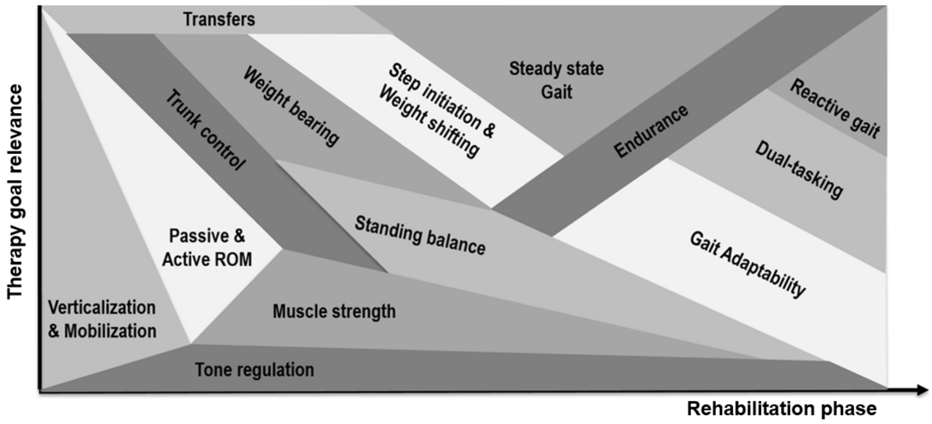


Figure 4.1: One example setting during the rehabilitation course [60], y-axis occupation depicts the significance and relevance of each goal at any time. ROM stands for range of motion.

other is not sufficient for everyday walking. Therefore, gait adaptability and dual-tasking in Figure 4.1 are chosen to feature our prototype in the implementation, in order to speed up the transfer of motor function progress into real-life skills outside therapy. Gait adaptability is defined as the ability to adjust the gait pattern to adapt to different walking environments. Furthermore, dual-tasking is meant to aid patients to avoid the so-called dual-task interference [62], which usually happens when performing two tasks simultaneously. Both therapy goals can be further divided into a series of concrete subgoals as shown in Table 4.1.

Therapy Goal	Subgoals	Task descriptions	Real-life examples
Gait Adaptability	Slalom walking	Slalom over the length of the workspace	Walk on a curved road.
	Obstacle avoidance	Bypass obstacles	Avoid objects (trees, road signs, etc.) in the way.
	Speed adaptations	Increase/decrease walking speed	Speed up to catch the departing vehicle. Slow down the pace to stop walking.
	Sudden stop	Make oneself no longer move	Stop walking to avoid bumping into someone.
	Turning	Perform a 180 or 360-degree turn	Rotate around so as to return to look backwards.
	Sidewards walking	Step sideways	Walk sidewards to pass a narrow space.
Dual-tasking	Planning	Perform actions in a logical order	Before cooking, one needs to: I. fetch the food (from the refrigerator); II. wash the food (near the sink); III. process the ingredients (at the table).
	Memory	Keep something in mind while performing actions	When shopping in a grocery, one needs to remember which items to buy besides upright walking.

Difficulty ↓

Table 4.1: Example of possible therapy subgoals for gait adaptability and dual-tasking and its real-life experience

The subgoals of gait adaptability are listed in an order of increasing difficulty, which covers different walking scenarios in daily life. The dual-tasking goal incorporates cognitive tasks into physical exercise. A simple but common example of the necessity of the latter is when someone is thinking hard about something while walking, he/she is prone to bumping into something or tripping over something. Thus, therapy subgoals such as planning and memory are proposed to help patients overcome dual-interference.

4.1.2. Rehabilitation technology

To assist in achieving gait adaptivity and dual-tasking therapy goals, at least two critical requirements should be met when opting for a gait-training device. First, the adopted technology should provide a natural walking experience to patients. Second, protection measures are necessary to prevent patients from falling. Natural walking asks for a workspace that is close to real-life walking. For one thing, the walking surface should be spacious enough for patients to contentiously take a step. For another thing, the way of walking is preferable to be overground walking rather than walking with treadmill devices. Not only does rehabilitation with treadmills produces more gait invariance, but it also restricts some significant movements in gait rehabilitation such as sudden stop or turning. While overground walking can increase the freedom of movement, it also requires more sophisticated robot dynamics to catch patients in the case of falls.

A three-dimensional overground body weight support (BWS) system RYSEN [39] of Motek is utilized in this project to seek a balance between these two requirements. As shown in Figure 4.2, the width of the rectangular workspace is between 1.3 and 2.4 meters, and the length is between 6 and 11 meters. Compared with Nintendo Wii Balance Board and treadmills, such a large area, if properly used, will ensure a flexible and diverse gait rehabilitation experience without suffering from gait invariance. Besides, the surplus of power for both horizontal and vertical movement is sufficient to prevent falling while not causing excessive accelerations, thus lowering the risk of hurting the patient. What's more, the walking trajectory of a patient can be measured in the RYSEN. When applying no force to patients along the horizontal direction, i.e. used as a BWS only, the RYSEN can provide insignificant tracking errors [39]. Therefore, the position information from the RYSEN system makes it easy to track patients without the need to wear additional sensors.

Figure 4.2: Concept diagram of RYSEN - A 3D overground body weight support system [63]

4.1.3. Prototype architecture

The main components of the prototype and their relationship are illustrated in a scheme in Figure 4.3. To start a gait training, the therapist first selects a therapy goal for the patient through the interface. The progress data of each patient per therapy goal is stored in the database, which is displayed through the interface as well. Together with the therapist's clinical experience, the proper starting difficulty level for the selected exercise is decided.

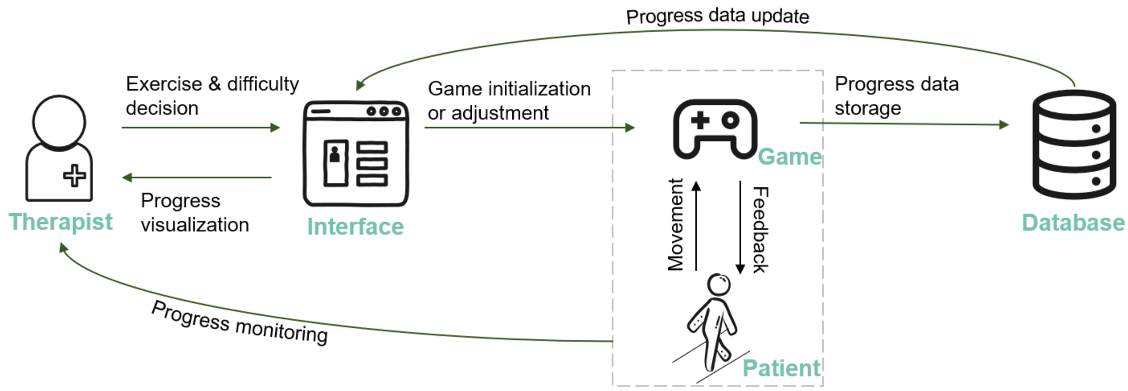


Figure 4.3: Scheme of the system

The core of this prototype, developed with the Unity engine, is the interaction between the patient and the game, which are connected with a bidirectional arrow in the scheme. The game captures the patient's motion information as input from the tracking device and generates game content accordingly. In a clinical environment, it is possible that a therapist has to look after multiple training sessions of different patients at the same time. Consequently, he/she may not be able to pay attention to the performance of each patient from beginning to end. The game then autonomously adjusts the difficulty level itself by utilizing the adaptation scheme described in the previous section. The collected performance-related information in-game which is used to predict the coming difficulty level is also visualized to the patient at the end of each level segment for feedback. The autonomous game system will not take the therapist's place completely. At some point in today's training, the therapist may wish to modify the difficulty level in addition to the game's adaptation strategy based on his/her observation over time. To better support such a difficulty control from the therapist's side, manual adaptation that changes the difficulty level through the interface is also available.

4.2. Design of level generator

A careful game design provides a solid support for the implementation of a procedural level generator. This section first gives a justification of immersion type, game scenario, as well as game art selection. To generate appropriate and effective game content, a mapping from a list of therapy goals into gameplay actions is then made and justified. Last, it gives a list of rules concerning the utilization of the rectangular workspace as well as patient detection and representation in the context of gait rehabilitation with the RYSEN.

4.2.1. Choice of the immersion type and game setting

Immersion type indicates the interaction way between the patient and the game. Floor projection is the proposed immersive technology that fits the RYSEN setup. Two critical features of the RYSEN are taken into consideration when making the selection. First, the immersion type should make full use of RYSEN's three-dimensional overground body weight support system. In another word, the immersion type should be able to stimulate the patient to explore within the rectangular workspace instead of taking steps or even standing still at the same place. Second, the patient's position and rotation information provided from the RYSEN should be considered as helpful data for both interaction and evaluation. Floor projection preserves a more natural walking experience and genuine visual-spatial relationship compared with HMDs. It also advantages itself in better scalability and cost-efficiency compared with interactive LED floor. The flexibility of the floor projection scheme is only reflected in the adaptability to different sizes of the RYSEN workspace. For a given size of the RYSEN, the ground projection can make the projected area exceed the size of the work area when necessary. The extra projected content is able to provide additional game scene through the visual channel to ensure the immersion and richness of the game. It can also provide some information that the doctor expects the player to see. The game system takes the patients' central position and rotation information from the RYSEN device as an input. By combining it with time information, the position of game elements, and the patient's dimensions, the system is able to monitor the training progress in a relatively complete and accurate way.

The proposed game setting encourages players to accomplish each desired rehabilitation movement within a natural environment by adopting nature-related scenarios. For one thing, there are abundant nature-related inspirations to offer various scenes according to different clinical goals. For another, a nature-related setting is able to cater to a wider range of patients of different ages, genders, personalities, and cultural backgrounds. Displaying nature-related game elements in pixel and vector art presents concise objects while reducing visual complexity. Compared with photorealistic style, they are less susceptible to the impact of the objective environment of the projection, such as the lumen and resolution of the projector as well as the reflection conditions of the ground.

4.2.2. Mapping between therapy goals and the movement challenges

To keep the research compact while ensuring a good variety, four subgoals are selected for further study in the prototype.

Slalom walking is overall the easiest subgoal in gait adaptability, which also has the potential to be integrated with other sub-goals. In slalom walking, the patient's position data is collected to detect whether he/she is walking on the generated path. Together with time information, the average walking velocity can be further derived to help clinical evaluation comprehensively. The second selected subgoal is **obstacle avoidance**. Apart from detecting if the patient keeps himself/herself on a path, the position information from RYSEN is also used to check collision between the patient and obstacles. Besides, performing obstacle avoidance training could happen on different road conditions, which could be either straight path or winding path. In this case, the combination of this subgoal with slalom walking can be implemented to learn what extent such integration can affect the global difficulty and bring benefits to gait rehabilitation. **Sidewards walking** is the third subgoal. In this subgoal, the rotation information also plays a vital role. By analyzing the angle between walking direction and facing direction, patient's performance in this sub-goal can be measured. In addition, unlike walking forwards, walking sidewards requires asymmetry efforts for lower limbs. In this case, it is worth investigating whether the proposed adaptation strategy can still support a personalized and effective training for patients with different conditions in both legs. The last subgoal is **memory task**. Unlike previous subgoals, this exercise is categorized as a dual-tasking therapy goal, which asks for both physical effort and cognitive effort. With the design and implementation of this subgoal, both generation levels and adaptation scheme can be studied to discover their potential.

Figure 4.4 illustrates the concrete game designs in several natural scenarios, which include garden (a) (b), beach (c), and forest (d). Game designs for gait adaptability goal emphasizes the precise and effective gameplay movements. By contrast, the design for dual-tasking goal pays more attention to the meaning and fun of the gameplay to balance both physical and cognitive efforts during training.

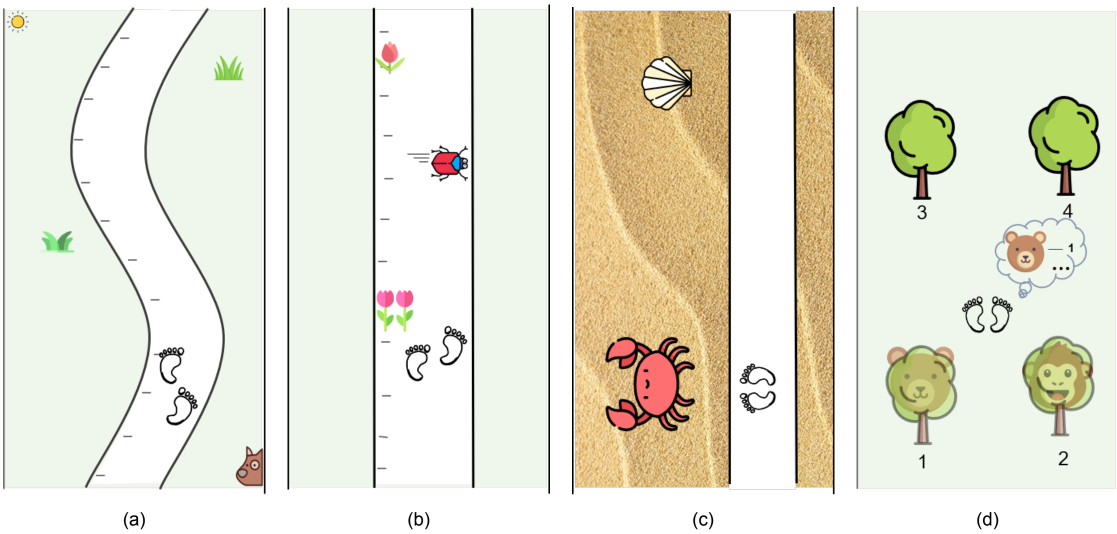


Figure 4.4: Concrete game designs for (a) slalom walking, (b) obstacle avoidance, (c) sidewards walking and (d) memory task therapy subgoals

Table 4.2 gives further elaboration of designs for each clinical subgoal and their connections with gameplay movements. Based on clinical experience, the scalable parameters that have effect on the difficulty of each subgoal are also mentioned in the last column.

4.2.3. Patient detection and workspace subdivision

The implemented prototype tracks and evaluates patients' training based on position and rotation information. It is possible that adding other walking ability related factors such as stride length, gait stability, and gait symmetry, can make the evaluation even more comprehensive. However, tracking such information requires additional markers. Wearing these, together with existing protection equipment, can cause extra hindrance to patients' normal walking. Utilizing markerless registration of body kinetics such as Kinect could be a solution, but the calibration procedures can require extra time. Considering the targeted group are in their later at later phase of gait rehabilitation, such information is less focused when evaluating the performance. Between concise and comprehensive patient measurement, the former is selected in this prototype. The patient is represented in a top-down 2D view as the game is projected onto the floor. As shown in Figure 4.5, the arrow below the circles represents the orientation of the patient. Each of the three circles has its own role in the level generation and patient detection:

- C_v is a visual outline of a patient. It is not for collision checking but describes a minimum acceptable space that will give patients the confidence to walk into this area, the diameter of which is usually equal to or larger than the normal distance between legs shown in Figure 4.6 (a). In the implementation, for instance, the width of the path, the distance between obstacles along the

Subgoals	Gameplay movements	Scalable parameters
Slalom walking	As shown in Figure 4.4 (a), a path in a sinusoidal layout is rendered for players to interact with. The player should keep himself/herself in the winding road when walking from start to end.	Parameters including the **width** of the path can be adjusted to change the difficulty level. The road can be irregular (i.e. with possible **random** factor in amplitude and frequency) to increase the difficulty level.
Obstacle avoidance	As in Figure 4.4 (b), a list of obstacles such as flowers, moving insects are placed along the path. When walking on the path, players should avoid them.	Three parameters including the **size**, the **number** and the moving **speed** of the obstacles can be adjusted to affect the difficulty level.
Sidewards walking	Mimicking the walking way of animals is also intriguing. In Figure 4.4 (c), by moving sidewards with the crab to the end, players will win a shell as a gift.	Both the **width** and **length** of the path can be adjusted to create different levels of difficulty.
Memory	In the memory game in Figure 4.4 (d) require patients the find out all animal pairs. When walking in the workspace, a patient needs to remember animals and their corresponding positions and possibly make appropriate path plans.	The number of **pairs** can be adjusted to change the difficulty.

Table 4.2: Elaboration of mapping from four separate therapy subgoals to gameplay movements and corresponding difficulty-related parameters

path should be greater or at least equal to diameter D_v.

- C_o is the collider circle which is used to check effective collisions between patients and game elements. As mentioned before, the current detection method in the RYSEN does not support precise track of patients' feet. Thus, patients are persuaded to avoid the obstacles instead of stepping over them for effective feedback. When bypassing obstacles, the distance between the legs may be smaller than standing or walking normally. To kkep encouraging patients to perform effective avoidance, the diameter is set to a closer distance between legs shown in Figure 4.6 (b) instead of the normal one shown in Figure 4.6 (a).

- C_g is a circle collider with a smaller diameter D_g, which represents the patient's center of gravity. This collider focuses on the center position of the patient. For example, it can be utilized to detect whether patients are on the road, or whether they enter a specific function zone of the RYSEN workspace.

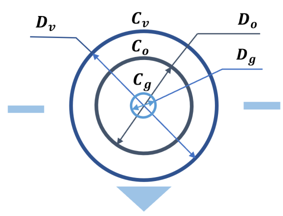


Figure 4.5: Three typical circles for patients' detection and level generation

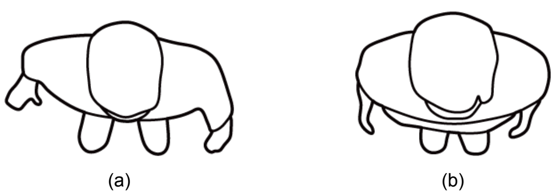


Figure 4.6: Human body diagram (top-down view): (a) normal walking or standing, (b) a case when legs are closer to each other

The functions of these three circles complement each other. In practical training, therapists can be assisted to provide reasonable training levels and obtain a reliable measurement of patients' position and performance by tailoring a list circle radius values for each of them.

To support interactions with patients, the RYSEN workspace is divided into three zones along its length as shown in Figure 4.7: left rest zone, training zone, and right rest zone. Two rest zones are mostly located at both ends of the workspace, where the patient finishes the last round of training, receive feedback, and prepares for the coming training session. The horizontal length of the rest zones should at least larger than D_v, to offer enough place for patients to stand still and make a turn. The training zone is the place where the levels are displayed. In this zone, the patient performs the desirable action by interacting with the game elements. At the same time, the prototype keeps track of the movement data and carries out an evaluation based on it. Because the length of the working area is generally less than 11 meters, depending on the patient's rehabilitation phase, a level is usually divided into several sections. In each section, the patients start from one end of the training zone and finish at the other. Some tasks such as sidewards walking, however, would be demanding for patients to walk sidewards up to ten meters long at the beginning. Shortening the length of the training zone is thus a solution. In this case, the location of the rest zone is no longer fixed at the nds of the workspace. Instead, the start and end positions for each level will be flexible according to the length of the training zone.

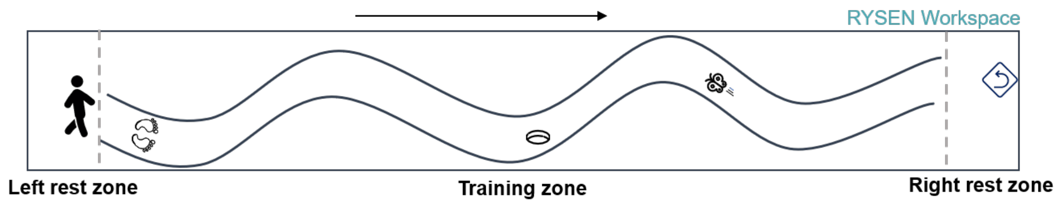


Figure 4.7: Diagram of three zones in the RYSEN workspace

4.3. Detailed description of movement challenge generation

This section focuses on the details of parameterized generation of four separate movement challenges based on the mapping table in last section. It starts with the fundamental generation, slalom path, the difficulty of which can be adjusted based on two parameters. With the detailed information of the walking path, generation rules for both obstacle avoidance and sidewards walking are then elaborated. At last, the memory task scene is described.

4.3.1. Gait adaptability challenges

Movement generation for three subgoals, including slalom walking, obstacle avoidance, and sidewards walking will be elaborated.

A. Slalom Walking

The center of the path for slalom walking follows a trend of a sinusoidal curve. The width of the road and the randomness factors are two main variables in difficulty adjustment. To make better use of the RYSEN workspace while ensuring road completeness and game fairness, the remaining variables are observing the following rules.

First, the default amplitude A extends the road to the upper and lower ends of the workspace.

Second, the frequency f of the slalom road should within an appropriate range which makes the road dense enough but does not cause overlap considering the width of the road. Otherwise, patients may walk in a straight line from start to end. Last, the phase ϕ should make the slalom path generated right in front of the patient to engage them. Based on these, a list of road positions are derived:

$$\mathbf{y} = randAmp \cdot A \cdot sin(f \cdot \mathbf{x} + \phi + randFreq) \tag{4.1}$$

where $randAmp$ describes the randomness in amplitude while $randFreq$ indicating randomness in frequency. Random factors should also obey the rules mentioned above. As for the $randAmp$, its value should always be less than or equal to 1. Similarly, $randFreq$ should not cause the path overlap. Besides, those random factors should take no effect at the starting point so that the ϕ can still ensure the path starts from the patient's position.

To visually present the slalom road and detect if the patient is walking on it, both collider and texture are applied. Figure 4.8 shows the procedure of mesh generation. P_1, P_2, and P_3 are three road points generated with equation 4.1.

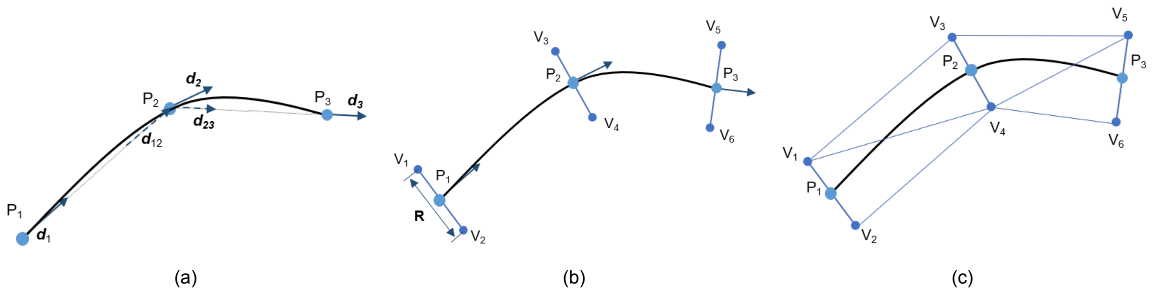


Figure 4.8: Path mesh generation: (a) compute the path direction at each point; (b) calculate the position of path vertices; (c) add triangle mesh to the path

First, the path direction at each point is computed. The direction of the starting point is the direction pointing to the next point (e.g. vector d_1 in Figure 4.8(a)). The end point's direction, on the other hand, points from its previous point (e.g. vector d_3 in Figure 4.8(a)). For the rest points along the path, their directions are the average of the sum of these two vectors (e.g. $d_2 = (d_{12} + d_{23})/2$ in Figure 4.8(a)). The positions of path vertices pair for each path point are then computed in equation 4.2 and shown in Figure 4.8(b).

$$V = P_i \pm 1/2 \cdot R \cdot d_i' \tag{4.2}$$

where the d_i' is the normalized orthogonal vector of d_i and R is road width. The triangle mesh is then built based on three adjacent vertices as Figure 4.8(c). The slalom path generator is presented in Algorithm 1.

B. Obstacle avoidance

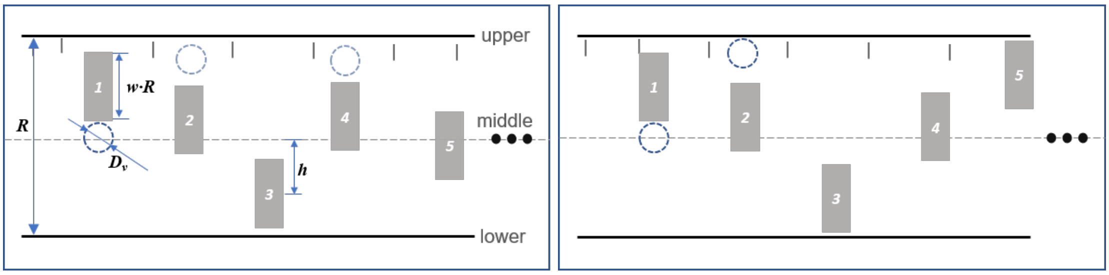
In levels designed for obstacle avoidance subgoal, the obstacles are placed randomly along the generated path. In the early stage, obstacles remain static at their initialization position. To balance the diversity brought by the randomness and side effects on the difficulty levels it may cause, some rules are proposed when placing fixed obstacles.

First, the distances between two obstacles should be greater than the visual outline of the patient (i.e. D_v) to provide a walkable route. As the obstacle avoidance goal aims to improve the patient's

Algorithm 1: Slalom path generation

Input: road width value R and randomness extent
Result: Generation of a slalom path with texture and collider
calculate a set of road points $\{P_1, P_2, ..., P_n\}$ along a sinusoidal curve (with possible randomness);
for $i \leftarrow 1$ **to** N **do**
  find and normalize the direction d_i at P_i;
  compute the orthogonal vector d_i';
  compute the position of two vertices V_{2i-1} and V_{2i} for P_i based on d_i' and R;
  convert V_{2i-1} and V_{2i} into coordinates in the uv space;
  if $i < N$ **then**
    store index information of vertices for triangle T_{2i-1} and T_{2i};
  end
end
construct mesh and collision area based on derived vertices and triangles;
apply texture on mesh using uv values;

ability to bypass obstacles and route planning, the placement of obstacles should encourage patients to achieve it. Hence, the second rule, in general, is to avoid offering straightforward routes, which can be either too spacious or intuitive. As illustrated in Figure 4.9 (a), the width of each obstacle wR is proportional to the road width R. The offset of each obstacle is h and the direction is $sign$. The minimum size of the obstacle is greater than $R/2 - D_v$ and less than $R - 2 \cdot D_v$ (i.e. will not block the road completely).



(a) (b)

Figure 4.9: Obstacle placement example (a) one possible obstacle placement and the undesirable position of obstacle 5 (b) same obstacle arrangement for obstacle 1 to 4 but with a proper placement of obstacle 5

To describe the continuous empty space, the road is divided into three types of empty space, which are upper, middle, and lower empty space. For example, in Figure 4.9 (a), obstacle 1 and 3 offers free space around the middle of the road, and obstacle 1, 2, 4, and 5 leave out free space at the lower part of the road. Obstacle 2 to 5 offer upper continuous empty space, where the patient can take a straight route without the need to avoid any of these four obstacles. Figure 4.9 (b) gives a solution, which changes the position of obstacle 5 to 'block' the straight path. Table 4.3 quantitatively summarizes the conditions for leaving upper, middle, or lower empty space and the placement of next obstacles to end the continuous space. The details are presented in Algorithm 2 following the similar ways of the above analysis and based on Table 4.3. If h and $sign$ meet one or two conditions in the table, the related $accum_sign$ is then increased by one.

The levels for dynamic obstacles avoidance can be implemented based on static obstacles. Starting from the initial position, the h then changes smoothly between $-\frac{1}{2}R(1-w)$ and $\frac{1}{2}R(1-w)$. To give patients clear clues on which route to choose, the moving obstacles are supposed to maintain a

Empty area	Conditions	Solutions
Upper empty space	$0 \le h \le \frac{1}{2}R(1-w) - D_v$, $sign > 0$ or $0 \le h \le \frac{1}{2}R(1-w)$, $sign < 0$	$\frac{1}{2}R(1-w) - D_v < h < \frac{1}{2}R(1-w), sign > 0$
Middle empty space	$\frac{1}{2}(D_v + wR) < h < \frac{1}{2}R(1-w)$	$0 < h < \frac{1}{2}D_v$
Lower empty space	$0 < h \le \frac{1}{2}R(1-w) - D_v$, $sign < 0$ or $0 \le h \le \frac{1}{2}R(1-w)$, $sign > 0$	$\frac{1}{2}R(1-w) - D_v < h < \frac{1}{2}R(1-w), sign < 0$

Table 4.3: Conditions for three empty spaces and suggested position for the coming obstacles

suitable moving speed, i.e. h should be adjusted at a fixed rate.

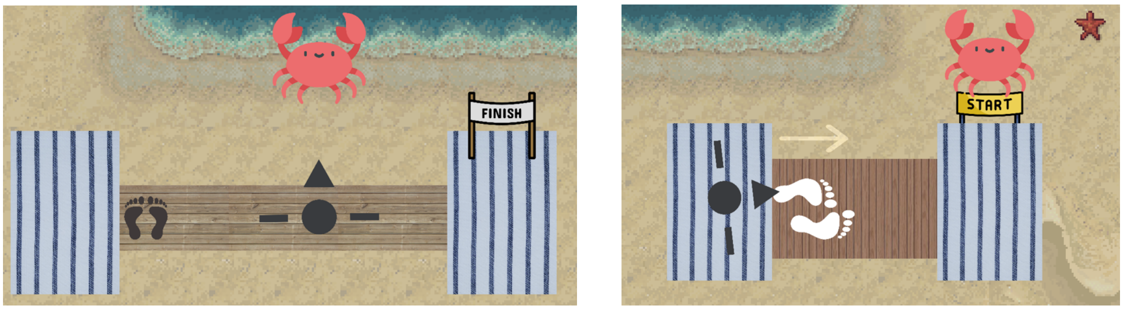
Algorithm 2: Static obstacle placement

Input: Total obstacle number To, obstacle size w, road width R, and length L of training zone
Result: Obstacle positions $\{O_1, O_2, ..., O_n\}$ for patients to avoid
Initialization: $\Delta x \leftarrow \lceil L/(resolution - 1) \rceil$ `// resolution - number of road points`
$N \leftarrow \lceil (D_v + w \cdot R)/\Delta x \rceil + 1$ `// how many road points a obstacle takes up`
$accum_1 \leftarrow 0$, $accum_{-1} \leftarrow 0$, $accum_0 \leftarrow 0$; `// accumulated empty space`
$lastSign \leftarrow 0$; $I_0 \leftarrow 1$; `// index of road point P`
$S_1, S_{-1} \leftarrow max\{2, 0.4 \cdot To\}$, $S_0 \leftarrow max\{2, 0.4 \cdot To - 1\}$; `// reference for accumulation`
for $i \leftarrow 1$ **to** To **do**
  $I_i \leftarrow$RandInt($N - 1 + I_{i-1}$, $resolution - (To - i) \cdot (N-1) - \lceil N/2 \rceil + 1$) ;
  if $accum_1 < S_1 - 1$, $accum_{-1} < S_{-1} - 1$ ***and*** $accum_0 < S_0 - 1$ **then**
    $h \leftarrow$ Random(0, $0.5R \cdot (1-w)$) ;
    $sign \leftarrow$ randomly choose either 1 or -1;
    if *sign = lastSign* **then**
      $accum_{sign} \leftarrow S_{sign}$; `// obstacle can't on the same side over twice`
    else
      update $accum$ information based on h and $sign$;
    end
  else
    choose proper value of h and $sign$ for corresponding empty area;
    clear corresponding $accum$ data;
    update remaining $accum$ information based on h and $sign$;
  end
  compute the position and rotation of O_i ;
  $lastSign \leftarrow sign$;
end

C. Sidewards walking

Compared with previous subgoals, sidewards walking training is considered to be more difficult to accomplish. As suggested by therapists, the initial distance for patients could start from around 3 meters each time, which is less than the length of the typical training zone shown in Figure 4.7 in the RYSEN workspace. Besides, as described in Section 4.2, a non-player character crab is introduced into the game for sidewards walking. Not only can the crab be the patient's companion during the training, but also the crab's way of moving is consistent with the desirable movement. Considering the patient is supposed to walk as straight as possible, the vertical space the exercise takes up (e.g. 1 meter at most) is also less than the width of the training zone. Based on the analysis above, the typical training zones will be divided into sections along the horizontal direction to suit the ability of the patient. The vertical space can also be well utilized, apart from a path for sidewards walking, the remaining area can be used to display the movement of the crab as shown in Figure 4.10 (a), which follows the position of the patient.

With the progression of the game difficulty, it is possible that the starting point is in the middle of the RYSEN workspace while the length for the current sidewards walking level is larger than the half-length of the training zone. In this case, the game first guides the patient to walk in an opposite direction to a new starting zone which has the same length as the normal rest zone. The crab will also be waiting for the patient at the new starting zone as Figure 4.10 (b). After the patient reaches the ideal position, a new sidewards walking level with adequate length is generated.

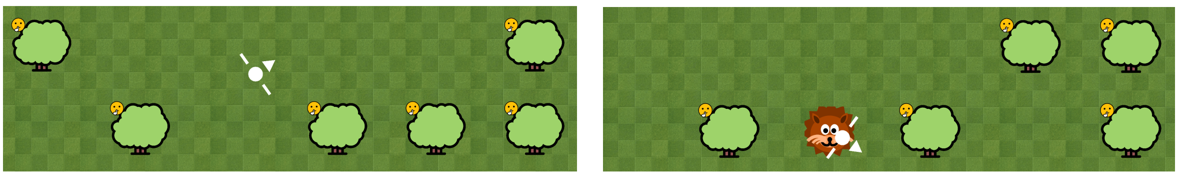


(a) (b)

Figure 4.10: Sidewards walking level example:(a) typical scene for sidewards walking from the left rest zone to the right rest zone, with the crab following the patient, (b) signs guiding the patient to walk normally to the new starting zone when the length for the new sidewards walking exercise exceeds the length that can be provided from the current zone.

4.3.2. Dual-tasking challenges

In the game design for memory therapy subgoal, the trees in the levels stands for the puzzle of the task and patients are required to remember the animal behind it. First, a matrix storing all feasible potions for tree placement is built. The procedural levels utilize the whole RYSEN workspace as the training zone. Considering the size of the workspace, the width of the training area can accommodate up to two rows of trees, the length of which is $(2 \sim 2.5) \cdot D_v$. The remaining space along the longitudinal direction can be used as a passage for patients to pass. The maximum capacity of trees in each row depends on the length of actual workspace. Fixing the positions of tress could not only bore the patients but also simplifying the memory difficulty. The generator places the trees at random position based on the previous matrix after assigning animals to them based on random shuffle. Figure 4.11(a) (b) shows the example of three pairs of puzzles.



(a) (b)

Figure 4.11: Memory task levels with different tree placement: (a) at the beginning of the game (b) when the player stands still in front of a tree for a while, the animal behind the tree will appear

Patients can start memory task training at any place of the RYSEN. Each time a patient walks to a tree, there's a process for him/her to confirm the option, that is, discover the animal behind this tree. The basic movement which is standing still is meaningfully encoded here. As shown on the sign nearby the tree in Figure 4.11, after staying still for a period of time (i.e. the center of the patient remains on the tree), the animal hiding behind the tree will appear. It will remain in its current state until the patient finds the next animal. If the two animals are the same, then both animals and trees that shelter them will disappear, otherwise, the two animals will hide. A patient succeeds when he/she 'clears' all the trees in the level.

Random placement of puzzles (i.e. trees) and answers (i.e. animals behind it) on the one hand prevents players from learning the game routines, but it also brings a certain degree of imbalance in movement challenges. For example, in one training session, the patients happened to match the same animal in the first two attempts, which greatly reduced the memory complexity and increased the likelihood that the patient will complete quickly. Another possibility could be that two trees sheltering the same animals are rather remote from each other, so a patient needs to walk further than average. After considering the above issues, it is no longer wise to assess a player's performance only by game time or average walking speed. Instead, the focus of the game for this subgoal is to exercise and encourage patients to better balance both physical and cognitive tasks to complete more complex tasks. Thus, the accuracy of matching, that is, the number of repeated visits to the same tree, is considered to be a superior indicator of the patient's ability.

4.4. Adaptive steering of level generator

This section introduces the details of adaptively steering a movement challenge generator for each therapy goal. The prototype assesses the patient's performance based on the aforementioned player model and adjusts the difficulty level by applying the parameter-progression schemes and level integration strategy. According to the features of each therapy goal, the implementation is described in a way that can better highlight the superiority and universality of each adaptation scheme. It also describes the possible involvement of therapists' control and interaction method.

4.4.1. Dynamic difficulty adjustment

Both sequence progression scheme and parallel progression scheme are applied to adaptively control the level generator for slalom walking subgoal based on the player model. Following the idea in Section 3.2, a typical evaluation form for slalom walking is shown in Table 4.4 based on both accuracy and efficiency aspects.

Evaluation aspects		Accuracy		Efficiency
Factors		Off-road times F	Off-road duration percentage P	Average speed V
Reference values	Initial values	1	10%	0.7 m/s
	End values	Remain unchanged		Decreases 15% (i.e. $15\% \times 0.7$)
Recommended weights		0.65		0.35

Table 4.4: Evaluation table for slalom walking subgoal

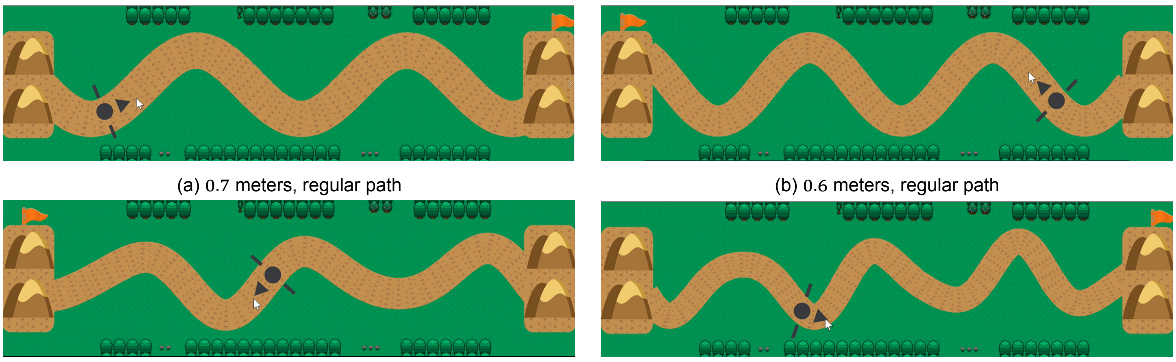
In each level segment, the off-road time factor F refers to the frequency that a player walks out of the road and the off-road duration percentage P indicates the percentage of duration the player spends outside the road to the total time. Merely evaluating player's accuracy performance based on off-road times F could offer the chance for players to cheat. Even if the player only commits one mistake in one level segment, such a mistake can last for the whole level segment to make himself/ herself 'successful', which is undesirable. Introducing off-road duration percentage factor P to restrict the time that a player is off the curve is beneficial. On the other hand, if the factor off-road times F is ignored, players could also take a shortcut on a denser sinusoidal road if their collider diameter is set relatively large. Based on the analysis, both off-road times F and off-road duration percentage factor P should be taken into account to evaluate a player's accuracy performance in slalom walking. Besides, encouraging patients to finish the current in less time can make patients stretch themselves, thus speeding up the transfer of motor abilities. In each level of slalom walking exercise, the distance a player has to walk to succeed in each exercise can vary from curves to curves even in the same difficulty level. This is mainly caused by the randomness in frequency and magnitude values. As a result, average speed factor V is considered to be a fairer metric to evaluate a player's performance from the efficiency aspect instead of the factor total time. With the difficulty increasing, it can be foreseen that the sinusoidal curves would become more irregular and narrower. If the reference average value remains the same as the initial level, it could be harder for patients to balance accuracy and efficiency, which may in turn affect the engagement of the player and even rehabilitation outcome. Hence, making predefined reference values difficulty-related as equation 3.2 when necessary is meaningful.

The score of the patient in the current level segment is then calculated based on equation 3.1 to represent the proficiency. When a patient keeps on the path very well but at a slower pace, his/her score is 0.3. When a player hurried to the point but did not stay on the road, his score will be a negative number, which means such behaviors are not encouraged by the system. Only when both efficiency and accuracy are satisfied, will a patient get the 1 score (the highest score). If accumulated, the game system automatically improves the difficulty level at a certain moment depending on the value of s in equation 3.4 or 3.5. The decision for the range and increment of two difficulty-defining parameters is listed as follows, which can also be adjusted by therapists via an interface when needed.

- **road width** (continuous variable): ranges from 0.3 (i.e. visual outline of the patient D_v) to 1.0 meters, with steps of 5 (i.e. 8 tiers in total) ;
- **randomness** (discrete variable): start from no randomness, to randomness in amplitude, then to randomness in frequency, and randomness in both at last (i.e. 4 tiers in total).

The progressions of the two parameters with a different choice of progression scheme are displayed in Figure 4.12. In the beginning, the path has a width of 0.7 meters with a regular shape (see Figure 4.12 (a)). With the sequence progression scheme, every difficulty improvement only increases the tier of one parameter in an alternate way. In the coming difficulty level, the $roadwidth$ parameter is first decreased by 0.1 meters (Figure 4.12 (b)). If the performance keeps increasing, the $randomness$ factor is then increased to tier 2, i.e. the amplitude is not fixed. At the same time, the width of the road is fixed (Figure 4.12 (c)). That is to say, with the sequence progression scheme, the slalom level follows the sequence from (a) to (b) then (c). By contrast, a parallel scheme increases the parameters when they are both eligible to be increased (as from (a) to (c)). Else, only the eligible parameter $roadwidth$ is manipulated (from (c) to (d)). The parallel progression scheme, in this case, means that when the

$roadwidth$ parameter is increased twice, the $randomness$ parameter is increased once. This can be explained by the fact that the $randomness$ is considered to have more impact on the difficulty level compared with $roadwidth$. Therefore, the $randomness$ parameter is increased only when a patient proves that he/she can continuously cope with the decrease in $roadwidth$.



(a) 0.7 meters, regular path

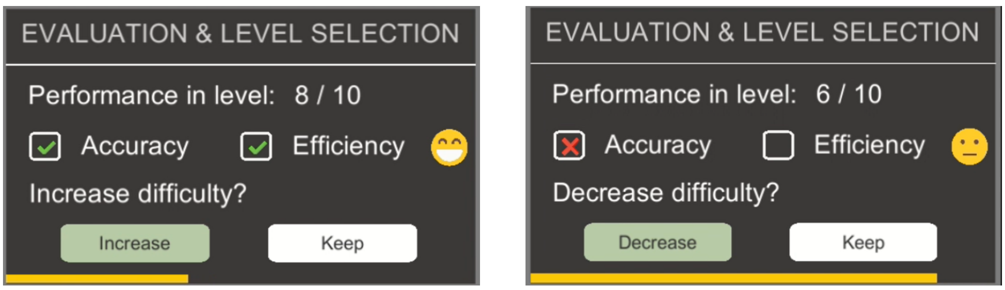
(b) 0.6 meters, regular path

(c) 0.6 meters, path with randomness in amplitude

(d) 0.5 meters, path with randomness in amplitude

Figure 4.12: Difficulty progression with different progression scheme. (i). Sequence progression scheme: (a)→ (b) → (c). (ii). Parallel progression scheme: (a)→(c)→(d).

To involve the therapists in the difficulty adjustment, the assessment of each patient in the current level segment is displayed to therapists via a panel as Figure 4.13. In real clinical scenarios, such a panel can be displayed on desktop PCs or mobile devices. Following the similar routine of player modeling, its information is visualized based on accuracy and efficiency aspects. Suggested difficulty options are concisely proposed to therapists for the coming training. Physiotherapists can either adjust the difficulty of the game based on their own observation and experience, or leave the system running automatically if they agree with the game system.



(a)

(b)

Figure 4.13: Level progression panels for therapists' control when the patient (a) succeed the current level (b) is failed in the current level.

4.4.2. Separate difficulty adjustment

Not all gait movements require symmetry effort for the lower limbs like normal walking. Assuming that the patient is facing a fixed direction, moving sidewards to the left requires more effort on the left legs and vice versa. Considering the target group who suffers from gait impairment may also have different conditions in each leg, the difficulty adjustment strategies can be fine-tuned in order to track the performance and adjust the difficulty for each direction.

The evaluation scheme in sidewards walking is in general similar to the one in slalom walking and is shown in Table 4.5. For the efficiency aspect, the game should inspire the patient to move at a higher rate by constraining the training duration for each level section. For the accuracy aspect, the patient is also supposed to be keeping himself/herself on the road. Another factor U describing the accuracy is to ensure the patient is moving sidewards instead of just performing normal walking. The prototype first checks if the patient is facing the crab's direction. After that, it measures the angle between the facing direction and moving direction. If the angle is not between $75 \sim 105$ degrees, it is determined that the player has not completed the action as required. If such undesirable movement lasts long, the patient is considered to not move sidewards accurately.

Evaluation aspects		Accuracy			Efficiency
Factors		Off-road times F	Off-road duration percentage P	Undesirable movement duration U	Average speed V
Reference values	Initial values	1	10%	1 s	0.7 m/s
	End values	Remain unchanged			Decreases 10% (i.e. $10\% \times 0.7$)
Recommended weights		0.7			0.3

Table 4.5: Evaluation table for slalom walking subgoal

Assuming a patient starts the sidewards walking exercise where the difficulty for both directions is the same. Due to the severer disability in the right leg, the patient walks slow and sometimes fails to continue moving sidewards. Separate difficulty adjustment is then applied to adjust the difficulty for each direction separately so as to provide suitable training for both legs as Figure 4.14.

(a) $roadwidth$: 0.8m, $roadlength$: 4m

(b) $roadwidth$: 0.5m, $roadlength$: 7m

Figure 4.14: Sidewards walking levels for sidewards walking to the right (a) and to the left (b) after applying separate difficulty adjustment for several round.

4.5. Integration of different therapy goals

In the context of gait adaptability and dual-tasking, apart from adjusting the difficulty level for each separate subgoal, combining movements for different subgoals in the same level can also affect the difficulty. Based on two requirements proposed in section 3.3, the relationship between subgoals are shown in Figure 4.15. A *natural combination* means that game elements designed for different subgoals can be visually presented at the same level segment simultaneously. On the other hand, the *connection* between level elements indicates those elements are usually placed at different level segments and thus need a transition. Elements that can be combined naturally are linked with the dash lines whereas the plus signs referring to the requirement of a smooth transition to a new scene.

Walking on a non-straight road while avoiding obstacles is not rare in daily life. Combining slalom walking and obstacle avoidance can increase the difficulty level as well as help the grasp of obstacle

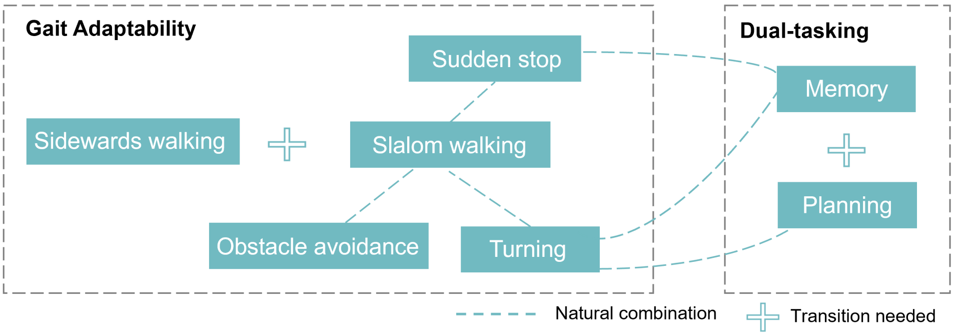
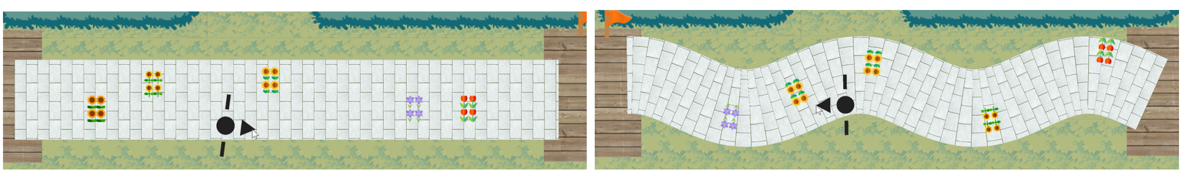


Figure 4.15: Possible relationship between subgoals for gait adaptability and dual-tasking

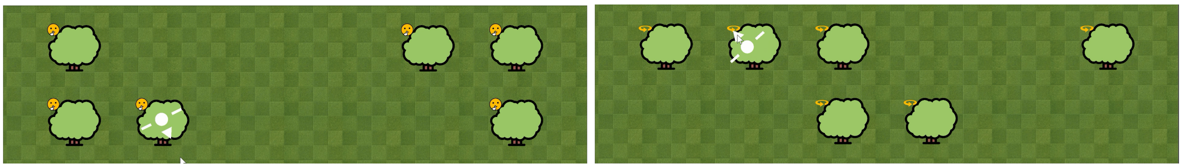
avoidance skills through providing a new challenging scenario. Similarly, a group of sheep could also be generated in front of the patient at a specific location of the slalom road to enhance players' capabilities to accomplish a sudden stop. By ensuring the flexibility of the generated road and providing sufficient information (e.g. road width, boundary information, starting positions, etc.) to other level elements, the combination can be both meaningful and intriguing. Although the combination of turning and memory therapy subgoals can be less common in the real life, such an integration can be smooth and interesting with a proper game design. By encoding the 'turning' movement with the meaning 'turn around the tree to find out the animal behind it', the game can make patients stretch their bodies on their initiative in this setting. By contrast, some game level elements are either of less meaning or difficult to tightly combine. For instance, it is unfeasible to let the player accomplish both sidewards walking and slalom walking at the same time. Under such a circumstance, utilizing smooth transition to the level for another subgoal is preferred.

The prototype implements the idea by first combining obstacle avoidance with slalom walking in Figure 4.16. Figure 4.16 (a) is a typical stand-alone obstacle avoidance level with five obstacles on the straight road. After the integration takes place, the width of the road remains the same, but the straight road becomes winding (as in (b)). Such a way of affecting the difficulty takes place when a patient is measured to grasp the current obstacle avoidance training well and needs consent from the therapist to better support their therapy plan. Besides, for each subgoal combination, the focused subgoal is the one with higher difficulty in general as shown in Table 4.1. This means the only subgoal with overall higher difficulty can incorporate easier therapy subgoals at appropriate times in order to add variance while ensuring smoother global difficulty changes. Following the similar philosophy, the memory task is combined with 360-degree turning. As compared in Figure 4.17, (a) is a typical levels made for memory task. The gestures beside each tree remind the patient to stop in front of the tree and wait for the animal to appear. The rotating sign reminds the patient that a 360-degree turn is needed in (b).



(a) (b)

Figure 4.16: Obstacle avoidance scene: (a) separate level (b) integrated level



(a) (b)

Figure 4.17: Memory task scene: (a) separate level (b) integrated level

4.6. Conclusion

This chapter presents the adaptation scheme described in the previous chapter in a standalone prototype. Four therapy subgoals for gait rehabilitation are selected through justification and designed for game development. Both difficulty adjustment methods and the player model show their versatility in different therapy subgoals. The therapy's controls are made possible at the end of each level segment.

5

Evaluation

This chapter aims to evaluate the effectiveness of adaptive steering of a procedural game level generator to support physiotherapists in achieving the desired gait rehabilitation goals. The first section introduces the design of the evaluation, which includes the research questions to be answered, the form of the measurement to answer the questions properly. The second section then describes the evaluation procedure in details. Finally, the collected results are visualized and analyzed.

5.1. Design

5.1.1. Goal

The evaluation session aims to answer the main question proposed in the introduction chapter. Three questions are proposed to investigate this in a comprehensive way.

1. How supportive are generated levels for therapists to fulfill each therapy goal?
2. How useful are the difficulty adaptation methods based on clinical experience?
3. How helpful is the provided interaction method to give therapists the control of automatically generated content?

The first question focuses on assessing the quality of each procedurally generated level. The generated levels should, fundamentally, assist therapists to encourage patients to stretch their bodies in a clinically desirable way. The diversity brought by the PCG method at each level is an advantage to long-term and repetitive gait training. Such variations, on the other hand, have effects on the difficulty in each level. Whether the generated levels achieve a good balance between them worths assessing. The second question puts the eyes on a difficulty-transition process, which assesses the usefulness of proposed adaptation schemes. Both *when* and *how* should be taken into account when evaluating such a dynamic process, which represents the timing and the smoothness of the difficulty adjustment. Last but not least, to support physiotherapists in conducting gait rehabilitation exercises for each patient, the automatic system is also supposed to offer therapists adequate control choices in real-time. Whether the provided interactive way in this project can act as a supportive layer between the therapists and the game system needs to be carefully assessed.

5.1.2. Method

In order to achieve the evaluation goal, the participant group, form of evaluation, and evaluated subgoals need to be determined first.

The participant group is composed of physiotherapists with experience in gait rehabilitation. Experience with the RYSEN setup would be an advantage in this evaluation session. To reach a larger group of therapists, participants are not limited to physiotherapists who are familiar with the RYSEN device considering the device is a rather new technology. For therapists with less knowledge in the RYSEN device, an introduction session will be given at the beginning of the evaluation.

The proposed way of evaluating the game prototype is in the form of pre-recorded videos and the following questionnaires. Due to the current COVID-19 situation, it is not feasible to meet each therapist face-to-face to test the game prototype. Compared to sending the developed prototype to physiotherapists, delivering video footage has various advantages. The first benefit is fair time management. After a general introduction to the basics of the game simulator, participants can move to the next evaluation phase without putting efforts into the learning of game controls. Given the current communication limitations, presenting our prototype in this way helps avoid potential issues in advance, such as different computer configurations or some distracting issues while playing. Moreover, it requires almost equal time for every participant regardless of their game playing knowledge. User-friendliness is the second advantage. Participants do not need to install any application on their computers. Instead, they can easily evaluate our prototype on their computers or tablets, which makes the evaluation process more flexible. In case participants wish to watch a particular game scene again (e.g. transition from level X to $X + 1$), they can simply drag the video progress bar instead of restarting the level X and repeating previous operations. Lastly, watching the rehabilitation training process through video can help participants have a clearer focus. Game control with mouse in the simulator is not capable of precisely representing the movement challenges in the genuine rehabilitation scenario. Without the need to control/simulate the performance of the patient in game, participants are able to concentrate on the reaction of the procedural generator itself such as how fair the evaluation of the player's performance for each level is, how smooth the difficulty transition between two levels is, etc.

Four subgoals are studied in the evaluation, including slalom walking, obstacle avoidance, sidewards walking, as well as memory task. The subgoals cover two main therapy goals in this project: gait adaptability and motor-cognitive dual tasking. As mentioned in the previous chapter, some of them can be naturally and meaningfully integrated with other sub-goals, while some are not. Besides, to evaluate a patient's performance, both position and rotation information collected from the RYSEN are well utilized in order to measure various factors, including rotation, facing direction, walking accuracy, and the velocity of movements. With careful design and implementation in the evaluation, it is reasonable to assume that its results are representative with these four selected subgoals.

5.2. Procedure

Inspired by the design of the evaluation in previous section, the evaluation is divided into three main phases, which aims at investigating the quality of generated levels, adaptivity usefulness and effectiveness of provided therapist's control. The details of the questionnaire can be found in the appendix.

At the beginning of the evaluation, an introduction text and explanatory video are first displayed to participants as a preparation. The text describes the RYSEN setup, project background and goals, and focus of this evaluation. The video further introduces how to start gait training and some game mechanics, including player representation and control, when to start the new training session, etc. The whole time consumption is estimated to be around 6 minutes.

5.2.1. Quality of generated levels

This phase aims to assess if the generated game levels overall meet physiotherapists' expectations to conduct gait rehabilitation. Because the movement with the mouse in this simulator cannot accurately represent the challenges in the real scenario, participants will be told that the presented failed/successful performances do not have a direct relationship with current level difficult in this simulator but just serve difficulty progression and performance evaluation. In other words, participants are encouraged to perceive the difficulty based on their own experience with daily gait rehabilitation rather than the performance of the avatar in the simulator. A list of tasks is described in detail as follows.

1. Showed participants a clip with one example level for its corresponding subgoal. The dubbing introduces the principle of the design, which includes the function of each generation game element, how patients are anticipated to interact with them in-game and which parameters in current are adjustable to change the level of difficulty.

2. Presented participants two to three more example levels for the same subgoal with the same value of difficulty-related parameters. This time, only necessary captions indicating the values of parameters are provided.

3. Asked participants to answer the related questions in the questionnaire from a clinical perspective, which concerns the mapping quality, variance in difficulty between levels, and benefit of randomness.

The evaluation in this phase first seeks to give participants a general impression of exercises for each subgoal. After acquainting participants with the game design, it then gave more examples for this subgoal. For one thing, it offers participants more time and instances to understand the idea for each subgoal so that they can give a more unbiased answer. For another, levels with the same parameter values over a period actually stands for a rather common case in gait rehabilitation - patients are required to undergo repeated exercises in order to regain their gait ability. With these levels, participants can not only experience whether the procedurally generated levels bring satisfactory diversity to patients to relieve boredom, but also test whether such a variation causes a noticeable difficulty change for the corresponding subgoal training. If the design fails to ensure roughly the same difficulty level, the subsequent evaluation results related to difficulty adjustment will be less convincing. In the end, the questions in the questionnaire were used to collect the opinions of each participant.

5.2.2. Adaptivity usefulness

This part assesses the usefulness of adaptation based on both *when* and *how* aspects. To keep the evaluation session compact, the general measurement of the player's skills, as well as the usefulness of difficulty adjustment instead of a long-term gait rehabilitation process is investigated.

In our implementation, first, the way of evaluating the performance of the patients was shown to participants for assessment. Specifically, we:

1. Showed three exercise scenarios in slalom walking based on the proposed player model. In the first scenario, a patient walks out of the road too many times, i.e. lack of *accuracy*. In the second case, this patient keeps on the road carefully but at a slower pace, i.e. lack of *efficiency*. The results for both scenarios are demonstrated via the player result interface (projected onto the ground). In the third scenario, the patient keeps on the road and walks at a good speed. Such performance is considered to be satisfactory and the result interface also notifies the patient of it.
2. Asked participants their opinions about measuring the patient's performance based on efficiency and accuracy in the questionnaire.

After that, two progression schemes were evaluated after equipping participants with a basic idea of each progression scheme, where we:

1. Provided explanatory material to participants, which describes the difference between two difficulty progression schemes together with an intuitive diagram.
2. First, let participant monitor slalom walking training for three levels from level X, where parameters increase in sequence. The patient succeeds in the first two levels and fails in the last levels. After that, three slalom walking levels with a parallel progression scheme are displayed. Still from level X, the patient succeeds in the first two levels and fails in the last levels.
3. Collected opinions of each participant on the appropriateness of each progression scheme and the potential benefits of having the choice between the two progression schemes in gait rehabilitation in the questionnaire.

The above tasks are followed by the assessment of subgoal integrations, the related tasks and details are shown as follows.

1. Let participants first monitor obstacle avoidance exercise for two levels. The first level is a standalone subgoal and the second level is set with the same parameters (i.e. same size, number, and speed of obstacles) but integrated with slalom walking.
2. Showed participants monitor memory exercise with two levels. The first level is a standalone subgoal and the second level is set with the same parameters (i.e. same number of puzzles) but integrated with turning.
3. Let participants express their perceived difficulty differences between standalone levels and integrated level in the questionnaire. Also ask their impression of such integrations, with the focus on the potential variety it could bring to difficulty adjustment.

Last, the evaluation of separate difficulty adjustment was conducted:

1. Let participants monitor sidewards walking exercise for six levels where three levels are to the left and three levels are to the right. In the beginning, walking sidewards to right and left are set at the same level. The patient always prefers one direction to the other due to the disorders in one leg. In this case, difficulties of walking to the right and left are separated from each other and the differences between difficulty levels will become obvious after six levels.
2. Asked the usefulness and versatility of such difficulty adjustment in gait rehabilitation in the questionnaire.

5.2.3. Therapist in control

This part investigates whether the current interaction scheme is sufficient to act as a supportive layer between therapists and the game to offer therapists efficient control of the content generation. In this phase, game control videos were provided to the participants. The following tasks were implemented:

1. Showed participants information about the player status and control options when a player is detected to be successful in the current level. All possible results after clicking each button or leaves buttons as default.
2. Showed participants the same information and results when a player is detected to have failed in the current level.
3. Let participants rate the information provided through the interface and their satisfaction level with the controls provided. Participants were also asked about the missed features in the interface to help them conduct gait rehabilitation.

The total time consumption for aforementioned phases is estimated around 35 minutes. At the end of this evaluation, an optional open field was provided to all participants to collect participants' thoughts on this project, which could be any suggestions, ideas, or any questions.

5.3. Results and analysis

In total, 12 physiotherapists with related backgrounds were reached and 9 of them gave their valid feedback. The results are collected and presented below based on three phases mentioned in the previous section.

Figure 5.1 to 5.3 summarizes the opinion of participants on the quality of procedurally generated levels. The first results (in Figure 5.1) recognizes the functionality of our mapping from therapy goals into gameplay actions. Except for slalom walking, the average scores of other subgoals evaluations are all above 4, and they are concentrated in 4 and 5 points. Based on the participants' comments below the slalom walking subgoal, some participants may mistake the 'corresponding therapy goal' for 'gait adaptability'. Such doubts will not last long as they move to levels designed for obstacle avoidance subgoals. They are likely to understand that slalom walking subgoals does not 'equal to' but 'belong to' gait adaptability therapy goal.

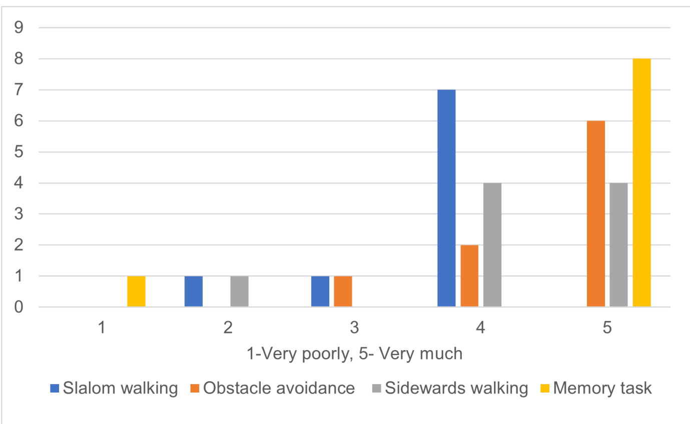


Figure 5.1: Replies to the question '*To which extent do the exercises shown meet your expectations for what a patient should do to accomplish each corresponding therapy goal?*'

As for results (Figure 5.2) regarding the difficulty differences between levels with the same difficulty-related parameters for each subgoal, they are more optimistic. For each subgoal, over 75% of participants agree that the shown levels for each subgoal are perceived with similar difficulty. The results help gain credibility of later conclusions in difficulty adjustment as analyzed before.

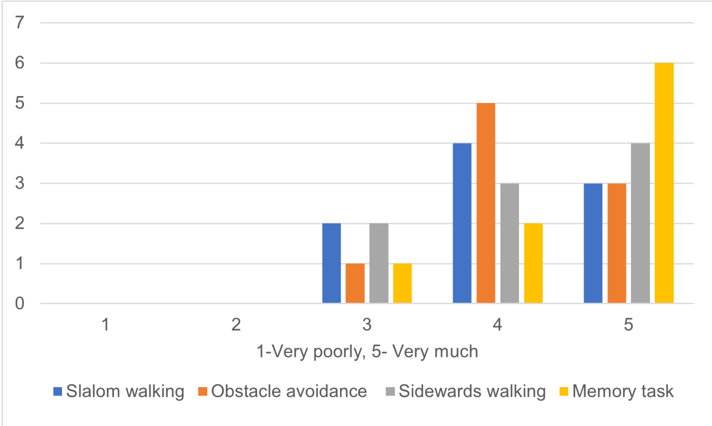


Figure 5.2: Replies to the question '*To which extent are the exercises shown for each therapy goal perceived with similar difficulty based on your clinical experience?*'

The diversity provided by procedurally generated levels is also agreed to be helpful to each therapy subgoal on the whole, as shown in Figure 5.3. It can be concluded that subgoals with more complex game elements in game design, such as obstacle avoidance and memory task, are perceived to have greater potential to provide desirable diversity. Besides, the more conditions that limit the level of difficulty changes, the more difficult it is to design the level of desirable diversity under the same difficulty. Take the sidewards walking as an example, the patient is required to face the same direction every time considering the asymmetry efforts required for both legs and different conditions of the patient's lower limb. Consequently, although levels designed for sidewards walking are perceived with a similar difficulty, their score in the helpfulness of diversity is the lowest among the four.

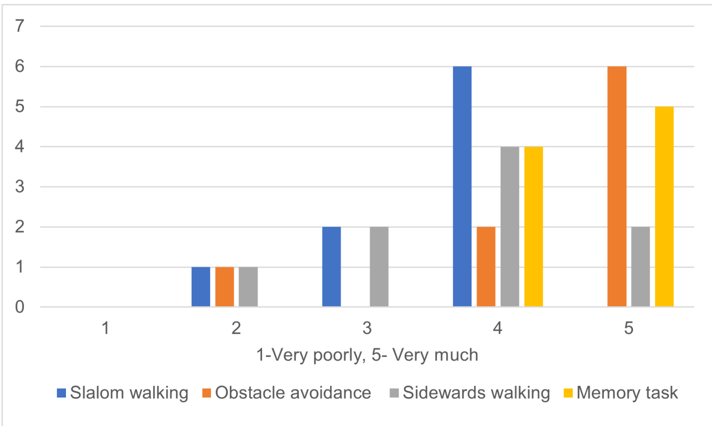


Figure 5.3: Replies to the question '*To which extent is the diversity of the exercises shown helpful for patients to accomplish each corresponding therapy goal?*'

Figure 5.4 to 5.9 summarizes the opinions of participants on adaptation usefulness. To start with, their opinions on the way of performance evaluation in the prototype are visualized in Figure 5.4. Nearly 90% of participants agree with the proposed performance measurement method from a clinical perspective. What's more, in the comment area below the questions, some participants showed their expectation to select their desirable aspects (e.g. only accuracy or both) and set the value movement velocity.

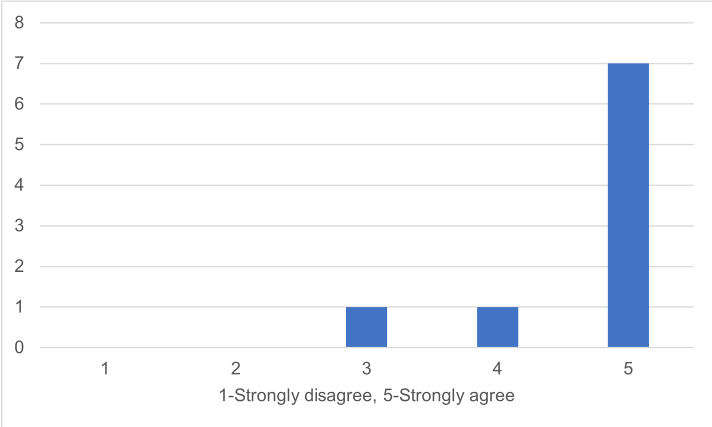


Figure 5.4: Replies to the statement '*Measuring the patient's performance based on efficiency and accuracy is clinically desirable.*'

Results in Figure 5.5 summarize the appropriateness of parallel progression scheme and sequence progression scheme. Compared with the parallel progression scheme, most participants go for the sequence progression scheme. In other words, only one difficulty-related parameter is changed every time is more clinically acceptable. Participants' feedback in the comment sections confirms this conclusion.

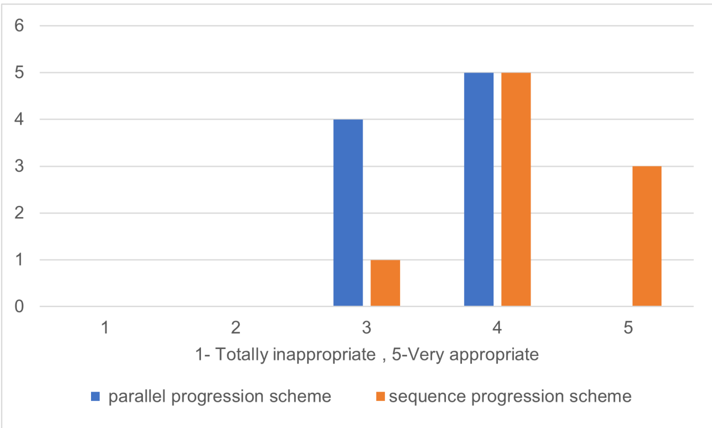


Figure 5.5: Replies to the question '*From the three levels shown above, how appropriate is the corresponding scheme to adjust the therapy goal difficulty for patients?*'

When asked whether having the choice between the two progression schemes is convenient to adapt to patients with different conditions, participants all gave positive replies as in Figure 5.6. Specifically, some participants left their comments saying that parallel progression would be a choice for him/her to slightly increase the difficulty for patients.

As illustrated in Figure 5.7, both integrated levels are perceived with higher difficulty compared with corresponding standalone levels. The integrated level for memory task subgoals is overall considered to be more difficult. Combined with the comments of the participants below, it is speculated that it may be because the physiotherapist is worried that rotating it many times may arise dizziness. Another

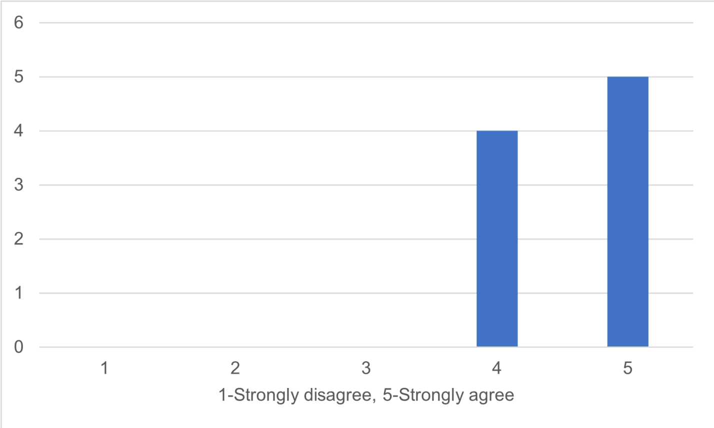


Figure 5.6: Replies to the statement '*The choice between the two progression schemes is convenient to adapt to patients with different conditions*'

participant gave his/her reason for rating 4 for the difficulty change of the integrated level designed for obstacle avoidance - the introduced slalom path is not the most difficult compared with moving obstacles. This comment is encouraging as it is consistent with our design philosophy of level integration.

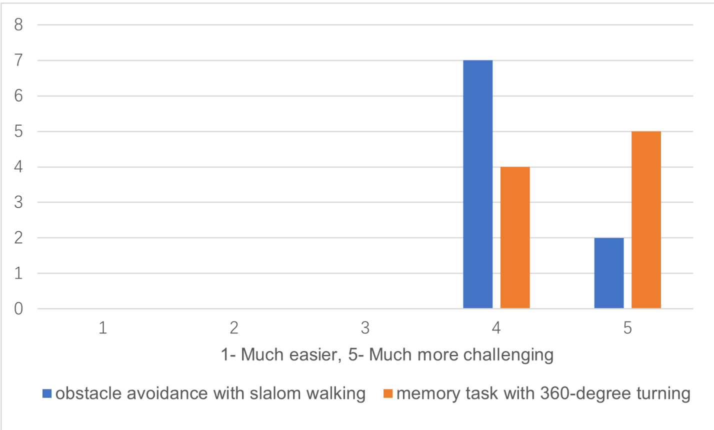


Figure 5.7: Replies to the question '*Compared to the standalone levels, how difficult did the levels become after their integration?*'

As in Figure 5.8, for the different degrees of recognition, all participants agreed that such integrations of subgoals can bring diversity to the adjustment of difficulty. It can be seen that participants' concerns about possible dizziness caused by 360-degree turn also affected the results in this question. In participants' suggestions, other movements such as squatting, 180-degree turn are also good alternatives.

Figure 5.9 shows participants' feedback on separated difficulty adjustment. From the distribution of the blue bar, it can be concluded that separate difficulty adjustment is considered to be rational and useful by most but not all therapists. The participant who rated a lower score (i.e. 2) preferred a symmetry training in his/her comment. The orange column further shows the participants' views on the versatility of this adaptation scheme in gait rehabilitation. The results are 30% neutral and 70% positive, which not only illustrate the rationality of separate difficulty adjustment itself but also confirm the importance of providing physical therapists with different adjustment schemes for each subgoal.

The last results shown in Figure 5.10 sum up participants' impressions on the information about the

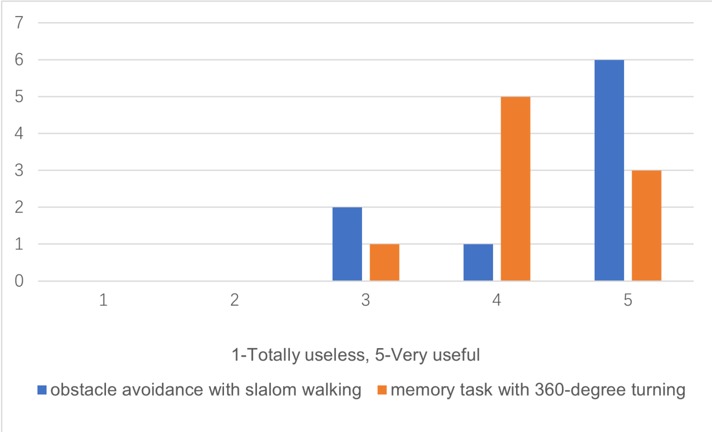


Figure 5.8: Replies to the question '*How useful do you think such integrations are to bring variety to difficulty adjustment?*'

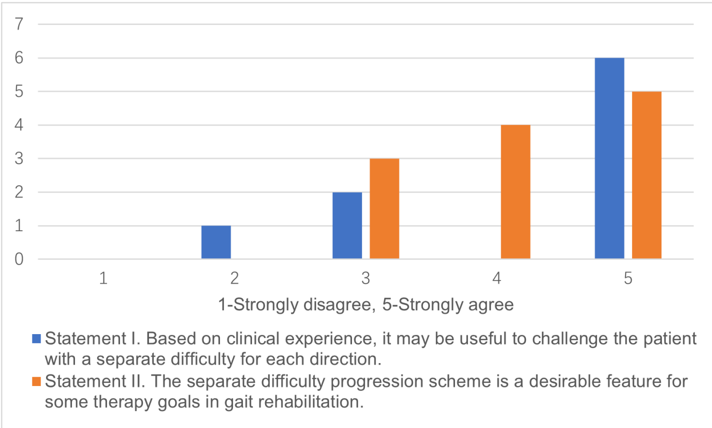


Figure 5.9: Replies to two statements concerning the demonstration of separate difficulty adjustment.

patients' performance as well as possible control options for tailoring the difficulty levels for patients. Both statements concerning therapists' control in the questionnaire are acknowledged by participants, with the control options achieving a slightly higher score.

Seven voices from different participants in the open field at the end of the questionnaire were collected. In general, participants are all very interested in the game and positive about the future of this project in gait rehabilitation. Three replies are highlighted here. Although less related to our evaluation goal, they can be a very precious complement to the project.

- Integration with a treatment plan. Now, each subgoal is rather isolated. It would be great to enable therapists to set a plan for each patient and so that patients can do some games in a row.
- Offer 'extra settings' to therapists with advanced knowledge. In demonstration videos, all parameters were set as default based on the experiment. However, some therapists are willing to adjust them for each therapy subgoal.
- Feedback matters. The feedback information to the patient, which was projected onto the workspace, is very good because they get specific feedback on their performance. This is not often seen in technologies in the field. It is important to give negative feedback in a proper way. For example, it is maybe nicer to inform patients if they improved with respect to the previous training session instead of telling them all the time that they are slower than normal.

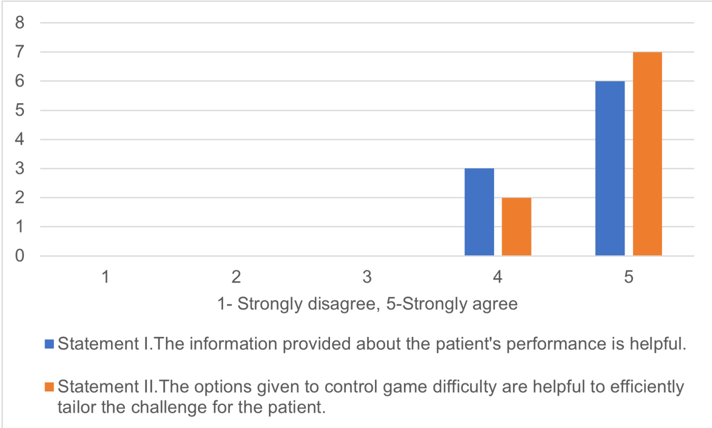


Figure 5.10: Replies to two statements concerning the demonstration.

5.4. Discussion

Based on the results, three questions in the first section of this chapter are answered respectively. The procedurally generated levels are overall supportive to assist therapists in fulfilling each therapy goal. For one thing, interactions between game elements and patients meet therapists' expectations for what a patient should do to accomplish each corresponding therapy subgoal. For another, these levels achieve a good balance between diversity and fairness. The variations brought by the PCG method are regarded to be helpful for patients to accomplish each subgoal. It is also concluded that the difficulty of each level is perceived with a similar difficulty, indicating they are not affected by such variations.

The adopted difficulty adaptation methods are overall appropriate and helpful to therapists based on this evaluation. Our proposed player model based on accuracy and efficiency aspects is perceived to be helpful clinically based on therapists' experience. Both parallel progression scheme and sequence progression scheme are considered to give appropriate difficulty transition, with the sequence progression scheme being slightly preferable compared with parallel progression scheme. Having the choice between the two progression schemes is considered to be convenient to adapt to patients with different conditions. Subgoal integration brings variety in difficulty progression. However, just as what is learned from comments below the level combination between rotation and memory task, careful designs are needed to avoid less reasonable difficulty increases. For gait exercises that require asymmetry efforts from lower limbs, separate difficulty adjustment is considered to be helpful overall. However, not all therapists prefer such asymmetry training. Considering the vital role of physiotherapists in gait rehabilitation training, it is beneficial to provide them with options to decide which adaptation scheme they would like to use.

The provided interaction method acts as a helpful layer between the game system and the therapists, which gives therapists control of what the automatic system is generating. Overall, therapists are satisfied with both provided information about the performance of the patients and the provided difficulty-related control options. Considering the shown therapy interface can be displayed on a mobile device in the real clinical scenario, its potential can be further realized to assist therapists to monitor multiple patients at the same time.

6

Conclusion and recommendations

6.1. Conclusion

This project aims at assessing *how adaptive steering of a procedural game level generator can support a physiotherapist in achieving the desired rehabilitation goals*. The approach is implemented in a game prototype and then evaluated. Despite the limitation such as the on-line evaluation and lack of long-term evaluation, some well-acclaimed concepts in this project are indeed able to offer valuable insight.

Going back to the three research questions proposed in introduction chapter, our work is concluded through answering these questions.

1. How can generated levels effectively support therapists in each therapy goal?
2. How to realize an effective difficulty adaptation to assist therapists in gait rehabilitation?
3. How to give therapists control on what the game system is going to automatically generate?

First, each generated level has the promise to assist therapists in providing a clinically desirable exercise for patients with a proper mapping from targeted therapy goals into gameplay actions. Qualified levels are the foundation of the entire gait training and it is advisable to involve therapists with advanced knowledge in their design. Compared with handcrafted levels, procedurally generated levels advantage themselves in diversity and lower labor cost. While randomness brings more uncertainty to training, it also affects the difficulty of each game level. In this case, how to balance the two is another significant issue in level design.

When and *how* to adjust the challenges are two critical aspects to realize an effective difficulty adjustment. To adjust the difficulty level at a good timing, a player model based on accuracy and efficiency aspects are recommended to measure the training progress and evaluate the patient's performance. According to the characteristics of different subgoals and the experience of the physical therapist, accuracy and efficiency should have different weights in the evaluation. Adjusting only one difficulty-related parameter each time is clinically desirable. Under the same configuration for difficulty defining parameters, increase more than one parameter appropriately is able to help therapists adapt to patients with different conditions. Combining different therapy goals together in single game level is proved to be another helpful choice to both vary the difficulty level and bring variety in its difficulty adjustment. Careful designs together experience from physiotherapists are necessary to avoid conflicts between subgoals and steep difficulty increases. For specific subgoals that require asymmetry efforts of lower limbs, separate difficulty adjustment is a good option to keep challenge patients properly. All proposed difficulty adjustment methods are meant to serve the gait rehabilitation training. Hence, it is therapists who decide which DDA method to use based on clinical experience, rehabilitation goal, and the conditions for the patient.

Both comprehensiveness and conciseness should be taken into account to give therapists better control of the automatic system. In this implementation, all difficulty-related values can be adjusted, ranging from the range and step of each parameter, starting and ending difficulty level, as well as difficulty adjustment schemes. To minimize such efforts while ensuring effective control of the rehabilitation progress, first, all-difficulty related parameters are set with default value through either experiment or experience, which can also be changed in the later stage. In other words, therapists can start the training by simply clicking the ’Start’ button. Also, performance-related information, together with training information (e.g. duration, walking distance, etc.) is visualized to therapists for making a decision. Last, only necessary and meaningful options are provided to therapists in real-time based on the patient’s performance.

6.2. Recommendations

Based on suggestions from participants in the open field of questionnaire, and on our reflection during adaptation design, the following aspects are recommended to be done in future.

Handy decision and modification in the related values for each patient. These values include the range and step of each parameter, starting and ending difficulty level, as well as the reference values in evaluation. Currently, our design only provides default values or manual input from therapists. The former ensures that these values have a higher probability to fit patients but are not guaranteed to suit everyone. The latter could cost more effort and has demands on the experience of the physiotherapist. Besides, some values may need to be fine-tuned in the real rehabilitation scenario. For instance, the reference walking velocity at the current level for this patient is set to be 0.9 m/s. Hard as the rehabilitant might try, maybe it is not possible for him to walk that fast. Taking into account the patient’s impact and rehabilitation plan, the physiotherapist may also agree that the patient can proceed to the next level of practice despite the game system does not consider the patient to meet the requirement based on the efficiency aspect. In this case, it is not wise for the therapist to go back to the evaluation setting page and change the value. One recommended solution is to pop up a window for therapists to modify the corresponding value, which may happen when there is a continuous discrepancy between the doctor’s choice and the system’s default recommendation.

Sophisticated and flexible level designs. Current implemented levels are rather simple with their focus on the generation of game elements related to movement challenges only. In this case, the variation brought by the inherent randomness of the PCG method is expected to be rather limited. In order to solve it, first, the game scene and narrative can be carefully designed. For example, every time the patient walks sidewards, the background of the beach they are on will change. Every time a patient comes to a level for a new subgoal, the game could tell the patient ’you are now coming to a new place (could be replaced by forest, mountain road, beach, etc.)’. Our participants showed greater interest in the levels with crab in the evaluation during the evaluation session. Inspired by this, a second improvement could be the appropriate utilization of NPC for various purposes. For instance, a running puppy could be the patient's buddy in levels designed for slalom walking and also inform this patient of his/her performance in the last round. The third suggestion would be to give therapists the chance to tailor the game levels for patients. When pointing out the potential dizziness issues in memory tasks in the evaluation, several therapists explained their ideas, which included a combination of 180-degree turn, squat, etc. Hence, the game could let the therapists decide which gait exercise they wish to incorporate.

Make each subgoal related to the whole rehabilitation progress. Currently, the adaptation is performed exclusively within each subgoal. In further work, first, the duration proportion of each subgoal could be made flexible [64]. A patient is supposed to perform obstacle avoidance training, sudden stop training, and backward walking training. If he/she is measured to perform well in the exercise made for the first subgoal in the early stage of today's training, the game will propose to spread the rest of the time to the other two. Furthermore, the rehabilitation period for each therapy goal could be adaptable, which means the accumulated performance of the patient could lead the game to prolong or reduce the treatment progress. By monitoring how the performance of one specific goal is improving, the game could propose that the patient only needs such training for two weeks instead of three weeks. In contrast, if the patient is still struggling at the beginning levels of a certain training after a few weeks, the game can extend the progress of the current treatment with the permission of the therapist.

A

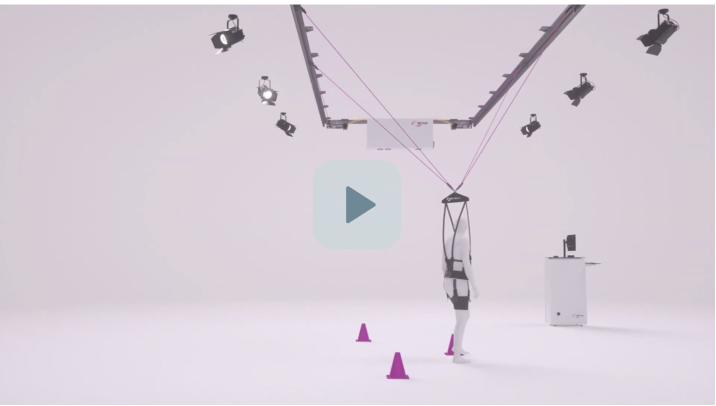
Questionnaire

A.1. Project Introduction

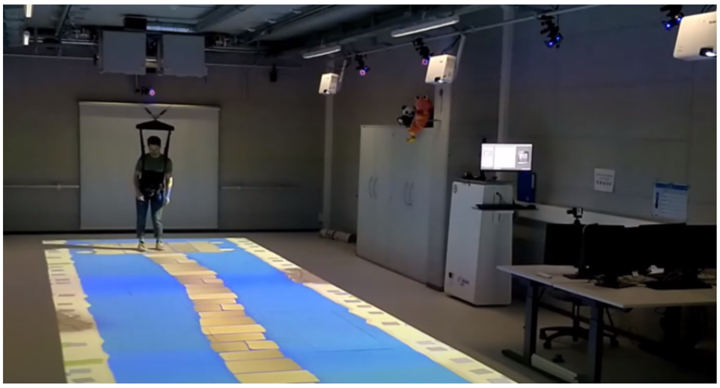
Conventional rehabilitation methods often involve boring and repetitive exercises. By automatically generating adaptive movement challenges, patients can be provided with a personalized rehabilitation experience. This project aims at investigating such adaptive generation methods and validating them in a stand-alone prototype.

As the game will be later provided in a bodyweight support system RYSEN, the content of the game will be projected onto the floor. I hope the following video and picture could make you familiar with RYSEN.

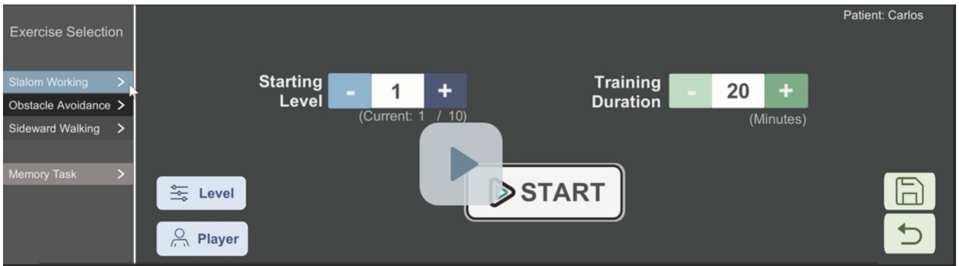
Brief introduction of RYSEN system



One example of interaction scenarios between the patient and the projection game



As preparation for this evaluation, please watch the first video below:



Exercise list

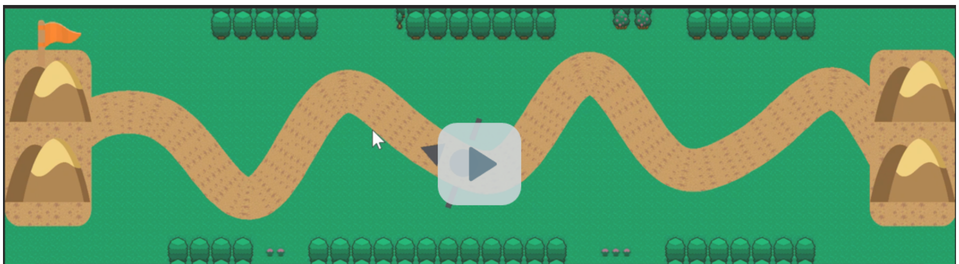
A.2. Quality of generated levels

This part aims at investigating whether the generated game-play levels are helpful to facilitate accomplishing each therapy goal.

A.2.1. Slalom walking

This therapy goal is made for improving the ability to adjust gait to environmental circumstances. Please watch the video for slalom walking and answer the corresponding questions:

Example video for slalom walking exercise:



Several slalom scenes with same road width and random factor

Regarding the shown slalom exercises, please state to which extent:

1. they meet my expectations for what a patient should do to accomplish this therapy goal.

   ○ 1 (Very poorly) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Very much)

2. they are perceived with similar difficulty based on my clinical experience.
   ○ 1 (Very poorly) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Very much)
3. the diversity they provide is helpful for patients to accomplish this therapy goal.
   ○ 1 (Very poorly) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Very much)

(Optional) Please share your suggestions, questions or ideas (if any) in this section.

A.2.2. Obstacle avoidance

This therapy goal is made for improving the ability to adjust gait to environmental circumstances. Please watch the video for obstacle avoidance and answer the corresponding questions:

Example video for slalom walking exercise:

Some exaples of obstacle avoidance scenes with same size and number.

Regarding the shown obstacle avoidance exercises, please state to which extent:

1. they meet my expectations for what a patient should do to accomplish this therapy goal.
   ○ 1 (Very poorly) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Very much)
2. they are perceived with similar difficulty based on my clinical experience.
   ○ 1 (Very poorly) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Very much)
3. the diversity they provide is helpful for patients to accomplish this therapy goal.
   ○ 1 (Very poorly) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Very much)

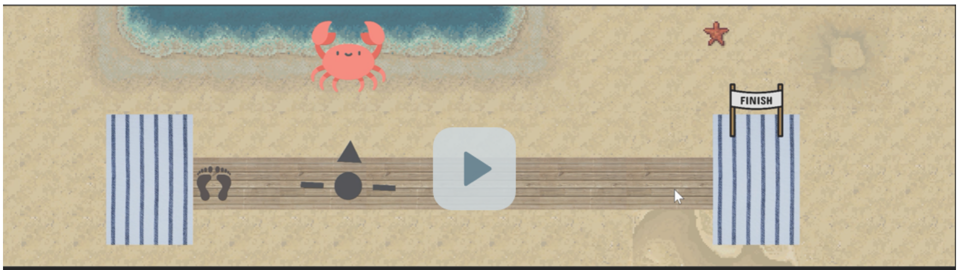
(Optional) Please share your suggestions, questions or ideas (if any) in this section.

A.2.3. Sidewards walking

This therapy goal is made for improving the ability to adjust gait to environmental circumstances.

Please watch the video for sidewards walking exercise and answer the corresponding questions:

Example video for sidewards walking exercise:



Some examples of sideward walking scenes with same road width and road length

Regarding the shown sidewards walking exercises, please state to which extent:

1. they meet my expectations for what a patient should do to accomplish this therapy goal.
   ○ 1 (Very poorly) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Very much)
2. they are perceived with similar difficulty based on my clinical experience.
   ○ 1 (Very poorly) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Very much)
3. the diversity they provide is helpful for patients to accomplish this therapy goal.
   ○ 1 (Very poorly) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Very much)

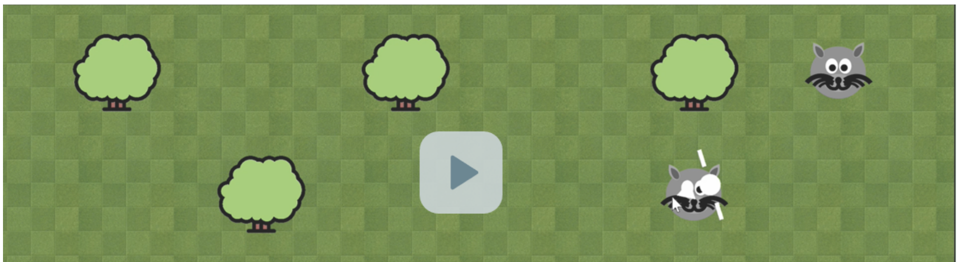
(Optional) Please share your suggestions, questions or ideas (if any) in this section.

A.2.4. Memory Task

This therapy goals is made for relieving dual-tasking interference.

Please watch the video for memory task and answer the corresponding questions:

Example video for sidewards walking exercise:



I. Stand still on a tree, until the animal hiding behind it appears
II. Remember and match them in pairs

Regarding the shown memory (dual-tasking) exercises, please state to which extent:

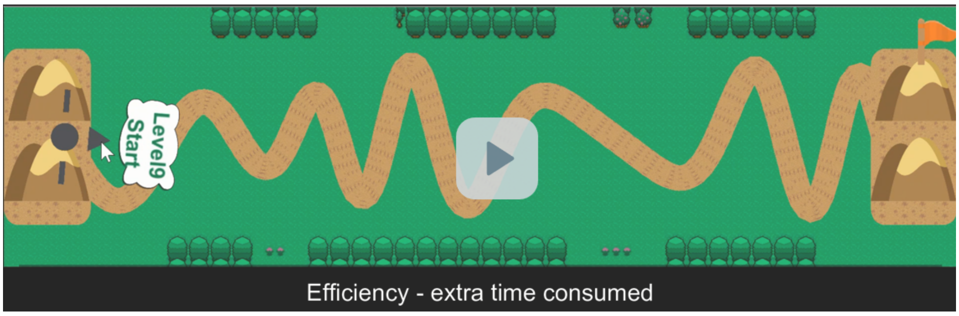
1. they meet my expectations for what a patient should do to accomplish this therapy goal.
   ○ 1 (Very poorly) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Very much)
2. they are perceived with similar difficulty based on my clinical experience.
   ○ 1 (Very poorly) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Very much)
3. the diversity they provide is helpful for patients to accomplish this therapy goal.
   ○ 1 (Very poorly) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Very much)

(Optional) Please share your suggestions, questions or ideas (if any) in this section.

A.3. Adaptivity usefulness

This part aims at assessing, from a clinical perspective, the appropriateness of how performance is measured and how game difficulty is adjusted.
The following video shows the proposed method to evaluate the patient's performance. Please watch this video and answer the question:

Explanation video of the patient's performance evaluation:



Measuring the patient's performance based on efficiency and accuracy is clinically desirable.
○ 1 (Strongly disagree) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Strongly agree)

(Optional) Please share your suggestions, questions or ideas (if any) in this section.

A.3.1. Progression schemes comparison

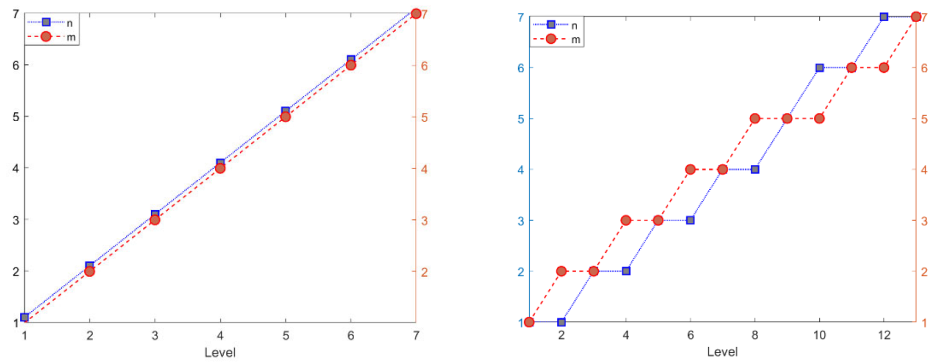
Here, we will compare the two parameter-progression schemes, parallel progression scheme and sequence progression scheme.

Explanation of two schemes:

Assuming that there are two parameters ***m*** and ***n*** affecting the difficulty level. As the difficulty level grows, both ***m*** and ***n*** should be increased.

- ***Parallel progression scheme***: parameters can increase simultaneously.
- ***Sequence progression scheme***: parameters are increased in sequence - only one parameter can increase each time.

For example, both parameter ***m*** and ***n*** have 7 tiers (tier refers to the level of complexity for each parameter). The figure 1 shows the trends of two parameters as the level improves:

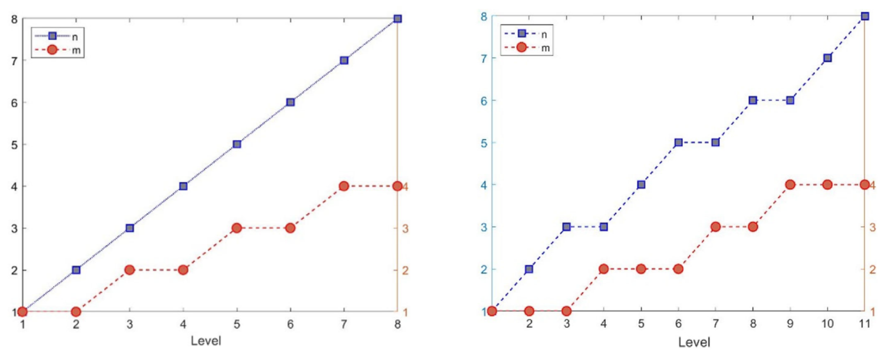


(a) (b)

Fig 1. Comparison between two schemes: (a). **parallel** progression scheme (b) **sequence** progression scheme

Figure 2 shows a more general case: two parameters have different number of tiers. For example, parameter ***m*** has 4 tiers and ***n*** has 8 tiers. Because ***m*** only has 3 tiers to increase, parameter ***m*** cannot always increase with ***n***.

Therefore, parallel progression makes it possible for two parameters to increase at the same time when they are both **ready** to be increased, which can be seen in Fig 2(a)'s level 2 to level 3. The sequence progression scheme increases the parameter in sequence and only **one** parameter can be increased each time.



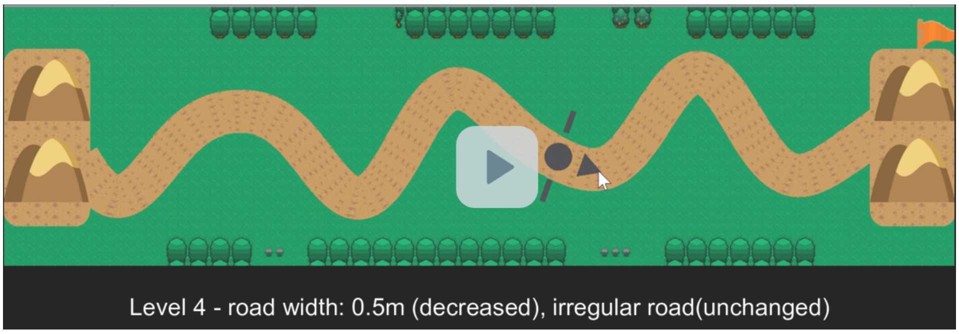
(a) (b)

Fig 2. Comparison between two schemes (a). **parallel** progression scheme (b) **sequence** progression scheme

Please watch the video concerning the parallel progression scheme and answer the following questions:

Note: The rapid difficulty changes will only occur in this test and in the real application such changes may take several evaluation sessions to change the difficulty level.

Example video for parallel progression scheme:



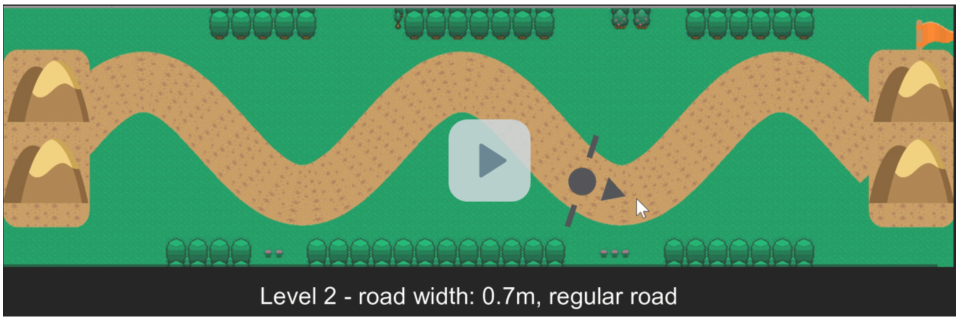
1. From the three levels shown above, how appropriate is the parallel progression scheme to adjust the therapy goal difficulty for patients?

○ 1 (Totally inappropriate) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Very appropriate)

Please watch the video concerning the sequence progression scheme and answer the following questions:

Note: The rapid difficulty changes will only occur in this test and in the real application such changes may take several evaluation sessions to change the difficulty level.

Example video for sequence progression scheme:



2. From the three levels shown above, how appropriate is the sequence progression scheme to adjust the therapy goal difficulty for patients?

○ 1 (Totally inappropriate) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Very appropriate)

Based on two example videos above, Please answer:

3. The choice between the two progression schemes is convenient to adapt to patients with different conditions.

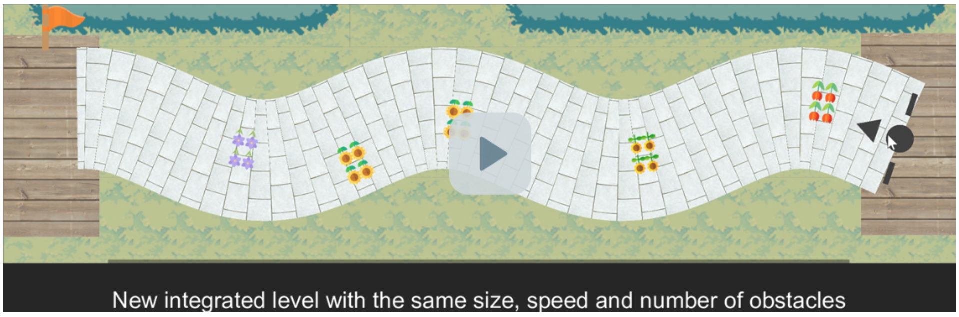
○ 1 (Strongly disagree) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Strongly agree)

(Optional) Please share your suggestions, questions or ideas (if any) in this section.

A.3.2. Therapy goal integrations

Please watch the example video for obstacle avoidance and its integration with slalom walking and answer corresponding questions.

Example video for therapy goals integration - Obstacle avoidance and slalom walking



1. Compared with the standalone obstacle avoidance level, how difficult did the level become after integration with slalom walking?

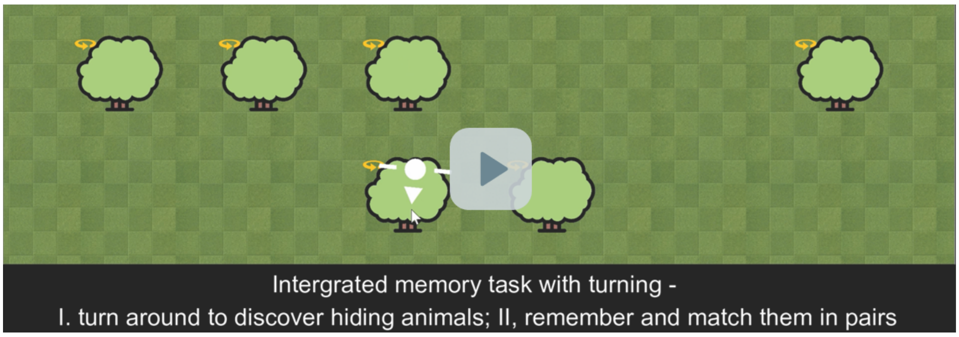
   ○ 1 (Much easier) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Much more challenging)

2. How useful do you think such an integration is to bring variety to difficulty adjustment?

   ○ 1 (Totally useless) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Very useful)

Please watch the example video for memory task and its integration with turning and answer corresponding questions:

Example video for therapy goals integration - Memory task and turning



3. Compared with the standalone obstacle avoidance level, how difficult did the level become after integration with slalom walking?

   ○ 1 (Much easier) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Much more challenging)

4. How useful do you think such an integration is to bring variety to difficulty adjustment?

   ○ 1 (Totally useless) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Very useful)

(Optional) Please share your suggestions, questions or ideas (if any) in this section.

A.3.3. Separate difficulty adjustment

Please watch the following example video and answer the corresponding questions:

Example video for separate difficulty adjustment (Sidewards walking):

1. Based on my clinical experience, it may be useful to challenge the patient with a separate difficulty for each direction.

○ 1 (Strongly disagree) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Strongly agree)

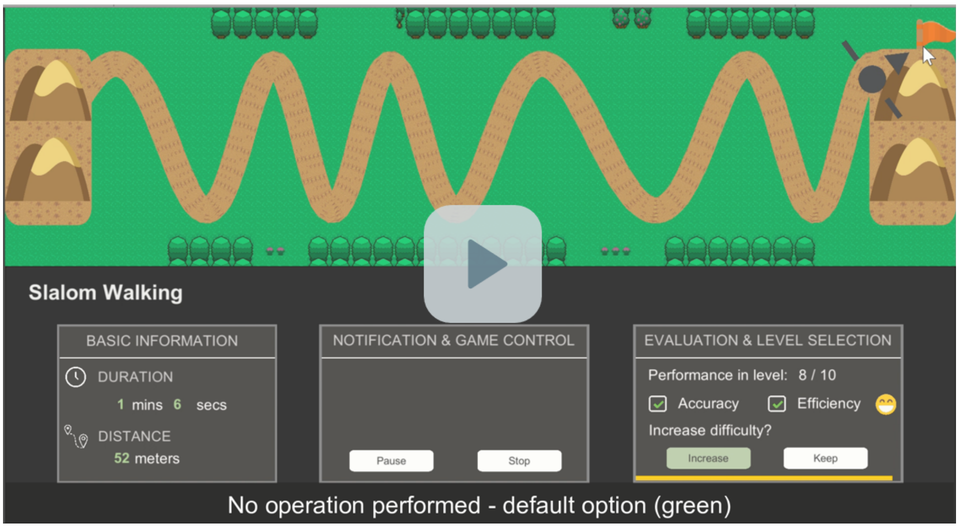
2. The separate difficulty progression scheme is a desirable feature for some therapy goals in gait rehabilitation.

○ 1 (Strongly disagree) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Strongly agree)

(Optional) Please share your suggestions, questions or ideas (if any) in this section.

A.4. Therapist in control

Apart from generating game content automatically, our game prototype also seeks to let therapists conveniently control level difficulty adjustment before each procedural generation session starts. Please watch the following example video and answer the corresponding questions:



1. How helpful is the information provided about the patient's performance?

   ○ 1 (Totally unhelpful) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Very helpful)

2. The options given to control game difficulty are helpful for me to efficiently tailor the challenge for the patient.

   ○ 1 (Strongly disagree) ○ 2 ○ 3 (Neutral) ○ 4 ○ 5 (Strongly agree)

Which other features would you like to see added to the interface to help you conduct gait rehabilitation?

A.5. Open field

Feel free to share your thoughts on this project. It could be suggestions, thoughts or any questions to this project.

This is the end of this evaluation! Thank you very much for your time!

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