MASTER THESIS

The effect of a multi-projected virtual rehabilitation environment during adaptation locomotion tasks

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Abstract

Millions of people every year are experiencing symptoms of movement disorder or postural control dysfunctions, which are the result of falling injuries. Most falling injuries are associated with identifiable or modifiable risk factors. A virtual therapy tried to raise the awareness of preventative measures to the individuals, teach them to adapt their negotiation abilities to the alterations of their motion due to age, disease or injuries and and thus, react accurately and fast again to reduce injurious falls. Eighteen subjects (14 males, 4 females; 30 mean age) perform avoidance tasks under three different test conditions. The three test conditions are divided based on the following criteria: the virtual environment is projected only on a front surface, in front of the treadmill that the subject stands; the front virtual environment is extended on a ground surface. However, the projected virtual environment in the two surfaces is sub-divided into two test conditions. The projected information between the two surfaces is consistent (i.e. same dimensions of the spherical virtual obstacles width, length, height between the two projections), whereas in the second condition there is inconsistency in the projected information between the two surfaces (i.e. same width, length but different height dimensions of the virtual obstacles between the two projections, the obstacles are now visualized on the ground as flat disks). The extend of a front virtual environment to the ground make the subjects perceive accurately the time of contact of their feet (tracked by a motion-capture sensor) with the virtual obstacles and therefore, act on time to step over them. No feedback is provided to the subjects about the position of their feet or their performance in the virtual rehabilitation environment. However, the extend of the front environment to the ground alters the motor behavior of the subjects. The front projection during the experiments used for the anticipation and the assessment of the obstacle dimensions, whereas the ground projection is used for the assessment of the distance of the virtual obstacle and the natural interaction. The ground projection is not improving the height perception of the obstacles on the platform. Assumptions are made to explain the behavior of the subjects and identify the platform's limitations. The inconsistency between the projected information in the front/floor surfaces reveal no substantial alterations in the behavior of the subjects. The behavior and experience of the subjects are compared to reveal correlations between the three conditions.

KEYWORDS: Improve Human Performance, Virtual Rehabilitation Therapy, Multi-projected Rehabilitation Environment, Step over virtual obstacles, Ground Projection

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The study is a collaboration of Utrecht University with the Motekforce Link company, as the final requirement of my Master degree at Game and Media Technology (GMT). Motekforce Link is a company situated in the city of Amsterdam, in the Netherlands. A company focuses on rehabilitation technologies and virtual reality systems to improve human performance. I am grateful to the Motekforce Link company, for providing me the equipment and the software to work on. The theoretical background of this study consists of knowledge, information and data gathered during the six month period worked as a full-time intern at Motekforce Link and the three extra months until the completeness of the Master Thesis (9 months Master Thesis at Utrecht University).

To this end, I would like to thank my family and friends for helping me achieve my goals on time. I want to express my gratitude to all the employees of the Motekforce Link company and Young Motek, who voluntarily participated in the experiments and they helped me to gather the required data of the Master thesis.

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List of Abbreviations

EU	**E**uropean **U**nion
VR	**V**irtual **R**eality
VE	**V**irtual **E**nvironment
RT	**R**eaction **T**ime
VRA	**V**irtual **R**ehabilitation **A**pplication
CNS	**C**entral **N**ervous **S**ystem
HMD	**H**ead **M**ounted **D**isplay
HDMI	**H**igh **D**efinition **M**ultimedia **I**nterface
GEQ	**G**ame **E**xperience **Q**uestionnaire

Chapter 1

Introduction

The substantial increase in the past decade in research on the prevention of falls among older persons gave space for the current study to take place in the Netherlands (Who, 2015). Chapter 1.1 gives an overview of the causes which lead to this increase. Chapter 1.2 looks into the functional and negotiation abilities of humans to perform adaptation locomotion tasks in a real or a virtual environment. Chapter 1.3 refers to the practices used to provide that information during the virtual rehabilitation experience. Chapter 1.4 is the state of the art, which explains how all this information is related to the current study and finally, Chapter 1.5 mentions the two research questions the study tries to answer to.

1.1 Background Problem

Every year, millions of people are experiencing symptoms of movement disorder or postural control dysfunctions, which are the result of falling injuries (Winter, 1995). The target group which suffers the greatest number of severe injuries (such as broken bones or head injuries) are older adults over sixty-five. Moreover, twenty-five to thirty-five percent of individuals aged sixty-five and over fall each year, which makes falls the leading cause of death accidents among older adults (Pavol et al., 2001).

The world's population is growing and aging simultaneously, this fact makes evident the urgent necessity to introduce new practices in the current healthcare system (Haub, 2013). EuroStat, WHO-Europe and European Injury Data Base (IDB) highlight the need of innovative technologies to impact the gait therapy in European countries. EU Commission, 2013 mentioned that the expenses of the direct hospital treatment in EU are around seventy-eight billion euros for the period of 2008 to 2010. In those expenditures, they have included the cost of hospitalization, rehabilitation, and additional care facilities. In the same study, they mentioned that the percentage of the total therapeutic expenses in EU is 7.8 % out of the total amount of the one thousand billion euros. This amount does not include the percentage of people who visited private healthcare facilities. The example of the Netherlands, in which the current study took place, reveals that the approximated percentage of Dutch people who seek private healthcare consultation consists of two-thirds of the population Verbeek et al., 2015. This is a high percentage that has to be added to the total therapeutic cost for every European country to reveal the real magnitude of the problem.

A wide range of systems (such as motion platforms, force platforms, instrumented treadmills, motion-capture systems) are combined with integrated VR environments to provide the tools for a virtual therapy. An example of such systems can be seen in Figure 1.1. The virtual therapy in the current study focuses on the prevention of injurious falls. A virtual rehabilitation therapy tries to teach the patients to adjust accurately to the changes in their motion due to age, disease or injuries, by learning through repetition. Thus, the patients learn to react fast and accurately again in order to break through their motion behavior and prevent falls in the future (Philips, 1987). Virtual reality (VR) applications and systems are used nowadays to improve the existing therapeutic practices by motivating the individuals to achieve faster the goals of the therapy. The constant decrease of the cost of such systems have made beneficial the use of VR platforms for the gait rehabilitation of patients in the healthcare system. VR platforms that try to simulate real life tasks are on the rise, nowadays (Santos et al., 2008).

FIGURE 1.1: A wide range of systems are combined with integrated VR environments to provide the tools for a virtual therapy (Martins et al., 2012)

The age alters the way that the subjects understand motion. The most frequent falling injuries occur to the elderly during daily activities, such as walking up stairs or overstepping a sidewalk. The age alters the functioning of the sensory and motor systems of the human body and have an effect in the stability or the walking capacities of a person. The percentage of people who are experiencing dysfunction in their movements due to age are increasing every year (Haub, 2013). The functional capacity of a person increases in childhood to peak in early adulthood and eventually decline, as can be seen in Figure 1.2. The rate of decline is largely determined by factors related to lifestyle behavior, age, disease-related condition as well as external social, environmental or economic factors (Haub, 2013). The interaction with the social and physical environment are the main reasons that lead the subjects to severe injuries (Tam and Grimm, 2010).

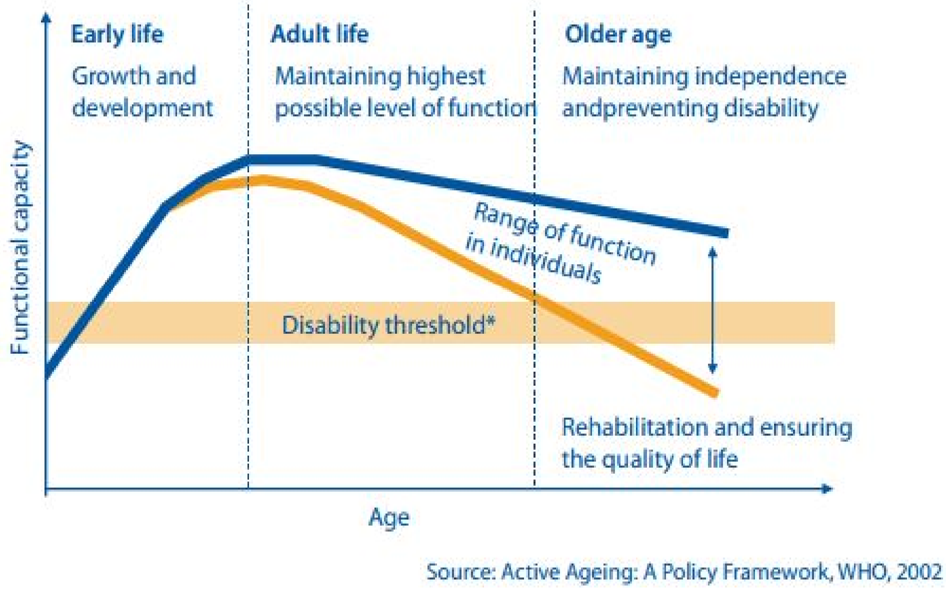

FIGURE 1.2: The functional capacity of humans based on age (Who, 2015)

Therefore, the virtual therapy is not only important for older adults who have already experienced dysfunctions or problems in their movements, but can also be applied in healthy individuals. The World Health organization, regarding fall prevention mentioned that '*(..)Any active-ageing strategy that strives to be effective in reducing the prevalence of chronic diseases and disabling conditions will need to adopt a life course perspective. This is especially important in the area of falls and falls prevention because many of the individual level determinants, which predispose a person to be at risk for injurious falls, begin to manifest themselves early in life.*' (Who, 2015).

The virtual therapy can teach younger individuals prevention strategies and build them the awareness to prevent falling injuries in the future by implementing gaming aspects in the rehabilitation training (Berger, 2006). VR platforms are combined with virtual environments (VE) to offer the possibility to the patients to perform daily tasks in an adjustable and controllable environments for them (Santos et al., 2008). Obstacle avoidance tasks, target steps or side steps can be adaptation tasks performed during a virtual rehabilitation training. Gait parameters are recorded during the therapy, to reveal the progress of a subject.

1.2 Adaptive locomotion

During a rehabilitation training, the subjects have to perform adaptation tasks, such as balance exercises or muscular coordination, in a safe environment. Muscular coordination is the adaptation of the human muscles to the environmental changes while performing locomotion tasks (Latash and Anson, 2006). Adaptive locomotion in the current study refers to the motion behaviors subjects have to perform to prevent a contact with an obstacle and thus, avoid a fall.

Humans rely on different information to recognize motion and perform locomotion tasks for the coordination and the balance of their movements. Visual, Vestibular and Kinesthetic sensory information are combined with the knowledge and the prior experience for the humans to achieve dynamic stability and therefore, decide on specific actions in order to avoid the contact (Taylor, 1997). The Vestibular sensory system is situated in the region of the inner ear of humans and helps them to maintain balance and coordinate their body movements (Brock, 1999). The Kinesthetic sensory system is the system that provides the CNS with the information about the motion and the location of the different body parts in relation to each other.

The Central Nervous System (CNS) is all those systems together, responsible to give directions, maintaining the balance and the stability of the human's body movements. Negotiation strategy is the behaviors subjects have to adopt to predict and act to avoid a future collision. The subjects have to recognize a potential danger and decide on appropriate actions to be performed (by the central nervous system (CNS)) and execute those actions (by the motor system) to avoid the contact with the obstacle and thus, prevent a fall (McKenzie, 2002) (Patla and Vickers, 2003). Falls in real life can happen by extrinsic or intrinsic factors (Fuller, 2000). Falls that occur as a result of intrinsic factors are dysfunctions in the movement, loss of balance or walking disturbances. Fall prevention therapy in this study focuses on those kind of injurious falls.

1.3 Depth Information

Many studies have tried to explain the way that humans perceive depth in real or virtual environments (Rolland et al., 1995), (Akai, 2007). In daily life, a person identifies an obstacle from a distance, detect motion and decide on the specific action to perform to avoid a contact. Vision plays the most significant role for humans in identifying this information, predicting motion and reacting accurately to prevent a fall (Higuchi, 2013). Humans combine the two images on each eye to perceive depth in a real life.

Depth information can be perceived in a virtual environment by one projected image (monocular cues) or two projected images (binocular cues) to each eye. A virtual reality experience with binocular cues can be achieved by the use of Head Mounted Displays (HMDs). A Head-mounted display (HMD) is a device placed in the head of the subject and projects one or two projected images to give a better perception of depth in the virtual environment. The results are good but comes with notable disadvantages during locomotion tasks, since they enhance disorientation, anxiety feelings and cyber-sickness phenomena (LaViola, 2000).

1.3.1 Monocular depth cues

The depth cues used in the current study are monocular cues, to provide the depth information to subjects about the the distance, the motion-parallax and the dimensions of the objects in the virtual environment. In the following sections, a number of monocular cue used in the rehabilitation application are going to be analyzed briefly.

Motion Parallax. Motion parallax is when the objects that visualized in a further distance from the camera position have a less apparent displacement than the objects appearing closer to it. Smith and Kosslyn, 2006 mentioned that '*(..) an object can be viewed from an infinite combination of possible angles and possible distances, each of which projects a slightly different two-dimensional image on a plane (and on the retina), varying in size, orientation or both.*'.

Linear Perspective. Perspective is the way of representing three-dimensional objects on flat surfaces. Linear perspective describes a system that the edges of the objects or the textures converge as the distance from the virtual camera increased. It is a model commonly used in painting to give the illusion of depth and distance on a flat surface. Parallel lines can be used in the textures to help the viewer's eye to understand the distance and the depth of the objects.

Lighting and color. Color and brightness are psychological characteristics of the light. Colors are the way the brain perceives the variation of the reflection or the emission of light from the different surfaces. Color variations can have an effect on the way humans perceive distance and affect the mental state of a person.

The red color has a strong effect in human behavior since it can triggers avoidance behaviors of subjects without their awareness (Cudworth, 2014). Elliot et al., 2007 mentioned '*(..) red is associated with the danger of failure in achievement contexts and evokes avoidance motivation*'. The extend use of the different color variations to affect the psychological and mental state of humans can be observed in the advertising and marketing industry (Tornetta and Blackbird, 2013).

Shadows and shading. Shadows provide an important visual information about the spatial relation and the dimensions of obstacles in a real or virtual environment. In an environment without shadows, the humans are unable to acquire correct information about the position or the location of objects in 3D space (Plenacostes, Demarey, and Dumas, 1998).

Shading refers to the integration of different levels of color brightness on the surface of a three-dimensional object and depends on the distance of each object's face from the light source. The color variation alters according to the angle and the distance of the surface from the light. The angle or the strength of a shadow are also parameters that may determine the depth perception of a subject (Kersten, Mamassian, and Knill, 1997).

Ground surface. The limitations of the field-of-view of a person affect the way humans observe objects and perform motor tasks during a real or virtual environment and hence, elevate the risk of falling (Jansen, 2012). During the virtual rehabilitation experience, the limited field of view of individuals will have an effect on their performance.

Gibson, 1950 is the first one who introduced the idea of using depth cues on a ground soil surface. Jansen, 2012, Brusini, 2007 are recent studies that have based on his idea and have tried to identify the role of the ground surface during locomotion tasks. Moreover, Sinai, Ooi, and Zijiang, 1998 mentioned that '*(..)as we frequently interact with objects on the common ground surface, it might be beneficial for the visual system to code an object's location using a ground surface-based reference frame.*'.

Mismatch of the visual & sensory information. The mismatch between the visual information (e.g. external cues) compared to sensory, motion information (e.g. internal cues) can cause motion sickness phenomena. Motion sickness during a VR experience is characterized by symptoms of nausea (from Greek *nausia*, 'seasickness'), such as disorientation, anxiety feelings and cybersickness (LaViola, 2000). In Jinjakam and Hamamoto, 2011, a study about the effect of multi-display surfaces on the experience of the subjects, the authors mentioned that motion sickness phenomena are stronger by the use of only one projector rather than the use of multi-screens. A front side, a right side and a bottom side screen have been tested during this study.

1.4 State of the art

The age alters the functioning of the sensory and motor systems of the human body and influences the stability and the walking capacities of a subject (Shumway-Cook and Woollacott, 2001). The study addresses the problem of falling injuries caused as a result of the reduction of the negotiation abilities of the subjects. The bad estimation of the distance or the dimension of an obstacle lead the individuals to trip over and thus, fall forward.

Falling prevention can be achieved by learning through repetition. A typical rehabilitation therapy is a monotonous process that discourages patients to continue with their treatment. A virtual therapy aims to improve the practices used in the rehabilitation of the patients and thus, make the subjects feel confident to perform tasks on a virtual platform as in real life, in a secure and safe environment for them (Schultheis and Rizzo, 2001). To this end, the subjects will learn to avoid obstacles more efficiently and thus, prevent falls in their daily lives. The virtual rehabilitation tries to motivate the patients to continue with their treatment, make them feel a sense of accomplishment and incorporate all the therapeutic exercises in a playful way (Berger, 2006). Virtual rehabilitation is the combination of virtual reality (VR) platforms with virtual environments (VE) to immerse patients in a virtual therapy.

The disease or aging can limit the visual-field of a person and therefore, increase the risk of falling injuries Brusini, 2007. Jansen, 2012 indicated the importance of vision during obstacle avoidance tasks. The limitations of vision can arise by intrinsic parameters, such as visual disabilities of a subject (e.g. blindness, low vision or color blindness) or by extrinsic parameters, such as the limitations of the device or the platform used. Those limitations in the visual field of a subject affect the understanding of the spatial relation of the objects in the environment and alter their motor behavior during locomotion tasks Brusini, 2007 (Jansen, 2012).

The most frequent falling injuries occur to the subjects during daily activities, such as walking across the street or overstepping a sidewalk (Winter, 1995). Humans have to perform adjustment tasks to avoid obstacles by identifying an obstacle in a distance, recognize its dimensions and decide on specific actions to perform in order to avoid making contact. The Boyd's OODA (Observe-Orient-Decide-Act) loop is a model which describes the behavior of humans to decide on correct actions (Brehmer, 2005). An interplay between the consciousness (Observe, act) and unconsciousness (Orient, Decide) process of humans. The 'observe' refers to the process of perceiving the information of the world, the 'Orient' is the process of understanding what that information means, which leads to decide and act to perform correct behaviors and thus, loop back again. This is a simplified version of the model and it can be visualized in Figure 1.3. However, the OODA loop model is not a linear loop model (step-by-step model) and the 'Orient' and 'Decide' steps of the model are too complicated and ambiguous to analyze further during this study. Therefore, in this research will mainly focus on the 'Observe' and 'Act' of the subject's behavior (consciousness process).

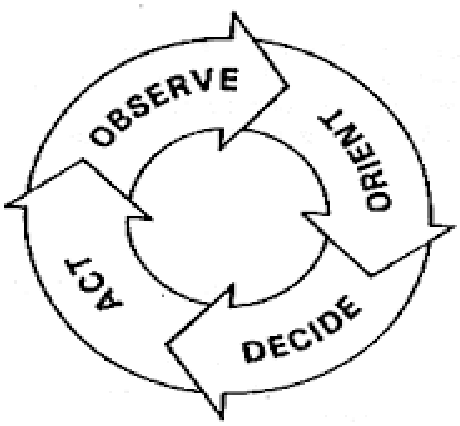

FIGURE 1.3: A simplified version of John Boyd's OODA Loop model, relates to all human behavior (Brehmer, 2005)

Several researches have highlighted the role of the lower body kinematics and floor projection during locomotion tasks (Marigold and Patla, 2002) (Patla and Vickers, 2003). However until today, a researched on rehabilitation platforms which combines two projected surfaces to visualize a virtual environment on a front and a ground surface, to improve the behavior of the subjects, has not yet been researched on. This study tries to reveal to what extent the visualization of the front virtual environment on the ground can affect the behavior and the experience of the subjects during obstacle avoidance tasks, as part of a virtual rehabilitation training. The hypothesis made during this study is that a floor projection combined with a front one will improve the performance and the experience of the subjects on the platform and thus, contribute to the better avoidance behavior of the subjects during the rehabilitation therapy.

1.5 Research Questions

There are two research questions the current study tries to answer to.

1. To what degree does the extension of a front virtual rehabilitation environment to the ground affects the behavior and the experience of the subjects over-treadmill walking?

Experiment 1 discusses in which way the use of a combination of two projections affects the behavior of the subjects over a virtual rehabilitation training. Question 1 examines to what degree the extend of a front virtual environment to the ground determines the behavior or the experience of the subjects who participated in the experiments on the virtual rehabilitation platform. There is a consistency in the motion and the projection of the simulated virtual obstacles between the two projections.

2. To what degree does the alteration of the projected information on the front/floor surfaces, of the same virtual environment, alters the behaviors or the experience of the subjects on the virtual platform?

Experiment 2 discusses the effect of the projected information on the ground surface during the obstacle avoidance tasks. Question 2 examines to what degree does the alterations of the projected information between the two surfaces alters the behavior or the experience of the subjects who participate in the experiments. The alteration of the projected information (i.e. inconsistency in the visualization of the virtual obstacles) refers to the projection of the spherical three-dimensional obstacles, as flat disks on the ground surface, on the treadmill where the subject stands. The motion of the obstacles from the front to the ground projection is consistent during all the experiment.

Chapter 2

Materials and Methods

A number of experiments conduct on a virtual rehabilitation platform. The purpose of these experiments is to determine to what extend the combination of a front with a floor projection affect the behavior and the experience of the participants. The first experiment consists of two test conditions, whereas the second one consists of only one. The subjects have to observe the obstacles in a front, anticipate them in the front or the front/floor surface and try to act accordingly to step over them.

The obstacles appear in the virtual floor, in the walking path of the subjects for the left or the right foot respectively. The leg agility tasks for each foot and the height of the simulated obstacles are randomized during the virtual rehabilitation application on the platform. In this chapter, we are going to present the demographic information of the subjects who participated in the experiments, the method & apparatus used, the experiment setup and finally, the implementation choices that we had to take to improve the final results.

2.1 Participants

Eighteen adults participate in the experiments (14 males, 4 females and 30 mean age) aged from 18 to 63. Demographic information about the subject's gender and age can be seen in Tables 2.1 and 2.2.

TABLE 2.1: Demographic information about the gender of the test subjects participate in the experiments (Appendix A.3)

Gender	Num. Samples	Percentage
Female	4	22.2%
Male	14	77.8%

TABLE 2.2: Demographic information about age of the test subjects participate in the experiments.

Age Groups	Num. Samples	Percentage
18 to 30	12	66.6%
31 to 40	3	16.7%
41 to 63	3	16.7%
Min:18 | Max:63	18	100%

The test subjects who took part in the experiments were employees of the Motekforce Link company. All the subjects who participate in the experiments have a normal, healthy condition. No subject report any known perception disorder or motor impairments. The study wants to reveal the alterations in the subjects' behavior and the experience between the different projected surfaces.

2.2 Apparatus

Mill/ReGait System. The C-Mill/ReGait is equipped with two HDMI CASIO projectors used to project the virtual environment in a front/floor surface. A Microsoft Kinect, first generation sensor with the SDK 8.1 for Windows-PC is used by the C-Mill/ReGait system.

The Window-PC used to connect those systems is a Intel(R) Xeon(R) CPU E5-1620 v3 3.50GHz with 8GB RAM. A Niv/idia GeForce GTX 750 Ti is used to render the virtual rehabilitation environment. The operating system runs on Windows 8, 64 bit. The set-up of the Kinect sensor with the system and the position that the Kinect is placed to track the behaviors of the subjects can be seen in Figure 2.1.

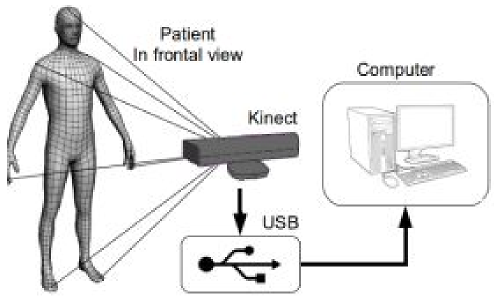

FIGURE 2.1: The set-up of the motion capture Kinect sensor (Juanita, 2015)

Virtual Platform. The C-Mill/ReGait system consist of a virtual reality multi-display platform for the gait rehabilitation of the patients. The C-Mill/ReGait is equipped with two projectors; thus, the virtual environment is projected on a flat surface, in front of the user, and on a ground surface, on the treadmill on which the subject stands. The Kinect sensor is placed in front of the user. Figure 2.2 illustrates an example of the rehabilitation application in the C-Mill/ReGait system.

The two projectors provide the stimuli, whereas the Kinect sensor is used to track the behavior of the subjects. A sufficient treadmill area gives the possibility to the subjects to simulate walking behaviors during the rehabilitation platform, as in a real environment. The red area on the ground specifies the area that the subjects have to stand, on the treadmill.

The flat, front surface that the virtual environment is projected on, measures $1.77\,\mathrm{m}$ wide and $2.20\,\mathrm{m}$ long. The ground surface that the virtual environment is projected on the treadmill, measures $1.32\,\mathrm{m}$ wide and $1.50\,\mathrm{m}$ long. A sketch of the C-Mill/ReGait system and the dimensions of each surface can be visualized in Figure 2.3.

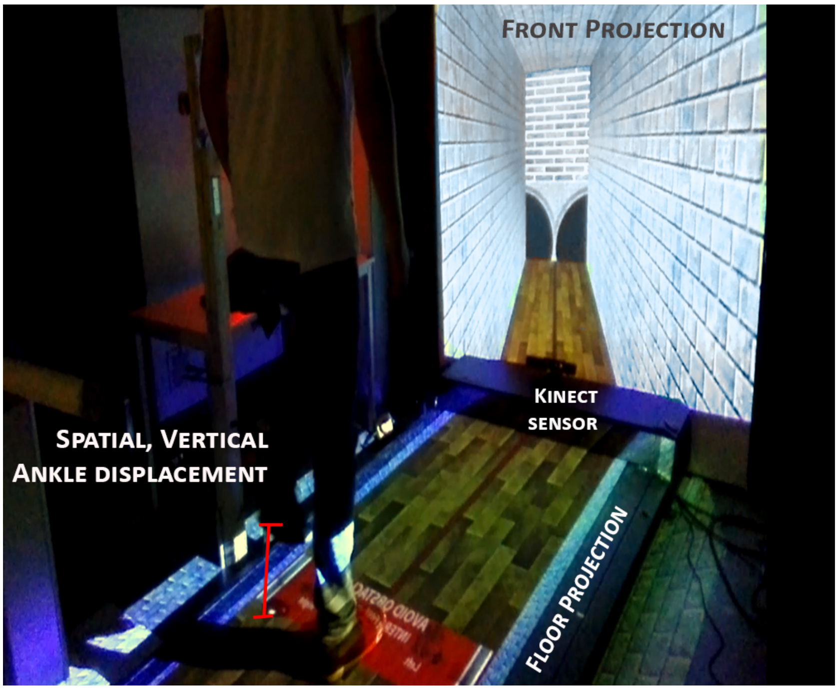

FIGURE 2.2: Illustration of the virtual rehabilitation application during our experiments on the C-Mill/ReGait system.

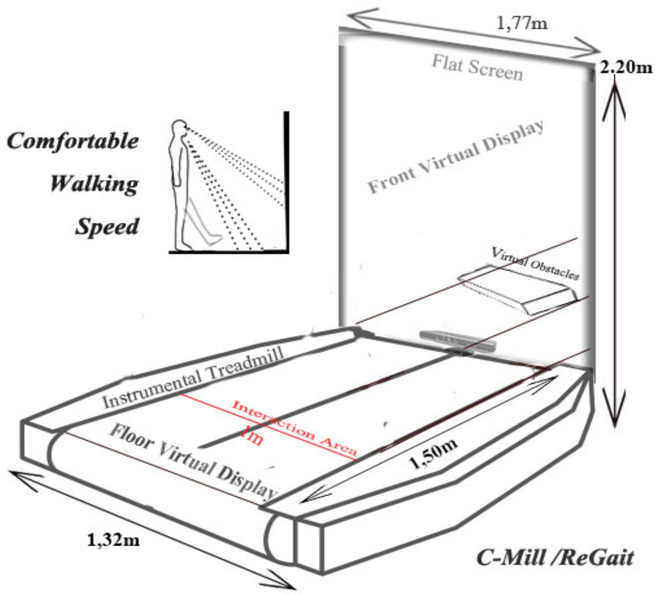

FIGURE 2.3: Sketch of the dimensions of the front/floor surfaces of the C-Mill/ReGait platform used for the experiments.

Kinect Motion-tracking sensor. Microsoft Kinect, first-generation is the motion-tracking sensor used in the C-Mill/ReGait system, to evaluate the motion behavior of the subjects during the rehabilitation training. The assumption made is that Microsoft Kinect, first-generation has the capacity to track simple locomotion tasks during the virtual rehabilitation training.

The Microsoft Kinect is a marker-less motion tracking system. The depth information is captured by the infrared sensor and the infrared camera (i.e. IR light and depth images), whereas the color information is captured by the RGB camera (i.e. color images). Therefore, Kinect can reconstruct color-depth images with pixel values, which correspond to the physical distance between the sensor and the tracking object. This information is combined with computer-vision algorithms at Kinect's core to track the position of the "joints" and the motion behavior of a subject in a 3D space.

Kinect has initially been used for game applications and exercise-based computer video games (exergames), but resent studies have revealed the possibilities of the use of the Kinect sensor for clinical applications (Paolini et al., 2014), (Galna et al., 2014). Research studies have compared the data gathered by a Kinect sensor with the data taken by a gold standard Vicon motion capture system. The analyses revealed that the Kinect motion-capture data are correlated to those obtained with the Vicon system in most of the cases (except hand postures). In the study by Paolini et al., 2014, mentioned that *'(..)despite the poor absolute agreement, there was a strong positive linear correlation between Kinect and Vicon measurement apart from standing trunk flexion and hand clasping.'*.

The results of the study by Galna et al., 2014 can be seen in Figure 2.4. The subjects had to raise and lower their foot position, as far and as fast as possible (extreme cases) to reveal the capacities of the Kinect sensor to provide accurate results.

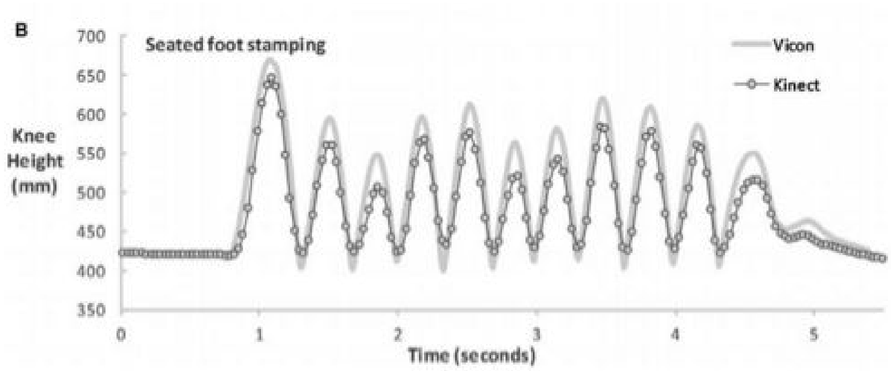

FIGURE 2.4: Vertical displacement of the knee marker. The data from the Kinect sensor is the black dots, whereas the tracks of the Vicon Motion Capture System is the Grey line (Galna et al., 2014)

Kinect was able to measure the timing of the Knee gestures accurately, however an underestimation of the range of the spatial motion of the Knee height can be observed between the Kinect's and Vicon's motion tracking data. Galna et al., 2014 identified that, *'(..)Kinect significantly underestimated range of motion for lateral flexion, hip kinematics during forward stepping and side stepping, vertical knee height during leg agility movements..*

The C-Mill/ReGait system wants to become a real-world clinically feasible solution for the gait rehabilitation, due to the low-cost, the portability and the training requirements of the platform. Due to the low-cost of the platform and the portability, the low-cost Kinect sensor is used to track the behavior of the subjects in the current virtual rehabilitation application on the platform.

Motor-behavior variables. A motor-behavior is classified by its goal. The goal of the motor-behavior in this study is the spatial, vertical displacement of the foot of the subjects to step over virtual obstacles. The ankle joint is measured as a function of time to reveal the spatial, vertical displacement of the foot of the subjects during the experiments. Maki and Mcllroy, 1996 indicated that 54% of all fall injuries are occurring due to slips, tripping or overstepping. The most frequent falling injuries occurred when the subjects are in motion, such as walking up stairs or overstepping a sidewalk (Campbell, Borrie, and Spears, 1989). Therefore the subjects have to walk on a treadmill surface to step over obstacles during the rehabilitation training on the C-Mill/ReGait system.

The speed that the subjects have to walk on the treadmill remains constant during all the experiments and it is characterized as the average/comfortable speed that healthy individuals have to walk without carrying any objects (Bohannon, 1997). According to the same study, the comfortable walking speed remains approximately constant between the different genders and age groups (Bohannon, 1997) and hence, the average/comfortable walking speed based on this data is measured at $1.4\,\mathrm{m/s}$. This is the speed used for the subjects to walk on the treadmill to step over obstacles during the rehabilitation therapy. A comfortable walking speed is chosen since it provides a more secure walking for the subjects and a sense of tranquility to continue with their treatment. Furthermore, the average/comfortable walking speed will provide better motion-tracking measurements during the locomotion tasks on the platform.

Software for Application Development. The gait rehabilitation application has been implemented in D-Flow. D-Flow is the software used for the application development by Motekforce Link. It provides real-time control between the systems used in the C-Mill/ReGait set-up, and the data coming from those systems. It is the bridge between the developers and the high-end virtual environment.

The main key features of the D-Flow software are:

- Synchronized data with other data streams, which are available in real-time application development
- Modular system, which allow for enhancements and integration with the treadmill and the virtual environment.
- Ogre3D rendering engine combined with the D-Flow software.
- Lua, the scripting programming language used in D-Flow

Data captured by Kinect is send to the D-Flow software directly, and therefore is immediately available for manipulation. Data send over the network to D-Flow in packages of multiple frames. From this point on, D-flow makes a distinction in which data are used for real-time processing and data that need to be recorded. The Mocap module inside D-Flow combines those data recorded of the motion capture system in a single data file, and adds a time-stamp. The frequency that is used for writing data is the frequency of the motion capture device.

2.3 Stimulus and Procedures

Three conditions are performed by each subject in the C-Mill/ReGait system, as part of the rehabilitation training. The order that the subjects are tested, in these conditions, is randomized during the experiments. The three conditions, by numerical order, are:

- The rehabilitation environment is projected only on a front surface, in front of the treadmill on which the subject stands.
- The rehabilitation environment is projected on a front/floor surface. There is a consistency in the projected information between the two surfaces. The three-dimensional spherical obstacles are visualized with the same dimensions (i.e. width,length and height) in both projections.
- The rehabilitation environment is projected on a front/floor surface. However, there is no consistency in the projected information between the two surfaces. The three-dimensional spherical obstacles on the front projection are now visualized as flat disks on the ground surface. The width/length of the obstacles stay the same, but the height cannot be visualized any more on the ground projection. An implementation choice to reveal how the consistency/inconsistency in the projected information between the two surfaces and the visualization of the height on the ground projection affect the behavior of the subjects.

The three different conditions can be visualized in Figure 2.5 and they will be analyzed further in the next chapters.

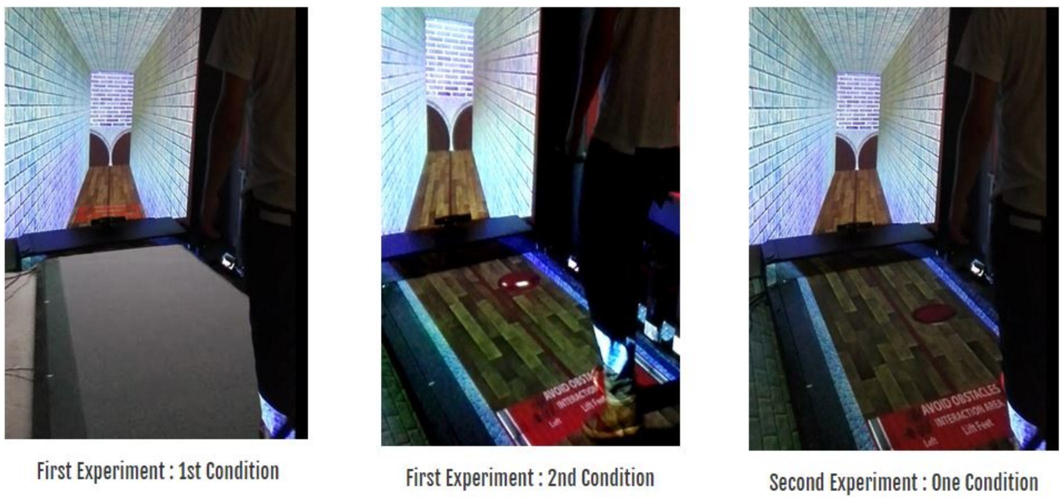

FIGURE 2.5: The three different test conditions tested during the current study on the C-Mill/ReGait system. The virtual environment is projected in a "Only Front Projection", "Front+Floor Surface (Consistency in the projected information)", "Front+Floor Surface (With inconsistency in the projected information)"

The subjects were assessed in three different test conditions, designed to measure the capacity to step over obstacles, in a virtual environment. The subjects have to perform motor tasks while walking on a treadmill with constant speed. The order that the subjects have to perform the three test conditions is randomized between the experiments. Moreover, the subjects have to switch feet to accomplish avoidance tasks for the left or the right foot during the trials. The left or right avoidance tasks are also randomized between the trials to avoid external parameters alter the results. The floor of the virtual corridor is sub-divided into two areas by a projected red line in order to separate the tasks for each foot. The subjects have to perform avoidance tasks for only one of their feet per trial. This is an implementation choice to achieve consistency between the performance of the left and the right foot during the training on the platform.

2.3.1 Virtual Environment.

Virtual Rehabilitation Environment. The rehabilitation environment during the training application consists of a virtual corridor. The dimensions of the corridor is $3.5\,\mathrm{m}$ high and $2.5\,\mathrm{m}$ wide. A texture with bricks is applied to the walls of the corridor to provide the subjects with a metric measurement to identify the height of the obstacle in the environment. Normal size bricks are used for the texture of the walls in the rehabilitation environment $25\,\mathrm{cm}$ length and $15\,\mathrm{cm}$ height. Moreover, parallel lines are used in the textures of the walls to help the viewer's eye to understand the distance and the depth of the objects in the virtual environment. The concept of the current rehabilitation application can be seen in Appendix A.1.

The subjects have to walk in the virtual corridor while spherical obstacles appear in their path. An example of the different motor-behaviors that subjects have to perform on the platform can be seen in Figure 2.6. A front wall in the virtual corridor blocks the horizon of the subjects in the rehabilitation application. The distance of this wall to the area that the subjects have to step over the obstacles (i.e. interaction area) is characterized as anticipation area and it is $10\,\mathrm{m}$ in all the experiments as can be seen in Figure 2.7. This is an area for the subject to anticipate the virtual obstacles and understand their height dimensions in the virtual environment. This area is projected in the front projection or is divided between the front/floor projections, depends on the condition.

Interaction Area (i.e. Area of collision). The area of interaction is defined as the static red area visualized on the floor of the virtual corridor. It is the area that the subjects have to stand in to step over the virtual obstacles. The red interaction area is also provides a feedback to the subjects about the area that the collision with the virtual obstacle is about to occur and can be seen in Figure 2.8.

The interaction area is projected on the ground so that the subjects would not get too near to the Kinect sensor. The distance of the Kinect sensor to the tracking subject is approximately $1.5\,\mathrm{m}$. The optimal distance of the sensor from the tracking object to achieve a full body reconstruction is $1.2\,\mathrm{m}$ to $3.5\,\mathrm{m}$. The limitations arise by the range of the camera and the infrared light used by the Kinect sensor. Jun et al., 2011 mentioned that the optimal position for a Kinect sensor to be placed is in the front of the tracking object.

FIGURE 2.6: Different behaviors that the subjects have to perform while Walking on the treadmill, with constant speed. The subjects have to lift their right or left foot respectively. to step over virtual obstacles appearing in their path.

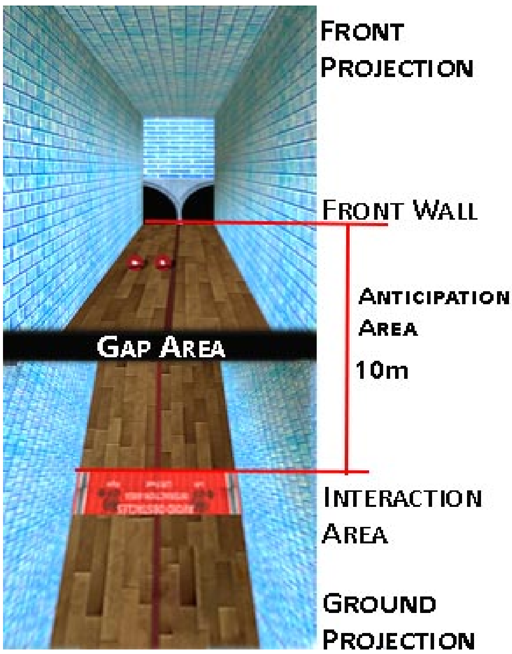

FIGURE 2.7: The different areas the rehabilitation environment on the platform is sub-divided

FIGURE 2.8: The area of action that the subjects visualized on the floor of the virtual corridor. It is the area that the subjects have to stand in to step over the virtual obstacles. The interaction area is static, therefore it is always visualized in the same location on the floor of the virtual corridor.

Virtual Obstacles. A highly saturated red texture is applied to the virtual obstacles to evoke emotions about the danger of failure (Elliot et al., 2007). In this way, the test subjects will be motivated to step over the virtual obstacles while walking, as they will have done in real life.

The obstacles avoidance tasks the subjects have to step over during the rehabilitation training can be seen in the Figure 2.9. In the top left and top right images, the obstacle with twenty and the thirty centimeters dimensions are visualized. In these two scenarios, a number of aligned obstacles are appearing, the one next to each other, in each trial to cover the area of interaction for the left or right foot. Therefore, avoidance behaviors of the subjects by moving left or right on the treadmill rather than lift their foot to step over the obstacles, are extinct. The obstacle tasks, based on their difficulty can be seen in Table 2.3.

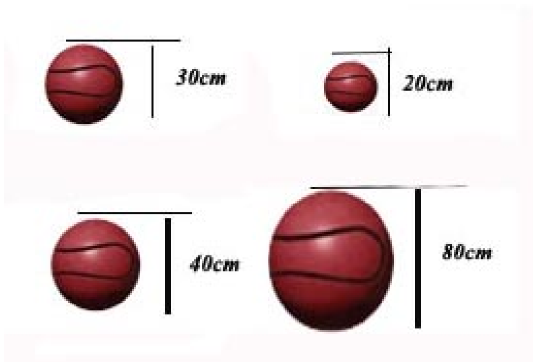

FIGURE 2.9: The three-dimensional spherical avoidance tasks that the subjects have to step over in the virtual rehabilitation application on the platform. The heights of the obstacles are ranging from 20 cm to 80 cm.

TABLE 2.3: Levels of difficulty of the four avoidance tasks

Obst. Height	Diff. Level	Summary
20cm	Easy	Easily step over the obstacles
30cm	Challenging	Needs a good perception of obstacles height dimensions
40cm	Difficult	Difficult to step over them during treadmill walking
80cm	Impossible	Cannot step over them during treadmill walking

2.3.2 Experiment Design

Pilot tests. Seven pilot tests were conducted at the beginning of the experiments. Two main parameters were tested in the system; different obstacle height to reveal the limitations of the subject's motor behavior to step over obstacles and two different obstacle shapes (spherical and cubical objects). During the pilot test, the obstacle heights tested were ranging from $20\,\mathrm{cm}$ to $1\,\mathrm{m}$. Four obstacle heights are chosen to be used in the final experiments to reveal the alterations in the behavior of the subjects. The data gathered during the pilot tests have not been included in the final data analysis in this study. They have only been used for feedback purposes and help us make implementation decisions to improve the virtual rehabilitation therapy on the platform.

During the captured data by the Kinect sensor, an error can be observed in the results of the "joints" recognized by the Kinect library and the anatomical joints of the subjects. This error is difficult to be measured since it depends on various parameters, such as the background noise during the different experiments (lighting conditions, the color of the clothes, color of shoes and more). However, it has been observed during the pilot test, that the ankle joint contain less noise in comparison with the position of the center of the feet recognized by the Kinect library. Hence in this study, the ankle joints are tracked to reveal the spatial displacement of the feet of the subjects during the experiments.

Final Experiments. The first experiment consists of two test conditions, whereas the second experiment consists of only one. Each test condition consists of eight trials (4 ball sizes * 2 feet = 8 trials), a total of twenty-four trials per subject. One test trial consists of only one obstacle avoidance task, that the subjects have to step over with the left or the right foot. The order that the obstacles are spawned in each foot is randomized during the test condition, to avoid differences in the behavior of the left or right foot of the subjects. Moreover, no feedback is provided to the test subjects about the placement of their feet in the three-dimensional world or the way they have performed during the experiments. The subjects continue walking on the treadmill until they have finished with all their trials. The implementation choices made to achieve consistency between the different experiments. The motion-capture data during locomotion tasks and the answers of the subjects in the web-based questionnaire are analyzed further and compared to reveal alterations in the performance and the experience of the subjects in the test conditions.

In the rehabilitation training, the subjects perform simple motor tasks. These tasks were to lift their foot in a relative height according to the height of the simulated obstacles spawned in the virtual environment, projected in a front or in a front/floor surface. The subjects were instructed to continue walking on the treadmill until they have finished with all their trials. The red textured area on the virtual floor is the area in which the subject has to stand and perform actions in order to step over the obstacles.

2.3.3 Experiment setup

Three test conditions are tested with the C-Mill/ReGait system. The subjects have to walk on a treadmill, with constant speed and try to step over obstacles appearing in their walking path, each with different height dimensions. The perception of depth in the rehabilitation application is perceived by the subjects through monocular cues and the implementation of a VR display. The VR display is a way to alter the point-of-view of a subject in real-time in the three-dimensional world. The position of the head of the subject is used as a reference frame for the view angle that the subject is looking at in the virtual environment. This is a simplified solution to give the illusion of depth without the use of HMDs or eye-tracking techniques. The position of the head is tracked by the Kinect sensor which is placed in front of the test subjects. The visualization of the red, static interaction area on the virtual ground area is used to provide a feedback to the test subjects for the position they have to perform actions in the virtual environment and the location on the treadmill in which they have to stand.

Experiment One: Two Test Conditions

The negotiation strategy the subjects have to adopt to prevent a future collision in the virtual environment, is first to recognize the potential danger in front, decide on appropriate actions to perform on the next steps ahead and then execute those action to avoid the contact with an obstacle and prevent a collision. In the experiments the subjects have to observe the obstacles in the front projection and perform action in the front/floor surface accordingly. These two states are characterized as parts of the process of consciousness, whereas all the states in between from that of awareness to the action are parts of the unconscious. The hypothesis made is that the two surfaces will achieve one coherent world experience, which will contribute to a better perception of the height dimension of the virtual obstacles and the experience of the subjects during the virtual training.

The subjects have to decide to lift their foot in the appropriate height to step over the virtual obstacles, on the correct timing to avoid the contact. The role of the floor projection in the behavior of the subjects will be identified during the experiments. Two test conditions are conducted during the first experiment to reveal the alterations in the subject's behavior and the experience.

First Condition: Only Front Projection. The virtual rehabilitation environment is projected only in a front surface, in front of the treadmill on which the subject stands. The distance from the point that the virtual obstacles are first time visualized by the subjects until the area of interaction (i.e. collision area) is characterized as anticipation area. The interaction area is the red area visualized in the floor of the virtual corridor and during this condition projected on the front projection as can be seen in Figure 2.10.

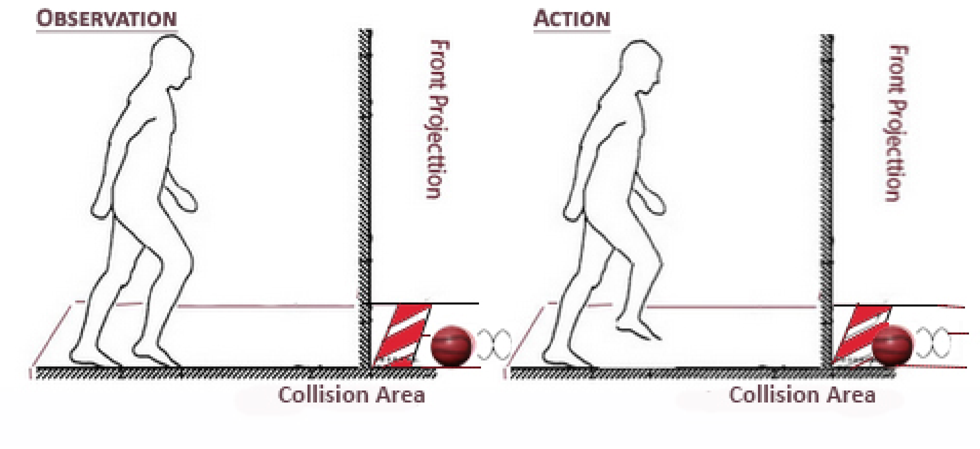

FIGURE 2.10: In the first condition of the first experiment, the virtual environment is projected in a front surface, in front of the treadmill. The interaction area (i.e. collision area) is visualized in the floor of the virtual corridor, projected in the front surface.

Second Condition: Front/Floor Projections (Consistency in the projected information). The virtual environment is projected on two surfaces. The front virtual environment is extended on the ground surface. There is a consistency between the information projected between the two surfaces. The obstacles are visualized in both projections as three dimensional spheres with the same width, length and height. The interaction area is now projected in the ground projection, on the treadmill as can be seen in Figure 2.11.

Experiment Two: One Test Condition

Previous studies have already highlighted the role lower body kinematics or floor, projection surface can have in the extraction of information while performing locomotion tasks in a real or virtual environments (Marigold and Patla, 2002) (Patla and Vickers, 2003). Therefore, to reveal such phenomena a discontinuity in the projected information between the two surfaces is implemented. The hypothesis made is that the inconsistency between the projected virtual obstacles between the two surfaces will reveal alteration in the behavior and the experience of the subjects.

One Condition: Front/Floor Projections (Inconsistency in the projected information). The virtual environment is projected on two surfaces as in the second condition. The three-dimensional spherical obstacles are now visualized on the ground surface as flat disks. Therefore, there is inconsistency in the projected information between the two projected surfaces as can be seen in Figure 2.12. The area that the subjects have to step over the obstacles is again projected on the ground projection.

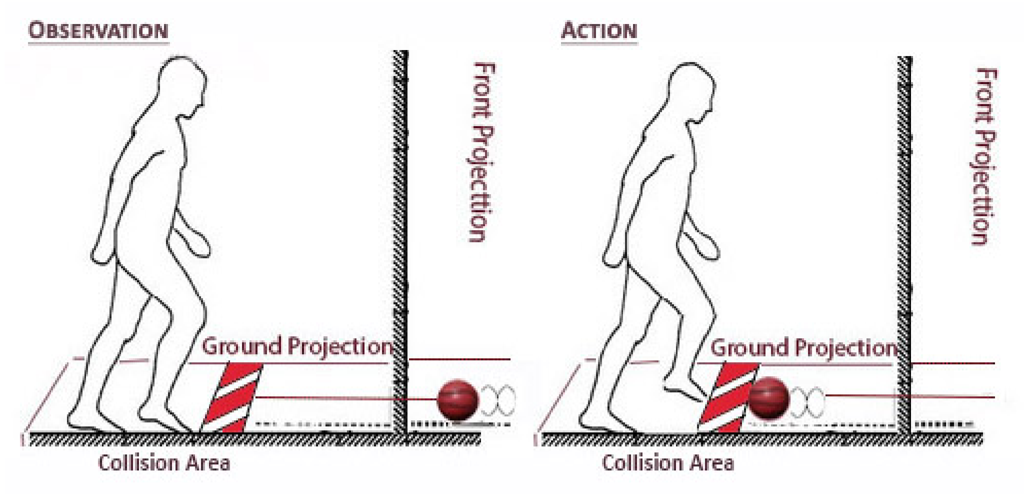

FIGURE 2.11: In the second condition of the first experiment, the virtual environment is projected in the front/floor surface. The obstacles are first visualized in the front screen and later on, on the ground surface, on the treadmill that the subject stands. There is consistency of the simulated virtual obstacles between the two surfaces.

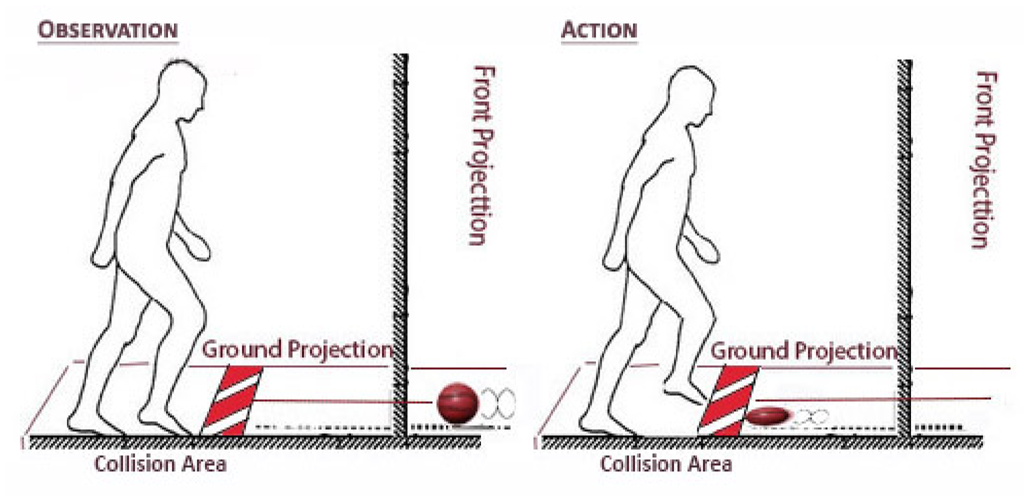

FIGURE 2.12: In the second experiment, the virtual environment is projected in a front/floor surface. The three-dimensional spherical obstacles of the front projection are now visualized on the ground as flat disks. There is inconsistency of the simulated virtual obstacles between the two surfaces.

2.4 Implementation Decisions

2.4.1 VR display

To achieve a feeling of one coherent virtual environment between the front/floor projection a virtual reality (VR) display has been used. The VR display (i.e. ego-motion) during this study, is a technique of controlling the point-of-view of the subject, real time, in the virtual three-dimensional environment. The VR display combined with head-tracking technique to provide to the test subject the illusion of depth. The assumption is that this implementation will create the feeling of one consistent world experience on the platform. The angle that the subjects visualize the virtual environment is altering based on their head position, tracked by the Kinect sensor, as can be seen in Figure 2.13.

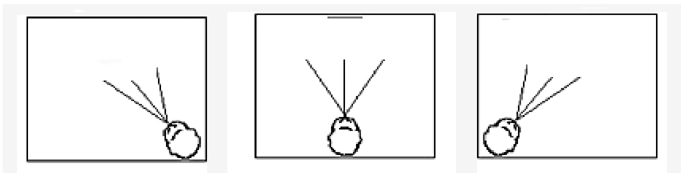

FIGURE 2.13: Walking straight ahead (Middle Image), angled slightly to the left (Right Image) or angled slightly to the right (Left Image), to perform action to step over the obstacles.

The Kinect sensor is used to track the position of the subject's head in the rehabilitation application. An illustration of these alterations in the virtual rehabilitation on the platform can be seen in Figure 2.14. An additional question has been added to the end of the web-based questionnaire to identify if there are any motion sickness phenomena during the rehabilitation training on the platform due to the VR display method.

2.4.2 Color variations

Colors can alter the perception of the distance of objects during a virtual reality experience and can have an effect on the mental state of a subject (Cudworth, 2014). Colors can help a person have a feeling of tranquility and safety which is an important parameter during a rehabilitation training. An example is the warm colors which are used in the hospital facilities to evoke to the patients feelings of relaxation and security.

In the rehabilitation application on the platform, soft colors are applied on the walls, the ceiling and the floor of the virtual corridor. The ceiling and the walls have a blue texture, whereas a brown texture is applied to the floor of the virtual corridor, to evoke a feeling of tranquility to the test subjects, which will help in the outcome of the therapy. The blue and brown colors are characterized as warm colors, which can create a sense of confidence and balance (Jain, 2010). On the other hand, a red colored texture is applied in the area of interaction, the area in which the subjects have to stand to step over the virtual obstacles. The red color can evoke avoidance behavior based on the study Elliot et al., 2007. However, the color is an abstract entity which can have different meaning between the different cultures, religions and ethnic groups.

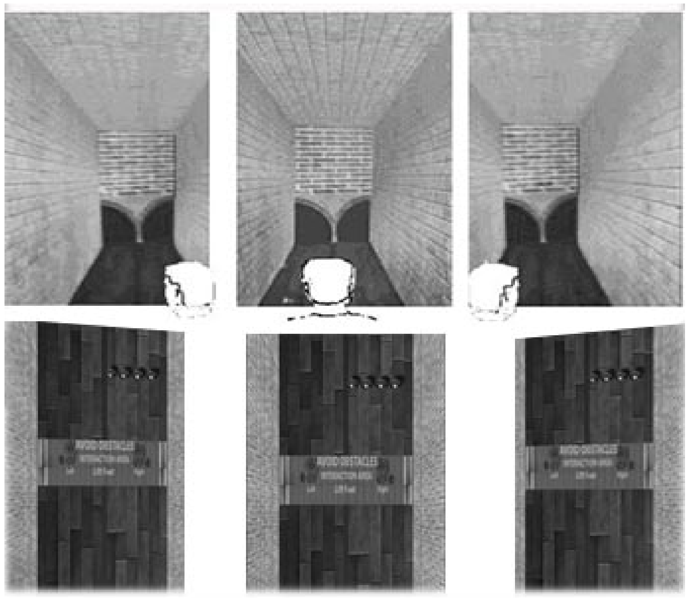

FIGURE 2.14: A right placement of the head position gives a right perceptive of the environment, whereas a left placement gives a left perspective, on both the front and the ground projected environments.

The color variations between the different textures, applied in the virtual environment, must not take too much attention from the avoidance behaviors the subjects have to perform. Therefore, the changes are according to a soft color palette in order to keep the test subject stimulated during the trials. During all the experiments, the colors and the textures of the environment remain constant.

Dynamic shadows are applied on the virtual environment by the Ogre3D engine used in D-Flow as can be seen in Figure 2.16. Moreover, a texture with bricks is applied on the walls of the virtual corridor. In this way, the test subjects will have a metric parameter to measure the dimensions of the obstacle appearing in the rehabilitation environment.

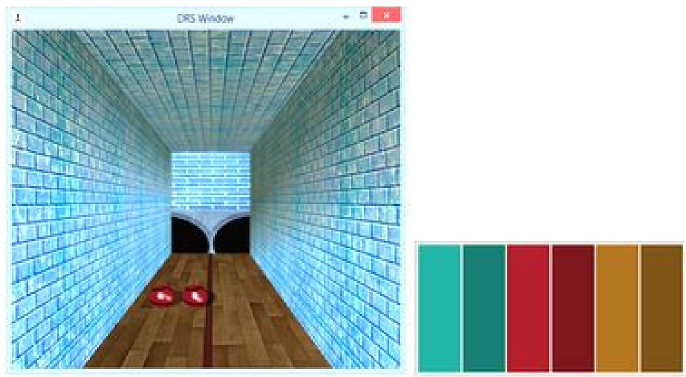

FIGURE 2.15: The color palette used in the virtual rehabilitation environment.

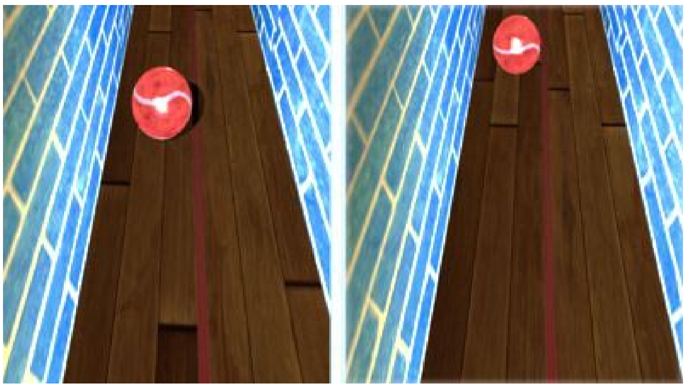

FIGURE 2.16: Dynamic shadows applied by the Ogre3D engine.

Chapter 3

Results

The subjects perform simple locomotion tasks on the C-Mill/ReGait platform. The motor-behavior of the subjects is recorded by the Kinect sensor, whereas the web-based questionnaire evaluates the experience of the subject after each test condition. In the first section 3.1, the performance of the subjects is measured as a combination of the vertical displacement of the ankle joint as a function of time. By ankle joint, this study refers to the joint recognized by the Kinect Library and not the anatomical joint of the subjects. In the second section 3.2, the experience of the subjects on the platform is evaluated after each test's condition, by a web-based questionnaire. The data analyses reveal alterations in the behavior and experience of the subjects in the platform.

3.1 Performance Evaluation

A successful scenario in this study is characterized as the case in which the subjects have raised their foot high enough and at the correct timing to avoid a contact with the obstacle. The correct timing is when the obstacle is about to collide with the real position of the test subject's feet while they are standing on the platform. The distance of the foot of the subjects (i.e. ankle joint) from the ground plane, recognized by the Kinect library, will measure the height that the subjects have lifted their foot to step over the obstacle avoidance tasks on the platform, during treadmill walking.

3.1.1 Data Analysis & Results

The graphs presented in this section reveal the spatial, vertical displacement of the joint ankle (y-axis) in centimeters, per frame as recognized by the Kinect motion-capture sensor, and it is a function of time (x-axis) in seconds. In this way, we want to reveal the overall behavior of the subjects on the platform.

The Kinect starts to track the behavior of the subjects when the distance of the obstacle from the position that the subject stands is smaller than 50cm. It is the area that the obstacle is about to collide with the foot of the subject in the virtual space. The vertical, red lines in the graphs represent the points in time that the collision is about to occur.

The dots on the graphs represent the mean vertical displacement of the foot position per captured frame. An interpolation line is used to connect all these points recorded by Kinect (i.e. curve line on the graphs). The graphs want to reveal the overall behavior of the subjects in each condition and the time of response, when the obstacle is about to collide with the foot of the subject. The blue color represents the behavior of the subjects for the 20cm, the green for the 30cm, the orange for the 40cm and the purple for the 80cm obstacle avoidance tasks as can be seen in the graphs in Figures 3.1, 3.2, 3.3.

We assume that the subjects who lift their foot in a maximum height less than 5cm did not understand the purpose of the rehabilitation therapy or did not feel enough motivated to lift their foot high enough to step over the virtual obstacle and therefore, fail to perform correctly. These subjects are characterized as outliers and have been removed from the data in the graphs to provide a better perception of the subject's behavior.

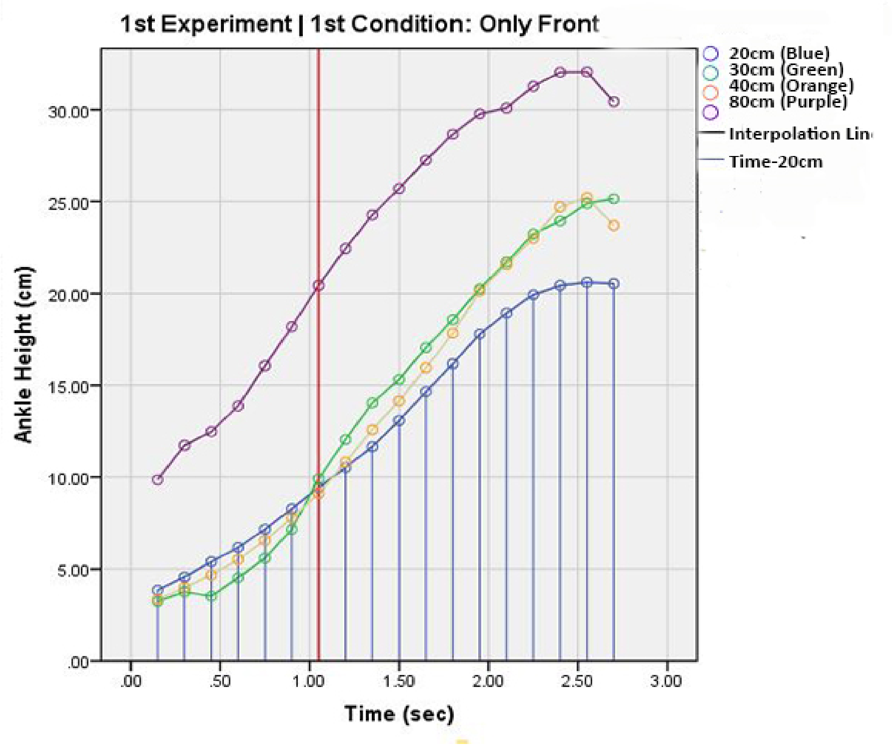

FIGURE 3.1: The mean, vertical displacement of the foot of the subjects, as recognized by the Kinect Library, during the virtual rehabilitation application in the first experiment, first condition.

The graphs in Figures 3.1, 3.2 and 3.3 reveal the latency between the collision moment and maximal foot height of the subjects. The collision moment is the point in time that the obstacle is about to get colliding with the foot of the subject. The position of the foot is recognized by the Kinect sensor as we have already mentioned. The floor projection on the treadmill helps the subjects perceive accurately the position of their feet in the virtual environment and therefore, act in time to avoid the contact with the obstacles. No feedback is provided to the subjects about the position of their feet in the virtual environment in any of the experiments. The subjects subconsciously use their real-foot position on the treadmill as a reference frame to measure the distance of the obstacles visualized on the floor projection. In the first condition that the virtual environment was only projected on a front surface the subjects showed latency between the reaction time and the maximum foot height, as can be observed in the graph in Figure 3.1.

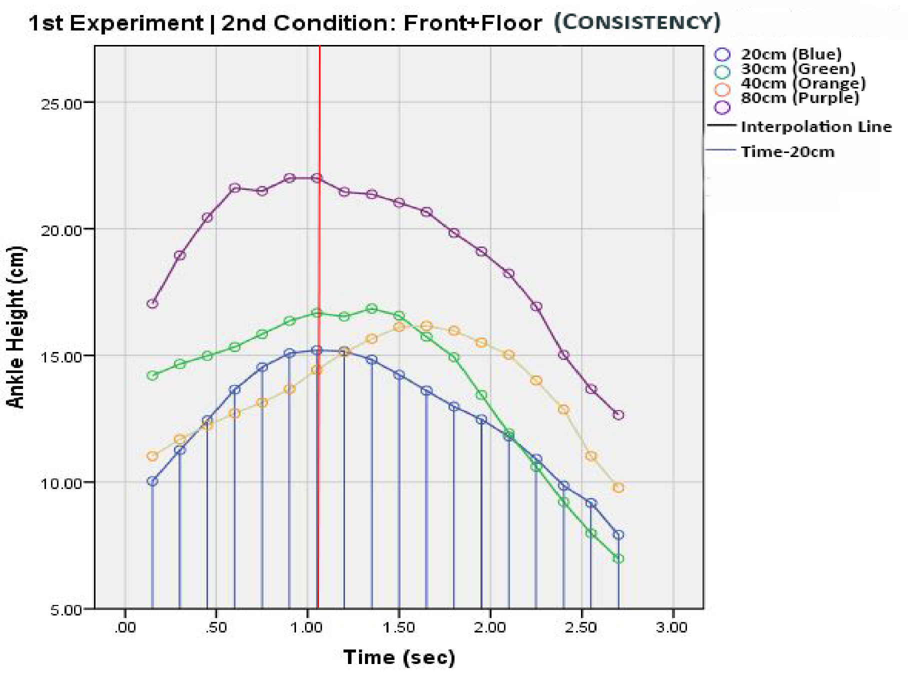

FIGURE 3.2: Vertical displacement of the foot of the subjects, as recognized by the Kinect Library, as a function of time during the virtual rehabilitation application in the first experiment, second condition.

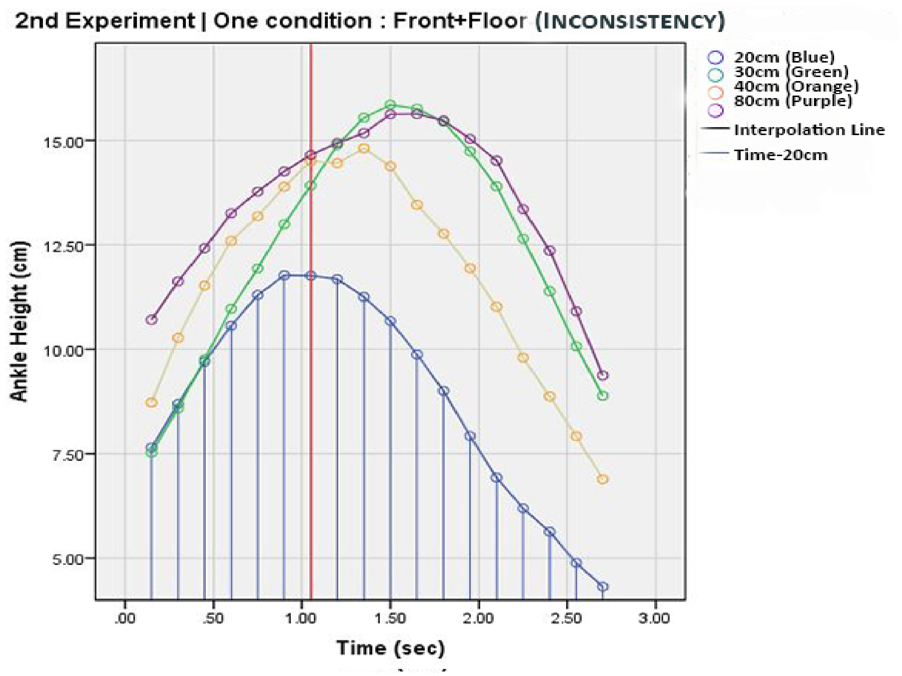

FIGURE 3.3: Vertical displacement of the foot of the subjects, as recognized by the Kinect Library, as a function of time during the virtual rehabilitation application in the second experiment.

It is observed by the three graphs that the subjects have a difficulty to perceive the height differences between the different avoidance tasks on the platform. In the condition in which the virtual environment is only projected on the front surface, the subjects lift their foot in a higher proportional height to step over the virtual obstacles, as can be seen in Figure 3.1. This behavior is observed by comparing the first graph with the other two conditions in Figure 3.2, 3.3. The line is flattered since only the averages are used to reveal this behavior.

The ground projection has altered the behavior of the subjects and their understanding of the height dimensions of the obstacle on the platform. The conjecture made is that the front projection during the experiments is used for the anticipation and the assessment of the obstacle dimensions, whereas the ground projection is used for the assessment of the distance of the virtual obstacle and the natural interaction with the ground surface. The ground projection is not improving the height perception of the subjects on the platform. The lower vertical displacement of the foot of the subjects during the combinations of the two projections, identified from the graphs, can explain the behavior observed by the subjects.

Moreover, the small alterations between the two conditions in which the virtual environment is projected between two surfaces (with consistency & inconsistency in the projected information in the two projections) prove the conjecture made that the ground projection does not alter the way the subjects perceive the height of the virtual obstacles on the platform. However, the small number of samples and the small alterations in the vertical displacement of the foot between the conditions do not let us make meaningful conclusions.

3.1.2 Statistical analysis

A t-test analyses have been performed to reveal the magnitude of the flattening of the curve in the graphs presented in section 3.1.1. The t-test performed on the local maximum foot height that the subjects lift their foot in each trial, in each test condition. A simple filtering has been performed on the data to improve these data.

The subjects who have lifted their foot in a maximum height lower than 5cm have been removed from the final data evaluation. The differences between the unfiltered data (i.e. with the outliers) and the filtered data (i.e. without the outliers) can be visualized in Tables 3.1 and 3.2 for the obstacle avoidance task of 20cm. Table 3.1 reveals the mean and the standard error of the maximum foot height of the subjects.

TABLE 3.1: Mean & standard error of the maximum foot height at the 20cm obstacle avoidance tasks in each test condition (With & Without Outliers).

Mean & Standard Error of Maximum Foot Height		
Condition (With Outliers)	**Mean**	**Standard Error**
Only Front	24.9	1.5
Front+Front (Consistency)	17.7	1.8
Front+Front (Inconsistency)	13.6	1.5
Condition(Without Outliers)	**Mean**	**Standard Error**
ONLY FRONT	25.6	1.4
FRONT+FLOOR (Consistency)	20.1	1.7
FRONT+FLOOR (Inconsistency)	15.9	1.5

TABLE 3.2: T-test analyses of the maximum foot height for the 20cm obstacle avoidance task, in each test condition (With & Without Outliers)

One Sample test

	TestValue = 20cm			
Condition (With Outliers)	**t**	**df**	**Sig.(2-tailed)**	**Mean Difference**
ONLY FRONT	3.4	35	.002	4.9
FRONT+FLOOR (Consistency)	-1.3	35	.210	-2.3
FRONT+FLOOR (Inconsistency)	-4.3	35	.000	-6.4
Condition(Without Outliers)	**t**	**df**	**Sig.(2-tailed)**	**Mean Difference**
ONLY FRONT	4.1	34	.000	5.6
FRONT+FLOOR (Consistency)	.056	30	.956	-.1
FRONT+FLOOR (Inconsistency)	-2.8	29	.000	-4.1

In Table 3.2, the *Test Value* is the height that the subjects have to lift their foot to step over successfully the obstacle. The *t* symbolized the test statistic of the one-sample test. The t is calculated by dividing the mean difference by the standard error. The *df* is the degrees of freedom of the test. For a one-sample t-test, df = n - 1. The *Sig. (2-tailed)* is the two-tailed p-value corresponding to the test statistic. The *Sig. (2-tailed)* value is ".000", this actually means that $p < .0005$. It does not mean that the significance level is actually zero. Finally, the *Mean Difference* is the difference between the "observed" sample mean and the "expected" mean.

The mean maximum height that the subjects lift their foot when only the front projection used is (25.6 ± 8) for the avoidance task of 20cm. We can observe that there is a statistically significant difference between the local maximum foot heights that subjects have lifted their foot to step over the obstacles and the height of the obstacle avoidance task of the order of $t(35) = 4.1$, $p = .000$ ($p<0.05$). The positive t value indicates that the mean height of the foot is greater than the hypothesized value. The subjects lift their foot 4.9cm higher than the height of the obstacle avoidance task.

The most accurate perception of height can be observed in the condition that the front virtual environment is extended on the ground surface, with consistency between the projected information in the two surfaces. The mean maximum vertical foot height in this condition is (20.1 ± 9.6). There is no statistical significant difference in the means since $t(35) = 0.56$, $p = .956$ ($p>0.05$). The subjects lift their foot 0.97cm higher than the obstacle avoidance task while walking on the treadmill, which is an impressive estimation.

The three tables presented in Table 3.3 for the 30cm, 40cm and 80cm obstacles, reveal that the subjects have lifted their foot in a higher maximum height when the virtual environment is only projected in the front projection. The conjectures made is that the discontinuity of the projected information between the two projections and the low resolution of the floor projection are some of the reasons which may lead to this behavior. The literature study identified that when there is disruption of the ground surface, the subjects are unable to establish a reliable reference frame and hence, the subjects fail to estimate correctly the height of the virtual obstacles (Sinai, Ooi, and Zijiang, 1998).

It is observed that the subjects have difficulty in perceiving accurately the height of the obstacles in all three test conditions. In the experiments, the subjects had the feeling that they can step over all the obstacles effectively, even of the 80cm avoidance task. This behavior can be explained since no feedback is provided to the subjects about they performance or their foot vertical placement in the virtual rehabilitation environment.

TABLE 3.3: T-test analyses for the mean maximum height of the foot of the subjects (without Outliers) in each test condition for the 30cm,40cm and 80cm Obstacle Avoidance Task

One Sample t-Test

	TestValue = 30cm			
Conditions	**t**	**df**	**Sig.(2-tailed)**	**Mean Difference**
ONLY FRONT	-.94	33	.360	-2.1
FRONT+FLOOR (Consistency)	-6.2	30	.000	-10.5
FRONT+FLOOR (Inconsistency)	-6.7	30	.000	-10.6
	TestValue = 40cm			
Conditions	**t**	**df**	**Sig.(2-tailed)**	**Mean Difference**
ONLY FRONT	-8.2	30	.000	-14.6
FRONT+FLOOR (Consistency)	-5.6	33	.000	-17
FRONT+FLOOR (Inconsistency)	-11.7	33	.000	-20.1
	TestValue = 80cm			
Conditions	**t**	**df**	**Sig.(2-tailed)**	**Mean Difference**
ONLY FRONT	-25.2	34	.000*	-43.3
FRONT+FLOOR (Consistency)	-27.2	33	.000	-50
FRONT+FLOOR (Inconsistency)	-30.4	33	.000	-56.9

3.2 Experience Evaluation

The web-based questionnaire uses five components to assess the experience of the test subjects per test condition, spanning over ten questions. The ten questions are answered by the subjects after each test condition. Four additional questions have been added at the end of the web-based survey to reveal the aftereffect experience of the subjects after the test conditions have been completed. In this way, we want to reveal the alterations in the experience of the subjects between the three test conditions.

The Game Experience Questionnaire (GEQ). The questionnaire used based on the Game Experience Questionnaire (GEQ). The GEQ was developed and validated by the Wijnand IJsselsteijn and his colleague (IJsselsteijn et al., 2009), in the Game Experience Lab at the Eindhoven University. Not much information can be found online about the GEQ or the evaluation process followed for the validity of this questionnaire. A study evaluating the work of Wijnand IJsselsteijn and his colleague identified that issue and mentioned that *'IJsselsteijn and his colleagues have not yet published any of the empirical results using the questionnaire or psychometric evaluations on its reliability and validity and the properties of its subscales in a peer-reviewed journal.'*. A deliverable about the GEQ can be found in Poels, Kort, and IJsselsteijn, 2009. The responses of the subjects have been analyzed based on the scoring guidelines provided by the GEQ documentation.

The GEQ structure. The GEQ has a modular structure. The different modules are the core, the social presence and the post-game module according to the GEQ documentation. The first two modules of the GEQ questionnaire are meant to determine the player's experience, feelings and thoughts while performing, whereas the last module is meant to determine the after experience, how the players felt after they have stopped playing the game. The GEQ was initially developed to assess the impact of deep engagement in violent video games. The questionnaire has been adapted to the needs of the current study by following the guidelines from the GEQ documentation.

Questionnaire Scoring Guidelines. A number of questions have been removed from the core module to fit the needs of this study and a number of additional questions have been added at the end of the survey to provide the extra information necessarily for evaluation of the experience of the subjects during the rehabilitation training.

The web-based questionnaire used during this study is a concise version of the core questionnaire. Two questions are used for the evaluation of each component. The alteration made, based on the documentation of the GEQ questionnaire in which the authors create an in-game questionnaire based on the core module (Appendix A.4). The in-game questionnaire uses only two questions for the evaluation of each component, rather than five which are used in the core module.

The format of the web-based survey used in the current study is a five-level Likert scale questionnaire from Strong Disagree to Strongly Agree, as can be seen in Table 3.4.

TABLE 3.4: Fivel-level Likert Scale Questionnaire

Strongly Disagree	Disagree	Neither Agree or Disagree	Agree	Strongly Agree
0	1	2	3	4

During this study, the experience of the subjects on the platform is defined as a combination of five score components. These components are: Flow, Tension, Challenge, Positive and Negative Affect. These components have been taken from the GEQ documentation [4]. The 'Competence' and 'Sensory & Imaginative Immersion' components that are included in the core version have been removed from this study, since they mainly focused on the development aspects of a game and therefore, are irrelevant to the current research study. Hence, the five score components used are calculated as the average of all the answers to the questions included in their component. The questions correspond to each can be seen in Table 3.5.

TABLE 3.5: Score Components and the number of each question (Appendix A.2), corresponds to each of component

Score Components	Question Numbers	
Flow	2	6
Tension	3	5
Challenge	8	9
Negative Affect	1	4
Positive Affect	7	10

3.2.1 Data Analysis & Results

The mean and standard error of the subjects' responses after the completeness of each test condition, in each question of the five-level Likert-scale questionnaire can be seen in Tables 3.6, 3.8 and 3.10. The subject's responses are analyzed to reveal the experience of the subjects during the different test conditions. We performed also a paired sample t-tests to reveal the difference in the responses of the subjects in the two questions correspond to each component. In Tables 3.7, 3.9 and 3.11 the mean difference corresponds to the average difference between the two variables. The standard error is the standard deviation divided by the square root of the sample size. The paired t-test statistic (denoted t), the degrees of freedom for this test and finally the p-value corresponding to the given test statistic t (denoted Sig.(2-tailed)).

Table 3.6 reveals the average of the responses of the subjects after the first condition, in the first experiment. In this condition, the virtual rehabilitation environment is projected only on a front surface. The average is calculated per question (Appendix A.2).

TABLE 3.6: Answers in the five-level Likert scale questionnaire in the Only Front Projection

Question Number	Mean	Standard Error
Quest. 1st	.6	.16
Quest. 2nd	1.9	.25
Quest. 3rd	.6	.22
Quest. 4th	.4	.19
Quest. 5th	.5	.17
Quest. 6th	1.7	.21
Quest. 7th	2.2	.25
Quest. 8th	2.1	.22
Quest. 9th	1.8	.26
Quest. 10th	2.1	.23

TABLE 3.7: Paired Sample Test for the Only Front Projection

Paired Sample Test "Only Front"

Score Comp.	Mean Differ.	Stand. Error	t	df	Sig.(2-tailed)
Flow "Q2-Q6"	.28	.27	1.0	17	.31
Tension "Q3-Q5"	.11	.18	.6	17	.54
Challenge "Q8-Q9"	.28	.23	1.2	17	.24
Positive Affect "Q7-Q10"	.23	2.6	.5	17	.63
Negative Affect "Q1-Q4"	.25	0.36	.7	17	.51

The Boxplots in Figure 3.4, 3.5 and 3.6 show the mean center of the subject's responses in the five-level questionnaire, and how spread are their values in each question. The orthogonal brown boxes show the variance of the values, whereas the middle horizontal line inside reveals if the responses in each question appear to be symmetrically distributed or not. In the box plots, the top of the box represents the seventy-five percentile, the bottom of the box represents the twenty-five percentile, and the line in the middle represents the fifty percentile. Two questions correspond to each component in the survey.

The lines that extended above and below of the boxes are called whiskers and represents the highest and lowest values that are not outliers or extreme values. Outliers are the values which are between 1.5 and 3 times the interquartile range (present as small circles), whereas extreme values are the values which are more than 3 times the interquartile range (marked with a star). The number next to the circle characterized which subjects are the outliers as can be seen in Figure 3.4.

In the Boxplot graphs in Figures 3.4, 3.5 and 3.6 the responses of the subjects in the five-level Likert scale questionnaire is on the y-axis, whereas the number of question in each condition is on the x-axis. By analyzing the first Boxplot graph in Figure 3.4, the answers in the eighth and the ninth question appeared to have similar centers. The same questions appeared to have larger variability than the other questions. The answers in the second, ninth and tenth questions are reasonably symmetric as can be visualized. The outliers can be seen in with small circles on the graph.

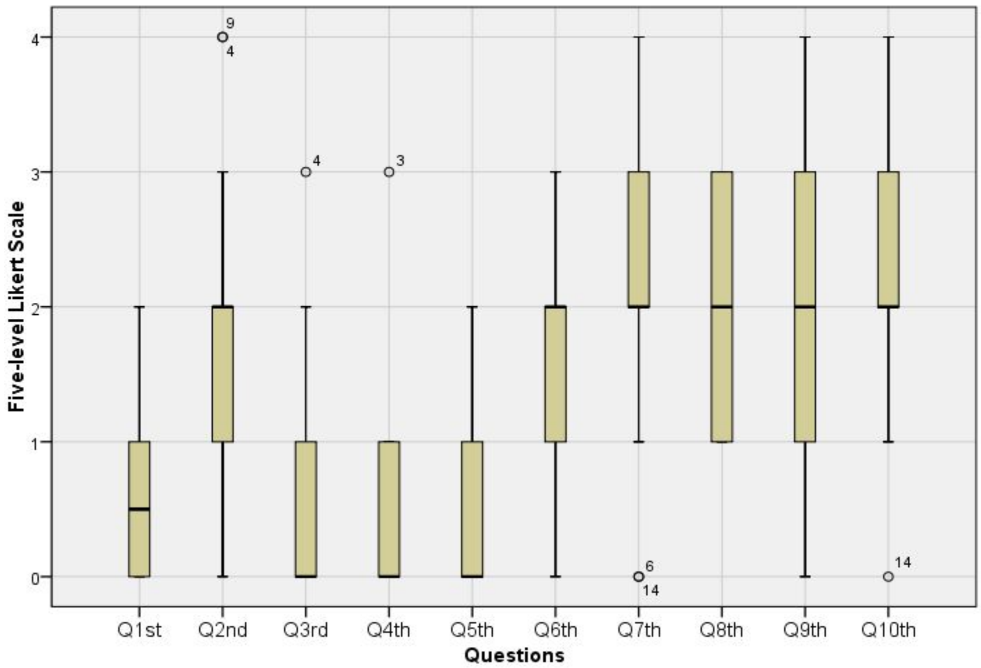

FIGURE 3.4: Boxplot for each question of the survey for the condition that only the front projection is used.

Tables 3.8 and 3.10 show the average of the responses of the subjects in the test conditions in which the virtual environment is projected in two surfaces (With consistency & inconsistency in the projected information between the front/floor surfaces). Table 3.10 the condition with inconsistency between the two projected surfaces, the obstacles are visualized on the ground as flat disks.

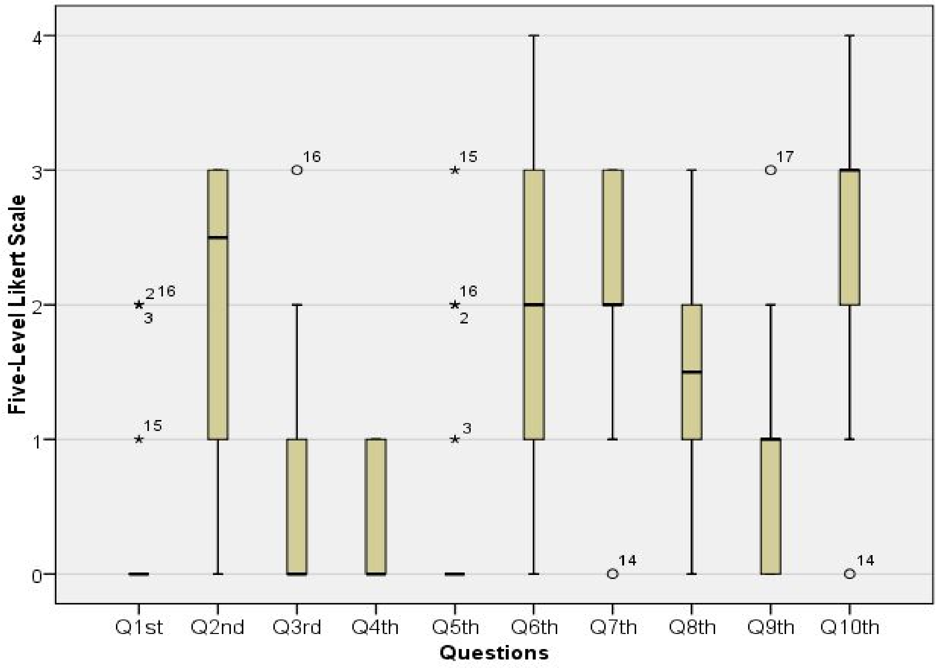

FIGURE 3.5: Boxplot in each question of the survey for the second condition, of the first experiment "Front/Floor surfaces with consistency in the projected information"

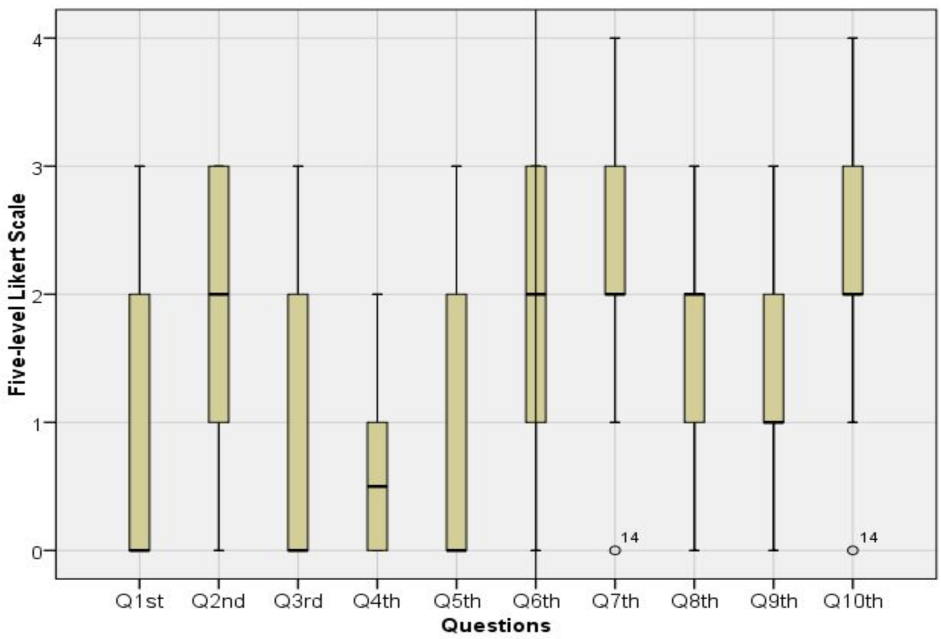

FIGURE 3.6: Boxplot for all the score components in each question of the survey for the second experiment "Front/Floor surfaces with inconsistency in the projected information (flat objects on the ground)"

TABLE 3.8: Answers in the five-level Likert scale questionnaire for the Front+Floor Projections with consistency in the projected information

Question Number	Mean	Stand. Error
Quest. 1st	.4	.18
Quest. 2st	2.1	.25
Quest. 3st	.5	.22
Quest. 4st	.4	.12
Quest. 5st	.4	.22
Quest. 6st	1.8	.27
Quest. 7st	2.2	1.9
Quest. 8st	1.5	1.7
Quest. 9st	.8	.2
Quest. 10st	2.6	.32

TABLE 3.9: Paired Sample Test for the Front+Floor Projections with consistency in the projected information

Paired Sample Test "Front+Floor (With Consistency)"

Score Comp.	Mean Differ.	Stand. Error	t	df	Sig.(2-tailed)
Flow "Q2-Q6"	.28	.21	1.3	17	.21
Tension "Q3-Q5"	.56	.09	.56	17	.58
Challenge "Q8-Q9"	.67	.2	3.4	17	.00
Positive Affect "Q7-Q10"	.24	1.4	.5	17	.19
Negative Affect "Q1-Q4"	.00	.00	.7	17	1.0

TABLE 3.10: Answers in the five-level Likert scale Questionnaire for the Front+Floor Projections with inconsistency in the projected information (flat objects on the ground)

Question Number	Mean	Stand. Error
Quest. 1st	.7	.24
Quest. 2st	1.8	.26
Quest. 3st	.7	.29
Quest. 4st	.6	.15
Quest. 5st	.8	.24
Quest. 6st	1.7	.26
Quest. 7st	2.2	.23
Quest. 8st	1.6	2.4
Quest. 9st	1.5	.19
Quest. 10st	2.3	.25

TABLE 3.11: Paired Sample Test for the Front+Floor Projections with inconsistency in the projected information (flat objects on the ground)

Paired Sample Test "Front+Floor (With Inconsistency)"

Score Comp.	Mean Differ.	Stand. Error	t	df	Sig.(2-tailed)
Flow "Q2-Q6"	.17	.20	.83	17	.42
Tension "Q3-Q5"	.06	.19	.29	17	.77
Challenge "Q8-Q9"	.11	.21	.52	17	.61
Positive Affect "Q7-Q10"	.11	.57	.5	17	.58
Negative Affect "Q1-Q4"	.17	.22	.77	17	.45

TABLE 3.12: Mean value of the score components in each test condition

Score Components Mean Value			
Score Comp.	**Only Front**	**Front+Floor(Consist.)**	**Front+Floor(Inconsist.)**
Flow "Q2-Q6"	1.89	2.1	1.83
Tension "Q3-Q5"	.5	0.44	0.75
Challenge "Q8-Q9"	1.95	1.23	1.61
Pos.Affect "Q7-Q10"	2.3	2.6	2.4
Neg. Affect "Q1-Q4"	.5	0.36	0.61

The tables and graphs presented in this section reveal that the variance and the spread of the subject's responses in the five-level Likert scale experience questionnaire is consistent during the positive score components. It can be also observed that the subjects become more challenged during the first condition, which only the front projection is used rather than the other two test conditions. This behavior can be also observed by the Boxplot graphs presented in this section (the score components consist of the "Q1-Q6" and "Q7-Q10"). In the first condition, since the subjects felt more challenged they lift their foot in a higher height to step over the virtual obstacles. During the combination of the two projections, the subjects felt more confident to perform tasks which affect their motor behavior. In each trial, the subjects have been asked if they believed they have successfully stepped over the virtual obstacles. Ninety-five percent of the responses were positive. To this end, the conclusion made is that the subjects could not visualize accurately the height of the obstacle during all the experiments.

Table 3.12 reveals that the *Flow* and the *Positive Affect* score components have a higher mean value in the condition that the front virtual environment is extended on the ground, with consistency in the projected information between the two projected surfaces. Moreover, the *Tension* and *Negative affect* score components are lower during the same condition. Therefore, we can conclude that the subjects had a better overall experience while performing avoidance tasks with the combination of the two projections.

3.3 Two Additional Questions

Two additional questions added at the end of the web-based questionnaire to reveal the aftereffect experience of the subjects and to reveal any other reason affect the experience of the subject during the three test conditions.

3.3.1 Aftereffect Experience

Two additional questions the subjects had to answer in the end of the experiments about the aftereffect experience on the platform were:

- "Did any of the conditions, which combines two projections to visualize the virtual environment in a front/floor surface, make you feel one coherent virtual experience?".
- "Did any of conditions make you feel like performing naturally on the platform?"

Table 3.13 reveals the percentages of the subject responses in the first question about if they felt like one coherent world experience during the rehabilitation therapy on the platform. Table 3.14 reveals the percentage of the subject responses in the question about if they felt like performing naturally on the platform.

TABLE 3.13: Did the two projections achieve one coherent world experience

One Coherent World Experience

Experiment	Conditions	Response Rate
First	FRONT+FLOOR (Consistency)	77.8%
Second	FRONT+FLOOR(Inconsistency)	0%
None		22.2%

TABLE 3.14: Did the two projections achieve to make the subjects feel like performing naturally on the platform

Performing Naturally

Experiment	Conditions	Response Rate
First	ONLY FRONT	16.6%
First	FRONT+FLOOR (Consistency)	77.8%
Second	FRONT+FLOOR (Inconsistency)	5.6%
None		0%

In both questions, seventy-seven point eight is the percentage of the subjects answered that the front virtual environment extended on the ground (with consistency in the projected information) gave them one coherent world experience and made them feel like perform naturally. The tables prove again that the combination of a front and a floor projection (with consistency in the projected information) achieved a better overall, indoor experience to the subjects during the virtual rehabilitation therapy, on the C-Mill/ReGait platform.

3.4 Limitation of the system

By comparing the behavior of the subjects in all the difference test conditions and avoidance tasks, it is observed that the subjects cannot perceive accurately the height of the obstacles in the C-Mill/ReGait platform. A number of conjectures are made to explain the behavior of the subjects and the reasons that they have lifted their foot in a lower proportional height during the combination of a front and a floor projected surfaces. Limitation of the platform are recognized in this section

First Conjecture. The gap area which interject between the front and the ground surface on the treadmill is measured forty centimeters. The conjecture made is that when the virtual floor environment is disrupted, the visual system cannot establish any reliable reference frame between the two projections. We have been based on the findings of Sinai, Ooi, and Zijiang, 1998 *'(..) when the common ground surface is disrupted, the visual system is unable to establish a reliable reference frame and consequently fails to obtain the absolute distance of the objects in the environment.'*.

Second Conjecture. By comparing the conditions when the front environment is extended on the ground, we can say that there are not substantial differences in the behavior of the subjects (with consistency and inconsistency in the projected information between the two projections). The conjecture made is that this behavior is affected by two parameters. The first one is the low resolution of the ground projection on the treadmill. This assumption is based in the observation that a number of the subjects during the experiments mentioned to us that they did not visualize the differences between the different conditions of the front/floor condition. The second one is that the ground projection does not have a strong effect in the behavior of the subjects and the way that the subjects perceive the height of the virtual obstacles. However, the small number of samples does not let us make meaningful conclusions on this matter.

Third Conjecture. The bad performance of the subjects can also be explained by their experience. The subjects felt less challenged while performing on the ground surface, since the obstacles are now projected on the ground from a top/plane view. Therefore, the subjects felt more confident that they can step over them and thus, lift their foot in a lower proportional height. A real-time feedback can help to avoid such phenomena in a future implementation.

To summarize with, even if the subjects have already perceive the obstacle height in the front projection, still this is not enough to make them lift their foot as high as is the first condition that only the front projection was used. However, we have identify that in all the three conditions the subjects have difficulty to visualize accurately the height of the virtual avoidance tasks.

Chapter 4

Conclusion

4.1 Summary of Results

The two research questions stated in section 1.4 addressed again in this section and conclusions are made from the analyses of the results.

***1.* To what degree does the extension of a front virtual rehabilitation environment to the ground affects the behavior and the experience of the subjects over-treadmill walking?**

The study identifies the importance of the floor projection in the correct timing of the subject's behavior. In the condition that the front virtual environment is extended on the ground surface, the subjects react on time to avoid the contact of their foot with the obstacles in the virtual environment without any feedback (no latency is observed between the moment of contact and the maximum foot height). The assumption made is that the subjects use their real-foot position on the treadmill, as a reference frame to measure the distance of the obstacles in the virtual environment. Thus, the subjects manage to overcome the limitations of the platform and react on time.

According to the experience questionnaire, the combination of the two projections (with consistency in the projected information between the two surfaces) achieved one coherent virtual world experience and made the subjects feel like performing naturally on the C-Mill/ReGati platform. However, this is not enough to make the subjects to perform more accurately and lift their foot higher to step over the virtual obstacles.

2. To what degree does the alteration of the projected information on the front/floor surfaces, of the same virtual environment, alters the behaviors or the experience of the subjects on the virtual platform?

In the second experiment that the spherical virtual obstacles, visualized on the front projection, are projected on the ground as flat disks, the subjects showed a small alterations in the vertical displacement of their feet in the same avoidance tasks. This proves the conjecture made that the ground projection does not alter the way the subjects perceive the height of the obstacles in the virtual environment. However, since we have a small number of samples and the limitations of the platform may alter the final result not meaningful conclusions can be made. The alterations in the motor behavior of the subjects are not enough for the validity of the conclusions.

In all three test conditions, the subjects have difficulty to establish a reliable reference frame about the height of the virtual obstacle on the platform. This is proved since all the subjects felt like they could manage to step over the obstacle even of the 80cm obstacle avoidance task. The avoidance task of the 20cm is excluded from this assumption since the subject could easily step over these obstacle and not a good perception of the height of them is needed.

To this end, the two projections did not help the test subjects to perceive more accurately the height of the virtual obstacles. The conclusion made is that the combination of the two projections, a front projection, in front of the treadmill, and a ground projection, on the treadmill that the subjects stand, will not contribute to the better perception of the height dimensions of the virtual obstacles on the C-Mill/ReGait platform. The subjects felt like performing naturally and had a better overall experience during the combination of the front/floor surface (with consistency in the projected information). However, this is not the case when the spherical virtual obstacle visualized on the ground surface as flat disks (second experiment). Therefore, the inconsistency in the projected information between the two projections alters the experience of the subjects.

4.2 Discussion

The world's population is growing and aging at the same time, which elevates the cost of the healthcare treatment. The technological advancements of the last decades can have a substantial impact on the practices used for the treatment of the patients. The current study tries to reveal the possibilities that arise from the utilization of a multi-projected virtual environment for the rehabilitation of patients on a virtual platform. In the long run, the goal of the virtual rehabilitation therapy it to teach the patients to step over obstacles more effectively in their daily lives.

C-Mill/ReGait is a real-world clinically feasible solution due to the low-cost, in comparison with other virtual rehabilitation platforms. The current study is a clinical research study, which aims to determine the effect of the extension of a front projection virtual rehabilitation environment to ground. A clinical research study wants to identify the reason or the effect of a condition on the behavior of a subject and not to make clinical decisions. Baker, 2006 referred that in a clinical research study a small error in the data will not have a substantial effect on the final evaluation and therefore, meaningful conclusions can still be made. However, an adequate number of samples will be needed for the validity of the conclusions.

The subjects in all three test conditions had to lift their feet high enough and on time, to step over virtual obstacles appearing in their path, while walking on the treadmill. The motion-capture data of the subject's behavior reveal that the perception of height is not improved when the virtual environment is projected on two surfaces. The answers of the subjects in the web-based experience questionnaire reveal that the combination of a front/floor projection, with consistency in the projected information, achieved a better overall, indoor experience. Moreover, one coherent virtual world experience has been achieved during the rehabilitation application, which has helped the subjects to feel natural while step over obstacles on the C-Mill/ReGait platform. However, this was not enough to make the test subjects estimate more accurate the height of the virtual obstacles.

4.3 Future Work

The statistics we obtain during the current study are by no mean perfect. The eighteen healthy individuals participated in the experiments are not a high rate to export conclusive results. Patients with postural control disorders or motion dysfunctions could also participate in the experiments to provide us a bigger variety of samples. However, the shorter in time of the current study did not give us the appropriate time to arrange that with hospitals or healthcare facilities in the Netherlands.

The limitation of the C-Mill/ReGait system identified during the study. Future improvements can be applied to the C-Mill/ReGait system. Improvement of the platform is to remove the gap area between the two projected surfaces and improve the quality of the ground projection on the treadmill. The conjecture made is that the subjects could establish a reliable reference frame about the distance between the two projected surfaces, but not about the height of the virtual obstacles. This behavior can be affected by those limitations and thus, a future investigation is recommended by the author.

A live-feedback is a way to inform the subjects about their performance, and therefore, push them forward and motivate them to perform better in next trials. A live-feedback is used in game applications to motivate the individuals continuing playing the game. By adding a real-time feedback in the rehabilitation application the subjects can be challenged to lift their foot in a higher height to step over the virtual obstacles. A real-time feedback, in the long run, will improve the understanding of the subjects about the avoidance tasks they have to perform and therefore, help them to achieve faster the goal of the therapy. In the virtual rehabilitation application, no feedback is provided to the subjects about their performance since this could alter the results between the different test conditions.

Binocular cues can also be used to improve the perception of depth during a virtual reality experience, through the use of Head Mounted Displays (HMDs). In the current study, we decide not to use such technologies since they enhance disorientation, anxiety feelings and cyber-sickness phenomena during locomotion tasks in a virtual rehabilitation platform (LaViola, 2000). A lot of research is conducted the last decades to minimize such phenomena and therefore, they can be used in future implementations in the C-Mill/ReGait system.

The literature study conducted in the current study proves that Microsoft Kinect, first-generation has the capacity to track simple gait parameters during locomotion tasks, during a virtual therapy. However, according to (Xu et al., 2015) *'The results showed that the accuracy levels when using the Kinect sensor varied across the gait parameters. Average heel strike frame errors were 0.18 and 0.30 frames for the right and left foot, respectively, while average toe off frame errors were -2.25 and -2.61 frames, respectively, across all participants and all walking speeds.'*. A Vicon, gold standard motion-capture system can be used with the system to minimize this error. However, this will have an effect on the cost and the portability of the platform and that's why it has been avoided in the current platform.

Moreover, eye-tracking sensors can be used with the system to improve the realism of the VR display used in the current rehabilitation application. In the study, the position of the head of the subject is used as a reference frame for the location that the subject is visualizing the virtual environment, a simplified solution. In the beginning of the study, we have experienced with an Intel RealSense camera and the SDK used for face recognition. After some experiments conducted with the camera, we decided that the capacities of the RealSense camera are not for our implementation since the camera is only capable of tracking the eyes of a user in short distance (Camera Laptop use).

To conclude with, we believe that the outcome of the therapy in the virtual rehabilitation platform has to be tested. Did the combination of the two projection in the C-Mill/ReGait platform achieve a faster recovery of the patients? Game-based applications have to be implemented with the C-Mill/ReGait system and a rehabilitation therapy has to be performed with the observation of a therapist to reveal such phenomena. Fall prevention is the "long-term" side effect of the behavioral changes of the patients. A future research could provide statistical data that proves that the game-based applications on the virtual reality platform have succeeded to reduce the injurious falls in the long run.

Appendix A

Appendix

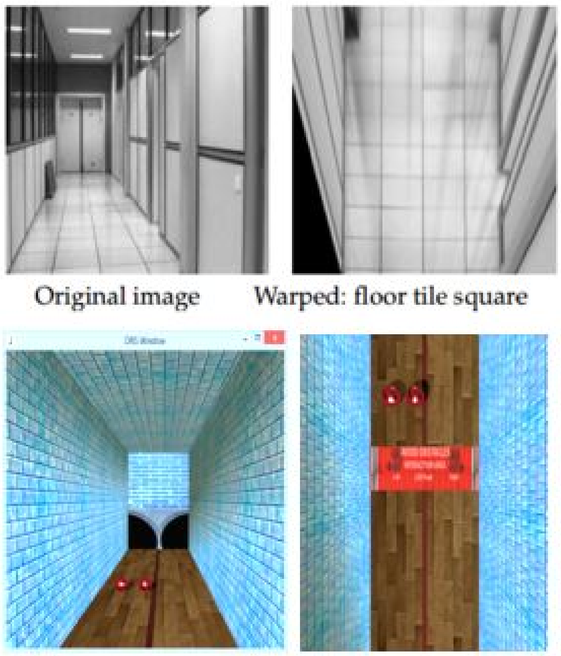

FIGURE A.1: The concept of the rehabilitation environment. A horizontal and a vertical field of view of a real environment (Upper Figure). The virtual rehabilitation environment implemented during the current study, composed by corridors with different textures (Down Figure)

TABLE A.1: Previous experience with the C-Mill/ReGait platform

Previous Experience with the platform	Response Rate %
No Experience	27.8
One hour	33.3
Ten to fifty hours	27.8
One hundred hours or more	11.1

Q1. It gave me a bad feeling *

	0	1	2	3	4	
not at all	○	○	○	○	○	extremely

Q2. I forgot everything around me *

	0	1	2	3	4	
not at all	○	○	○	○	○	extremely

Q3. I felt frustrated *

	0	1	2	3	4	
not at all	○	○	○	○	○	extremely

Q4. I found it tiresome *

	0	1	2	3	4	
not at all	○	○	○	○	○	extremely

Q5. I felt annoyed *

	0	1	2	3	4	
not at all	○	○	○	○	○	extremely

Q6. I felt completely absorbed *

	0	1	2	3	4	
not at all	○	○	○	○	○	extremely

Q7. I felt content *

	0	1	2	3	4	
not at all	○	○	○	○	○	extremely

Q8. I felt challenged *

	0	1	2	3	4	
not at all	○	○	○	○	○	extremely

Q9. I had to put a lot of effort into it *

	0	1	2	3	4	
not at all	○	○	○	○	○	extremely

Q10. I felt good *

	0	1	2	3	4	
not at all	○	○	○	○	○	extremely

FIGURE A.2: The ten questions the subjects had to answer after each test condition in the current study, based on core-version of the GEQ

What is your Gender? *

- Female
- Male
- Other

What is your age? *

How much experience do you have with the C-Mill/ReGait platform? *

- 0 hours
- 1 hour
- 10 hours
- 50 hours
- 100 hours
- 100+ hours

Do you have any known perception disorder? *

- Yes
- No

FIGURE A.3: Demographic Questions asked in the beginning of the web-based survey

1	I was interested in the game's story	GEQ Core – 3
2	I felt successful	GEQ Core – 17
3	I felt bored	GEQ Core – 16
4	I found it impressive	GEQ Core – 27
5	I forgot everything around me	GEQ Core – 13
6	I felt frustrated	GEQ Core – 29
7	I found it tiresome	GEQ Core – 9
8	I felt irritable	GEQ Core – 24
9	I felt skilful	GEQ Core – 2
10	I felt completely absorbed	GEQ Core – 5
11	I felt content	GEQ Core – 1
12	I felt challenged	GEQ Core – 26
13	I had to put a lot of effort into it	GEQ Core – 33
14	I felt good	GEQ Core – 14

FIGURE A.4: All the questions included in the Game Experience Questionnaire (GEQ) in the In-game module

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