AN INVESTIGATION OF EFFECTS OF THE PARTIAL ACTIVE ASSISTANCE IN A VIRTUAL ENVIRONMENT BASED REHABILITATION SYSTEM

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ABSTRACT

This thesis describes a study on a new active assistance in robotic rehabilitation in a haptic virtual environment for post-stroke patients. The novelty of this active assistance system lies in that the assistance is directly rendered on the result of a task performing. Active assistance will generally raise the confidence level of patients in performing a rehabilitation exercise. However, an overly high assistance level may induce cognitive fatigue with patients and thus decreases their motivation of performing a rehabilitation exercise. This thesis hypothesizes that a proper active assistance can improve the performance of a rehabilitation exercise, but will not reduce the motivation of patients in doing rehabilitation exercise. However, due to the difficulty in obtaining a proper number of patients for the experiment, the study turned to healthy people. Accordingly, a revised hypothesis is that active assistance on healthy people does not improve the task performance and not reduces the motivation of healthy people.

In this thesis, first, a test-bed with the haptic virtual environment was designed and constructed. The test-bed included a simple task i.e., following a predefined circle trajectory. Then, a statistical experiment was designed and an experiment was conducted on the test-bed. The experimental results test the hypothesis successfully.

The main contributions of this thesis are: (1) the development of a new active assistance system for rehabilitation in a virtual environment and (2) the experimental study on the motivation of healthy people with the developed active assistance system. A care must, however, be taken that the experiment was conducted on healthy people and the conclusion drawn from the study may not be valid on patients.

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LIST OF ABBREVIATIONS

ADL	Activities of Daily Living
HD	Haptic Device
HMI	Human-Machine Interaction
HVE	Haptic Virtual Environment
IMI	Intrinsic Motivation Inventory
LOF	List of Figures
LOT	List of Tables
PAS	Patient Assistive System
RT	Robot-Assisted Therapy
ULC	Upper Limb Conventional therapy
VE	Virtual Environment
VR	Virtual Reality

Chapter 1

Introduction Appendix

1.1 Background and Motivation

Every year fifteen million people suffer from a stroke and subsequently, around five million people become permanently disabled. This makes stroke one of the leading causes of adult disability. Approximately 80% of the first-time strokes result in hemiplegia (Dobkin, 2004). According to the statistics [1], stroke is a very common disease in Canada, and only a certain percentage of survivors can recover in the first few months (Network, 2011). Those who survive a stroke face significant challenges and the rehabilitation process becomes crucial for successful recovery. Thus, if a patient receives proper and timely rehabilitation assistance, then the chances of better progress and recovery increase.

Early initiation of rehabilitation activities that are carried out from the first days of stroke (if the general condition of the patient permits) help to speed up and make more complete restoration of the disturbed functions. Moreover, this set of activities allows to prevent the development of post-stroke complications, such as pneumonia, thrombophlebitis, contractures, pressure sores, and muscular dystrophy. The rehabilitation process offers various types of aids to post-stroke survivors, and, generally, all rehabilitation practices are grouped into four main categories.

The first category consists of a few types of physical activities such as:

- exercises towards the improvement of motor skills, muscle strength, and coordination (Stewart et al., 2006);

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[1] `http://www.statcan.gc.ca/pub/82-625-x/2014001/article/11896-eng.htm`

- exercises that focus on relearning the ability to walk using various supporting tools including walkers, canes and braces (orthosis) to stabilize and improve ankle strength (Duncan et al., 2005);
- forced-use therapy that restricts the use of unaffected limb while patients practice moving the affected limb to help improve its function (Wolf et al., 2006); and,
- exercises to improve range-of-motion for the patients that leads to muscle tension (spasticity) reduction (Sommerfeld et al., 2004).

The second category is the technology-assisted physical activities, including:

- an electrical stimulation that is applied to make weakened muscles contract and help to "reeducate" the affected muscles (Alon et al., 2007);
- various robotic devices that can assist the impaired limbs to perform repetitive motions and help them regain the strength and function (Kwakkel et al., 2007);
- a wearable technology, such as activity monitors, that helps to evaluate the activity of the post-stroke patients (Haeuber et al., 2004);
- technologies based on virtual reality (VR) which enables a patient to exercise in a simulated real-time environment (George et al., 2012); and,
- noninvasive brain stimulations to help improve a variety of motor skills - for example, the use of Transcranial Magnetic Stimulation (TMS) (Khedr et al., 2005).

The third category consists of cognitive and emotional activities, containing the following:

- a therapy focused on communication disorders to help patients to regain lost abilities in speaking, listening, writing and comprehension (Duncan et al., 2005);
- an evaluation of a patient's cognitive and emotional states, which is completed to construct a plan aiming to make the rehabilitation faster - a patient can be assigned a mental health counselor to discuss the rehabilitation process from the psychological point of view or choose to participate in support groups as part of the rehabilitation (Braun et al., 2006); and,

- medications for depression treatment that are necessary in some post-stroke cases as well as drugs affecting human motor function (Dobkin, 2004).

The forth category includes a few types of experimental therapies, including:

- biological therapies such as stem cells (Bang et al., 2005); and,
- alternative medicine treatments, including massage, herbal therapy, and acupuncture (Johansson et al., 2001).

To recover after stroke, survivors have to go through a cyclical process of continuous rehabilitation (Langhorne et al., 2011). Three stages of the process are typically identified, as Figure 1.1 suggests. Stage one is an assessment through which a patient's needs are determined and quantified. Stage two includes the setting of realistic and achievable goals, which should lead to an expected recovery. Stage three proceeds with an intervention of a group of specialists, including doctors, psychiatrists, physiotherapists and others who assisting the patient in making progress and achieving the goals. After the intervention stage a reassessment is made based on the progress already achieved by the patient, and further, the patient's overall condition is evaluated once more, and the goals may be adjusted if required.

Undoubtedly, stroke recovery is a long-term process as patients are in need of the specialists' assistance for months and some cases even years. The rehabilitation process typically follows a recovery schedule which is created based on the assessment of a patient's overall condition and needs following the stroke. Figure 1.2 shows a timeline for the function, disability and health recovery, which sets a framework for the rehabilitation process. Within this framework, once a post-stroke patient's condition is evaluated, a set of measures can be implemented to help the patient recover and overcome challenges with motor function and personal and social adaptation to the post-stroke state. Because the recovery process usually extends in time considerably, with several months on average to recover, the ultimate goal of rehabilitation is to make the make a patient to a quicker return to normal life.

If a stroke survivor is exposed to the rehabilitation therapy in a short time after the stroke, the chance of a full recovery potentially increases. However, due to a number of reasons, the rehabilitation process cannot be made universal. Each patient faces different

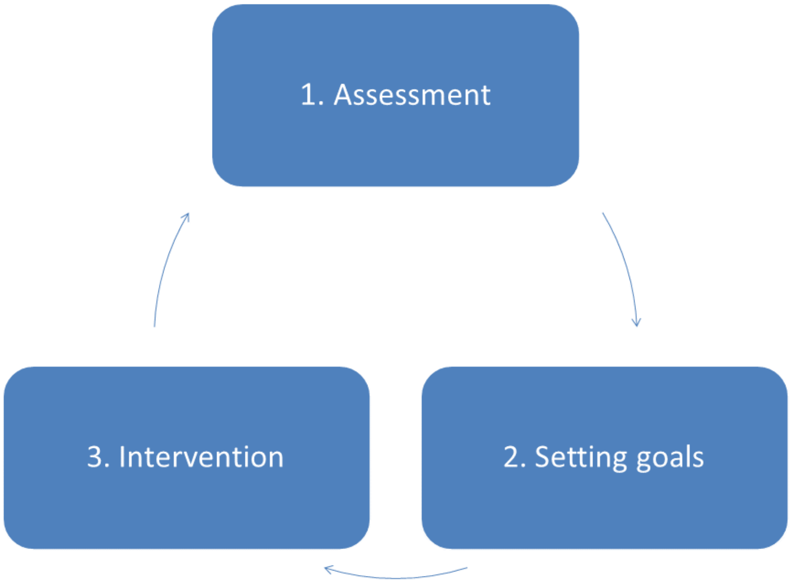


Figure 1.1: Cyclicity of rehabilitation process

obstacles because of various physical and emotional conditions and struggles, accompanied by various level of personal motivation. This negatively affects the progress and lengthen the rehabilitation period if a rehabilitation is not made on an individual basis (Maclean, 2000). Moreover, only a certified specialist can assist a post-stroke patient in the rehabilitation, and often there is a shortage of the specialists in the rehabilitation field (Durant et al., 2012). As a result, additional delays in the start of rehabilitation occur and this reduce the chance of a patient's full recovery. To help offset some of these challenges, a home-based rehabilitation for a patient may be used as an option (Anderson et al., 2000).

Over the last few decades, there has been a significant shift from the conventional approach to the utilization of progressive and advanced technologies. The worldwide development of robotic devices has opened opportunities for substantial improvements in various products, services, and processes, including the rehabilitation field, and made them more measurable, feasible, flexible and even more enjoyable. The use of the virtual reality technologies has been on the rise recently and has become very popular in many areas of people's lives. A simulated environment application affords to design a variety of scenarios for educational purposes in medicine, aviation, and military. Moreover, it is now feasible to simulate hearing, vision, smell and touch senses in virtual reality. There is evidence that the use of a haptic

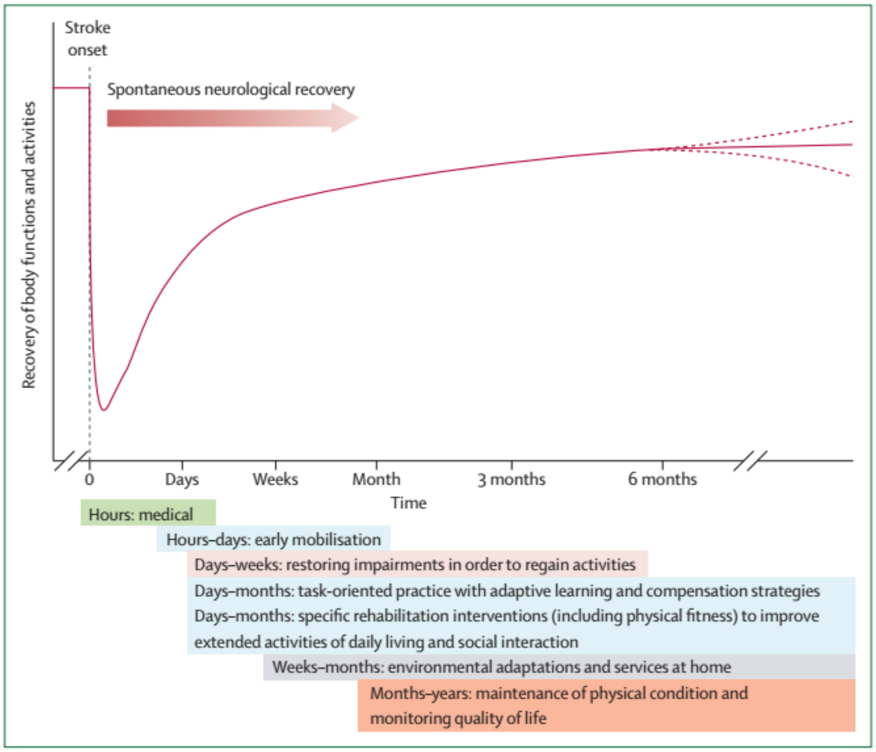


Figure 1.2: Hypothetical pattern of recovery after stroke with timing of intervention strategies (Langhorne et al., 2011)

virtual environment has a positive effect on gaining psychomotor skills on the earlier stages of education of the surgeons (van der Meijden & Schijven, 2009).

The use of the virtual reality has become available in the rehabilitation environment. If rehabilitation exercises are performed within a haptic virtual environment in which a patient's exercise is supplemented with the limited assistance from a rehabilitation system, the recovery process potentially becomes more successful. To assist a patient with a variety of exercises that are necessary for regaining a motor function, use of virtual reality technologies permits to prototype a task quickly and to make it more adaptable to the patient's needs.

The systems based on a haptic virtual environment have a distinctive set of characteristics, including portability, an option to be adjusted to the patient's needs, and an opportunity to apply the system immediately to start the rehabilitation process. There has been evidence from the work of da Silva Cameirão et al. (2011) that the use of the virtual reality system has a positive effect on post-stroke patients.

Over the course of the rehabilitation, a post-stroke patient has to reiterate a set of repetitive exercises which make the process utterly monotonic. Consequently, the patient starts experiencing cognitive fatigue and a lack of motivation and therefore, the rehabilitation process takes more time. This may be mitigated if the patient gets a limited partial assistance from the rehabilitation system.

1.2 Hypothesis

Any task performance can be characterized by two parameters: accuracy and completion time. In the area of the post-stroke patient rehabilitation motivation - a willingness to perform a rehabilitation task - is a key factor. Therefore, the work in this thesis is based on a hypothesis that a certain level of active assistance will improve the task performance but not reduce the motivation to the patient. However, during the course of this study, it turns out to be difficult to find a proper number of patients for the intended experiment. Therefore, the study had to be conducted with healthy people.

For the healthy people, it is reasonable to assume that there is no need to give any assistance for the simple task such as following a circular trajectory. Therefore, the hypothesis was revised to be as: to the healthy people, a certain level of assistance will not change the performance and will not reduce the motivation as well.

1.3 Objectives and Scope

The overall objective of this research is to study the above-mentioned hypothesis. For this, a test-bed needs to be developed and an experiment can then be carried out on the test-bed. Specific objectives were then defined.

Objective 1: to design and construct a test-bed for the rehabilitation assistance to patients who suffered from a stroke. The test-bed will be realized in a Phantom Omni haptic device with a haptic virtual environment. The rehabilitation task is restricted to following a circle trajectory. Though it is a simple task, the extension to any other task can definitely take advantage of the development in this thesis. The test-bed for rehabilitation assistance was expected to enhance an overall patient experience with the rehabilitation exercise.

Objective 2: to design and carry out an experiment on the test-bed to study the hypothesis in this thesis that is, the patient feels comfortable with the assistance while the training effect does not decline. Due to the reasons that (1) this was a preliminary study and (2) there was a lack of actual post-stroke patients available for this study, the experiment was only performed on healthy patients in this thesis.

1.4 Organization of the thesis

The thesis consists of 5 (including Chapter 1) chapters. Chapter 2 provides an overview of various approaches to the rehabilitation of post-stroke patients to give further justification of the proposed work including the hypothesis and objectives. Chapter 3 describes the design of the haptic virtual reality system. Chapter 4 presents the experiment to be performed on the designed test-bed system and for testing the hypothesis in the thesis. Chapter 5 concludes the work with a discussion of the research results, contributions, and future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter discusses general approaches to the rehabilitation and a general state of the knowledge of the rehabilitation engineering in literature. Section 2.2 introduces the basics of stroke and reviews general approaches in the rehabilitation process for post-stroke patients. Section 2.3 discusses the benefits of the machine-based or computer-based rehabilitation process. Section 2.4 explains the general knowledge regarding the design approaches for the rehabilitation system. In Section 2.5 the use of the virtual reality including the virtual environment in the rehabilitation process is reviewed. Furthermore, the main advantages and disadvantages of the use of virtual reality in the rehabilitation process are observed and discussed. Finally, in Section 2.6, the proposed objectives are revisited to justify their need and urgency.

2.2 Conventional approaches for rehabilitation

A stroke is characterized by a loss of the brain function caused by an interruption or a significant reduction of blood supply to human's brain. Two types of stroke are typically identified. The first one is an ischemic stroke which is caused by the interruption of blood flow to the brain. This type of stroke is very common among those who suffer from it: approximately 80% of strokes are identified as ischemic (Network, 2011). The second type is an hemorrhagic stroke caused by the rupture of blood vessels in the brain. Regardless of the type of stroke, it causes a considerable damage to human's body functioning and results in severe disabilities including loss of the vision, speech as well as possible sensation paralysis, and confusion.

The main principle of the post-stroke rehabilitation includes an early start of the rehabilitation process. Once a team of multidisciplinary specialists evaluates a patient's condition, a continuous and consistent rehabilitation plan should be prepared to respond the patient's needs. In over 80% of cases, motor disorders such as hemiparesis, monoparesis and others determine the degree of disability (Mehrholz et al., 2012). Not only does the rehabilitation of the post-stroke patients aim to restore motor functions, but other disorders including speech and sensory disorder, dysphagia, vision problems caused by the stroke need to be addressed. A factor that plays an important role in the whole rehabilitation process is the motivation and engagement of the patient and his/her family.

If a person experiences a stroke and survives, it is recommended to perform an initial assessment within first 48 hours (Langhorne et al., 2009). Based on the evaluation, a patient's current condition is determined and a rehabilitation plan, including the therapy that has to be prescribed, is created aiming to lead the patient to the successful recovery. Further, depending on the patient's condition, availability of specialists and tools in the rehabilitation center, the patient may be assigned to inpatient or outpatient rehabilitation process. It is confirmed that the sooner the rehabilitation process starts, the better are the outcomes of the process, i.e. the patient recovers faster and more efficiently (Bernhardt et al., 2009).

For the inpatient rehabilitation, the post-stroke patient has to stay in the hospital on a regular basis to receive the treatment and participate in therapy over the period of a few weeks or, in some cases, several months. While the outpatient process allows a patient to stay at home and visit the hospital or rehabilitation center only to receive the rehabilitation therapy.

As an alternative to the outpatient rehabilitation, a home-based rehabilitation can be offered to the patient. This option is considered when a patient lives long distance from a hospital, does not want or cannot spend time to travel to a hospital, and there is a minimal neurological impairment and minimal to moderate motor dysfunction which permits the patient to perform the rehabilitation sessions in the home environment. The patients receiving rehabilitation at home can improve the ability to perform activities of daily living (Legg & Langhorne, 2004). On the whole, it is suggested that the outpatient (hospital-based) and home-based therapies be equally effective (Teasell et al., 2012), and also no evidence is found that the inpatient rehabilitation outperforms the home-based rehabilitation (Anderson et al., 2000). However, in each case a current condition of the patient and his/her needs should be fully evaluated to form a decision on the rehabilitation options.

2.2.1 Post-stroke patient evaluation practices

The motor function of a post-stroke patient can be affected at various levels. According to (Gowland, 1990), there are seven stages of motor impairment, starting from presynergy (no muscle reflexes) stage to the normal stage. Table 2.1 summarizes the scale of a patient's condition. This classification is one way to assess a patient's condition for further treatment. Additionally, several other evaluation techniques are widely used to determine the severity of the stroke and define how it affects the ability to do daily activities. One of the methods is the Fugl-Meyer score (Fugl-Meyer et al., 1975).

Fugl-Meyer method evaluates the overall condition of the post-stroke patients with hemiplegia by assessing various parts such as motor function, balance, sensation, joint range and joint pain in the upper-limbs. Each part of the test contains tests for evaluation of patient's function. For each item in the method a patient gets a certain score depending on the ability to complete an item using a 3-point ordinal scale. With this scale a patient gets 0 if he cannot perform an item; 1 if he can perform an item partially; 2 if he can perform an item fully. The total possible scale score is 226. The overall score gives a reference point for further rehabilitation measures. In addition, based on the overall score it is possible to predict the motor recovery of an upper limb for the post-stroke patients (Kwakkel et al., 2003).

The methods for evaluation of the condition of the post-stroke patients are constantly evolving. Kernich (1996) provides a variety of scales to assess of the effects of stroke for the post-stroke patients. These scales include measuring of the level of the activities of daily living (ADL), mental status screening, assessment of the motor function, assessment of the speech and language function, and assessment of the depression level. These evaluations provide a starting point for the patient and medical professional in the process of the recovery.

In general, to achieve good results in the rehabilitation process, it is recommended that the patients affected by stroke perform high-intensity and repetitive task-specific exercises

Table 2.1: Stages of motor impairment from (Gowland, 1990)

Stage 1	Presynergy. Muscle (i.e., phasic) strength reflexes are absent or hypoactive. No resistance to passive movement (i.e., tonic stretch reflex) is felt. No active movement can be elicited either reflexively by a facilitatory stimulus or volitionally
Stage 2	Resistance to passive movement is felt. No voluntary movement is present, but active movement can be elicited reflexively by a facilitatory stimulus.
Stage 3	Spasticity is marked. Voluntary movement occurs in synergies (i.e., stereotyped patterns of flexion and extension). Movement results from higher center facilitation of associated reactions or spinal or brain stem reflexes.
Stage 4	Spasticity decreases. Synergy patterns can be reversed if the pattern of movement occurs first in the weakest synergy. Movements combining antagonist synergies can be performed if the strong components act as prime movers. The synergies lose their dominance, the spinal and brain stem reflexes commence being modified and integrated by higher centers utilizing more complex neutral networks
Stage 5	Spasticity waves. Synergy patterns can be reversed even if movement occurs first in the direction of the strongest synergy. Movements utilizing the weak components of the synergies acting as prime movers can be performed (i.e., difficult extensor and flexor synergy movements can be mixed). Spinal and brain stem reflexes become modified and integrated into a more complex network. Most movements become environmentally specific
Stage 6	Coordination and patterns of movement are near normal. Spasticity as demonstrated by resistance to passive movement is no longer present. A large variety of environmentally specific patterns of movement are now possible. Abnormal patterns of movement with faulty timing emerge when rapid (ballistic) or complex (ramp) targeted movements are requested.
Stage 7	Normal

with high intensity to regain the motor function (Lindsay et al., 2008). Patients should have access to a team of professionals who are able to help patients to overcome the physical and physiological consequences of stroke. Family of the patient plays an important role in the process providing help and support whenever it requires. The rehabilitation process supported by the positive and timely feedback may improve the recovery even better (Hubbard et al., 2009).

2.3 Machine assisted rehabilitation process

The purpose of rehabilitation robotics is to restore the patient's motor function, train him/her and assist in the health state improvement. With the rapid development of technology nowadays a few challenges in health care arise, including function regaining, independence retaining and individualized learning and training for special needs. Considering these factors, the optimization of the human motor function therapy becomes the goal for the rehabilitation process. Rehabilitation robotics continues to attract a large attention of researchers who assume potential prospects of using the robotic technology in the stroke treatment. There are four parts of the robotic rehabilitation (Kim et al., 2013):

- a machine or robot the patient will be dealing with,
- an assistance program that will define how the patient will interact with the machine,
- a task or program that will help the patient to regain its plasticity, and,
- an assessment framework that can be used to assess a patient's progress.

Today, when the robotic engineering is booming, a variety of robotic system is being developed to assist with the rehabilitation purposes. However, a few principles should be followed considering the robot is supposed to interact with a post-stroke patient who is highly vulnerable, including:

- Low force and speed of the operations;
- Tolerance to failure;

- Fault tolerance for the hardware and software parts;
- Fail safe design when the system fails to a safe state; and,
- Redundant sensing.

In the past 10 years, with the spike in the research of the robotic systems, rehabilitation engineering also got an boost. It was noted, however, that none of the systems in the review is used in the home-based environment because all of them required professional maintenance and calibration. Moreover, none of the mentioned systems is patient-oriented.

As a general feedback on the design of the rehabilitation system, Zhou & Hu (2008) stated that the following factors had to be considered: the cost, size, weight, function, operation, and automation. The designed system has to be affordable. The use of custom made elements should be avoided as mush as possible. The system should have an adequate size and weight to fit the compacted home environment. An approach to the design of a Human-Machine Interface (HMI) in a rehabilitation system should be addressed to suit better needs of a post-stroke patient. Finally, a real-time feedback and telemetry should be incorporated in such systems so that a patient has full interaction with a rehabilitation specialist.

A rehabilitation program is an important part of the recovery process. Once a team rehabilitation professionals defined the state of the patient a recovery plan is created to lead the patient to the more health state. Following the plan, the patient has to perform a set of exercises that will target the disability of the patient and will recover his motor function. In addition, a psychological support component can be added in the plan, if required.

The use of the robotic technologies allows the rehabilitation team to have access to the performance data of the patient going through the recovery process. Once the rehabilitation session ends, the overall performance data can be analyzed and corrections to the recovery plan can be made right away to improve the process. Such data, with a proper analysis, obtained from a group of patient could give an insight to the rehabilitation specialist what are the most efficient ways to approach a recovery process.

2.3.1 The robotic systems for the rehabilitation process

An extensive use of mechanical rehabilitation devices has been ongoing since the beginning of the twenty-first century. Compared to the conventional rehabilitation, the mechanical systems enable to earlier track the performance of the patient progress during the rehabilitation process. The performance data greatly matters since it allows the rehabilitation specialists to adjust the rehabilitation plan according to the current progress of the patient. Lum et al. (2002) compared the conventional therapy and robot-assisted therapy approaches. They found that the robot-assisted group of patients performed better. Moreover, the use of the machine therapy enabled the possibility of the measuring the clinical and biomechanical performance of patients recovery progress. This particular example demonstrated that the use of a more measurable approach to the rehabilitation practices would come up with better results.

A concept of a low-cost system that could potentially be used for home-based rehabilitation was presented by Johnson et al. (2007). In their system the components used were relatively cheap compared to the more expensive industrial counterparts. The authors were trying to find a compromise between a broader functionality and a lower cost of the rehabilitation system. The system was designed to be utilized in the environment under the supervision of rehabilitation professionals, where a patient had a low intrinsic motivation to exercise. As a result, the use of a robotic device helped to provide a personalized care and be adaptable to the rehabilitation process.

Analyzing several works, Patton et al. (2008) concluded that a patient who was exposed to the robotic-assisted rehabilitation did not have a significant difference in progress compared to those who were under the conventional therapy treatments. Further, if a patient was exposed to the robotic rehabilitation system at the right time and with a right amount of support the results of the rehabilitation were more noticeable, i.e. quality of effectiveness of therapy can be seen.

Norouzi-Gheidari et al. (2012) reviewed how the robot-assisted therapy influenced the stroke rehabilitation of upper-limb. Few criteria, such as the Fugl-Meyer scale (Fugl-Meyer et al., 1975), Functional Independence Measure scale (Keith et al., 1987), and Motor Status

Scale (Ferraro et al., 2002) were mentioned while evaluating the performance of the patients. The review concluded that the robotic-aid therapy (RT) in addition to the conventional therapy (CT) was more beneficial for post-stroke patients compared with only CT cases. The patients demonstrated significantly higher Fugl-Meyer score. One of the possible reasons for this is the high number of the repetitive exercises during the robotic-aid therapy.

Although, there is evidence that the robotic-aid rehabilitation systems provide significant results for the post-stroke patients, Mehrholz et al. (2012) surveyed multiple electromechanical and robot-assisted arm trainings and concluded that it was still unclear how and when such rehabilitation systems could be used. Because many research projects were aimed at improving the recovery process, it is difficult to make a choice in the direction of a system that gives significant benefits to the patients. In addition, it is difficult to define strict and precise criteria that could be used for the design of the robotic-aid rehabilitation systems.

As a way to improve the performance of a patient during an exercise, a gamification element can be added to the rehabilitation process (Jacobs et al., 2013). An opportunity to show the patient how he perform compared with a previous session, or compared with other patients in a similar condition could bring a competitive factor to the recovery process, which may increase a machine assistive patient's motivation to complete a long and monotonous exercise.

It is now generally accepted that a mechanical rehabilitation system should challenge a patient to perform an exercise; however, a question about the proper use of the rehabilitation robotics remains open and further studies have to be conducted.

2.4 Virtual Reality Rehabilitation Systems

As technology has been progressing rapidly for the last decade, rehabilitation engineering started developing a variety of machines that could assist, improve or replace the conventional rehabilitation therapy. With the advancement of the technology, the performance and cost of the rehabilitation systems should be decreasing.

Morrow et al. (2006) designed a low-cost rehabilitation system using P5 game glove and Java 3 dimensional (3D) simulation. The cost of the designed system was around 30 times cheap compared to more advanced system, which is based on CyberGlove (Jack et al., 2001a). However, these studies are mostly focused on the technical aspects of designing an inexpensive system that will have the functionality as close as possible to the more expensive counterpart.

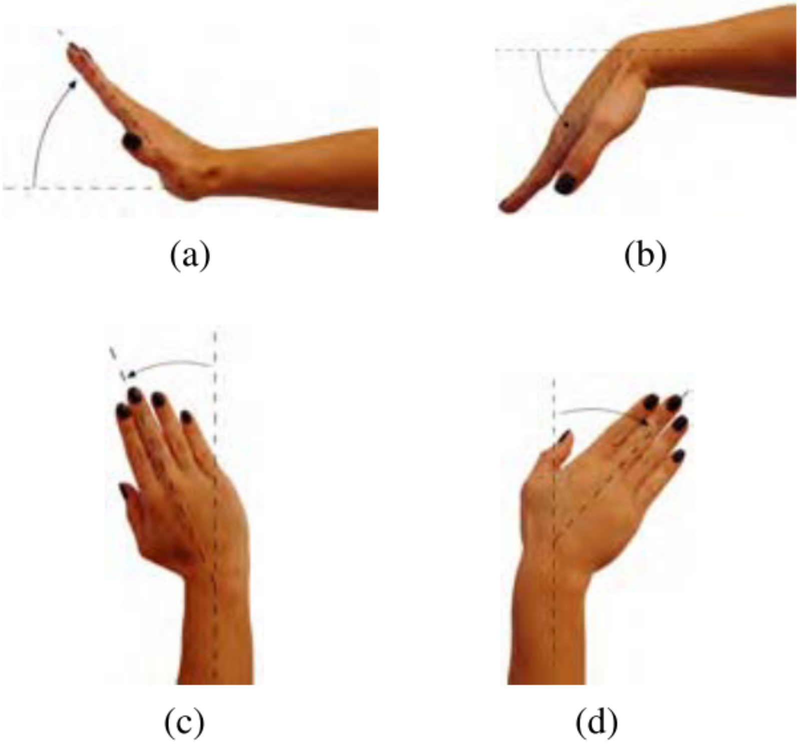
Veras et al. (2008) designed a virtual reality system based on the Phantom Omni and PUMA robot. The system incorporated a camera and a laser range finder for visual tracking and a Phantom Omni for positional measurement. With this system, an operator was able to get assistance in the direction of trajectory in at which the velocity increases. The developed system has not been tested to verify how potential patients would perceive such a system. Moreover, the use of additional sensor seemed unreasonable, because the Phantom Omni itself already had the encoders for receiving kinematics data.

Omar et al. (2010) designed a haptic device for finger and hand rehabilitation. In the design, a five bar linkage mechanism was used. In the system the requirements were indicated that the haptic workspace must cover the whole motion range of index finger, the system itself had low inertia and high manipulability. The system made it possible to perform an exercise for wrist extension, flexion, radial and ulnar deviation (Figure 2.1). Due to the use of Matlab/Simulink the authors claimed that the system's parameters could be adjusted during the exercises. Also, a variety of biomechanical parameters, such as position, velocity, acceleration and jerk could be recorded and used for further evaluation of the patient's condition. The system was verified in the hospital condition for three weeks and twenty sessions. Authors concluded that the use of their system allowed the patients to demonstrate better motor performance.

Maciejasz et al. (2014) summarized a variety of rehabilitation devices available to-date. Over 120 existing works were included in the survey. The systems in this review are categorized in terms of a type of assistance, such as:

- a machine can actively move a patient's limb,
- a machine can passively create resistance for patient's motion,
- a machine can be used just for tracking a patient's performance.

The main conclusion of the review was that among a large number of the rehabilitation systems, it was necessary to select the most promising systems that could potentially be



(a) (b) (c) (d)

Figure 2.1: Possible movement in hand rehabilitation from Daud et al. (2011): (a) Extension. (b) Flexion. (c) Radial deviation. (d) Ulnar deviation.

useful. For these systems, controlled and randomized trials with a significant number of post-stroke participants must be conducted, where the performance and patient's results would be compared.

2.5 Rehabilitation with the use of VR technologies

Hilton et al. (2011) discussed an approach for a design of virtual reality systems that could be used for upper-limb rehabilitation. During the study therapists and stroke survivors indicated that the use of virtual reality (VR) was helpful in the rehabilitation process. The main feature of VR, the simulation of a real world environment was recognized to be important for the rehabilitation process. Moreover, such a VR system allowed a therapist to track a patient's performance and adjust a rehabilitation plan.

As with the robotic rehabilitation systems, the advantages of the use of the virtual reality in the recovery practice had been questioned. Jack et al. (2001b) designed a VR system for the post-stroke rehabilitation that enabled him to evaluate the range, speed, and strength of the movement, as well as the finger fractionation. The study determined the potential advantages for improving the rehabilitation process in contrast with the conventional methods. Further, Henderson et al. (2007) concluded that the effectiveness of VR for rehabilitation was limited, and more studies were required to determine further potential of VR utilization. Bur et al. (2010) discussed the use of augmented reality systems for post-stroke rehabilitation. In the early development stage, the designed system allowed a user to interact with a virtual reality using real world objects. Thus, a variety of game- and object-driven scenarios can be created for more involving rehabilitation project (Bur et al., 2010).

As one of the conclusions of all these works, the use of the virtual reality environment in the recovery process enables to design the tasks for the patients in a wide range. Thus, a variety of tasks makes the process customizable and suits the main focus of the rehabilitation process which is to regain motor skill that can be used in the activities of daily life.

Saposnik et al. (2010) compared the use of a Nintendo Wii VR game with a recreational therapy, such as playing cards, bingo or Jenga. The results showed that the use of VR was a potentially effective alternative to the conventional rehabilitation practice. To summarize the results of use of the virtual reality in the rehabilitation process, Saposnik & Levin (2011) did a meta-analysis of the use of VR for stroke rehabilitation. Between 1966 and 2010, 35 studies related to stroke rehabilitation were analyzed, and the work concluded that the use of VR technologies could be potentially beneficial if used with the conventional therapy. With the use of VR during the rehabilitation process therapists observed improvements in motor impairment in the motor function.

Wilson et al. (2011) applied mixed approach to access the efficacy of the Elements VR system. The performance of the patients was evaluated using system-rated measures such as movement speed, accuracy, and efficiency. In this study, patients demonstrated a high level of involvement and satisfaction with the system. Also, Li et al. (2011) developed another haptic virtual reality system, as well as a specific technique that could be used for motor-skill evaluation of post-stroke patients. With this system, it was possible to evaluate a condition of Traumatic Brain Injury (TBI) patients. Such automation made possible to reduce a workload of the healthcare practitioners involved in the rehabilitation process. Crotty et al. (2011) reviewed the use of VR systems in rehabilitation practice. They compared the use of virtual reality and interactive video games with no therapy or alternative therapy on the upper limb, lower limb, and global motor function after stroke. The results demonstrated that there was a significant improvement after the rehabilitation with the use of VR systems. Later, Laver et al. (2011) added to the use of VR in the rehabilitation process. They concluded that the rehabilitation professionals required more information from research about the accessibility, usability, and the relationship between the performance of rehabilitation patients in the real world and the virtual world. Agostini et al. (2013) evaluated the effectiveness of non-immersive VR treatment for the restoration of upper limb motor function. The results of the study concluded that using the virtual reality in the rehabilitation process patients could significantly improve their motor function.

In all these works reviewed demonstrate, the use of the virtual reality in the rehabilitation practice tends to give contradictory results. Unfortunately, the rehabilitation process has too many uncontrolled factors that cannot be managed just by one unique rehabilitation system.

2.5.1 Haptic VR systems in the rehabilitation process

In the home environment, a patient can be rehabilitated without deterioration in activities of daily living. In addition, the patient could have a support of family members while he/she is gaining back the confidence in the activities of daily living.

Eriksson & Wikander (2010) proposed a design of a haptic interface using Matlab/Simulink. The work noted that this implementation was beneficial to use for developing new haptic interfaces with more complex mechatronics problems. Several haptic libraries (such as H3D API and CHAI3D) were mentioned in their work as well.

Numerous authors have demonstrated that the use of a haptic virtual reality system could be considered an efficient way for treatment of post-stroke patients. Daud et al. (2011) discussed efficacy of VR in the rehabilitation process. A haptic interface was designed and tested. The purpose of the interface was to help patients in restoring upper-limb function. In Daud et al. (2011) the usefulness of haptic device for the rehabilitation process was recognized. The designed haptic interface was potentially beneficial for a patient recovering from a stroke.

Oboe et al. (2010) developed a haptic teleoperation system for the remote motor and functional evaluation of hand in patients with neurological impairments. At the same time, Daud & Biral (2010) proposed a general framework for a rehabilitative oriented haptic interface.

Turolla et al. (2013) studied the use of a prototype of the haptic robot in the rehabilitation environment. The system demonstrated a significant improvement in the motor function for the patients. The following parameters are evaluated through the study:

- clinical, such as Fugl-Meyer upper extremity scale (Fugl-Meyer et al., 1975);
- nine hole pegboard test (Mathiowetz et al., 1985);
- biokinematics, such as time, velocity, jerkmetric, normalized jerk of standard movements.

Crotty et al. (2013) made an attempt to compare the use of telerehabilitation with inpatient approach, and also with no rehabilitation. As one of the findings in their work, they stated that there were not enough evidence to make conclusions about the successful use of telerehabilitation.

2.6 Concluding remarks

Undoubtedly, the rehabilitation process plays a crucial role for the post-stroke patients, and the sooner the help is provided, the higher the chance will be for the patients to have full restoration of motor functions. The use of current technologies is sure enough helpful in the recovery process.

Depending on the severity of stroke, a patient can be discharged from a hospital to continue a rehabilitation process as an outpatient, or in the home settings. Lack of the rehabilitation professional, the cost associated with the rehabilitation process may create a barrier to the fast and successful rehabilitation of the post-stroke patient. As it was mentioned earlier, the rehabilitation process is cyclical. The correction of the rehabilitation plan should be made depending on the performance of the patient.

All the researchers mentioned above have developed a variety of robotic rehabilitation systems with a broad range of initial specifications. After all, the benefits of each system can be determined only by directly testing the systems next to each other. Still, the basic requirements for a home-based rehabilitation system can be defined as (a) simple and understandable for patients; (b) adaptable to the patients' needs; (c) portable; (d) reasonable cost.

Using the modern technologies, the rehabilitation specialist can more precisely evaluate the condition of the patient. These allow making corrections to the recovery plan in time that best suits needs of the patient. Therefore, the advantages of the use of robotic systems for measuring the patients functional state are indubitable.

As a logical step, a robotic system can be used not only to measure a patient's performance during an exercise, but also to assist the patient during the rehabilitation exercise. Despite the fact that there is evidence of a positive use of robotic systems in the rehabilitation process, the use of such systems is limited by the clinical setting. The rehabilitation machines are not portable, use is limited only to a set of exercise, and generally, those machines are expensive.

To overcome the limitation of rehabilitation machines, a virtual reality could be introduced to it. This allows to extend a list of possible exercises that can be completed with the use of rehabilitation machines. In the same, the size of such machine could be reduced to make them more portable, which could be usable in the different settings, such as hospitals, or home environment.

Use of the haptic virtual environment (HVE) in the rehabilitation robotics allows for further extending the variety of exercises accessible to the patients. A rehabilitation robot acts as a manipulator for the HVE, providing a sensible feedback to the patient. In the same time, it could measure a patient's performance and provided a variety of assistance to stimulate the rehabilitation process.

The use of such systems has obvious advantages. However, there is currently insufficient information on the impact of such systems on the process of rehabilitation. Therefore, in this work I undertook an attempt to design an inexpensive system with use of haptic virtual reality. With this system, I tested the hypothesis which says: a proper level of assistance to patients in rehabilitation is a virtual environment will significantly improve a patient's motivation in performing the rehabilitation exercises and consequently, improve the recovery of the lost functionality of post-stroke patients.

CHAPTER 3

DEVELOPMENT OF THE TEST-BED

3.1 Introduction

Following the results of the multiple studies regarding the use of the robotics, the virtual reality robotic-aid rehabilitation systems seem like a good fit for the recovery process. In this work, it was assumed that the system will be used in the home-based environment by a patient with wrist paralysis. The patient is discharged home to proceed with the rehabilitation activities. Several factors are important to consider while establishing such a process. First, the portability of the system is important because often there is not enough space at home to have a big system installed. Second, the cost of the system is another significant factor. Third, the designed system for virtual reality should be able to facilitate a design of a wide range of tasks and track and store information about a patient's performance for further analysis by a rehabilitation specialist.

As it was addressed in the previous chapter, there is no guideline for the development of a haptic virtual environment rehabilitation system for home-based recovery. So, there is a need to study how to design and construct a haptic virtual environment rehabilitation system with active assistance.

In this chapter, I will discuss the design of a system that potentially could be used for the rehabilitation process of a post-stroke patient with the diseased wrist function. I will use the designed system to conduct an experiment to test the hypothesis that was defined in Chapter 1.

3.2 Choice of a haptic virtual environment device

To fulfill the requirements of the previous chapter, a prototype of a home-based haptic virtual environment rehabilitation system has been designed. Any robotic-aid virtual reality system for the rehabilitation has two essential parts. The first part is a manipulator that will provide an interface with the haptic virtual environment. The second part is a framework that provides means for developing a virtual environment. Therefore, the design consists of two parts:

- choose a hardware system in order to operate in the virtual environment,
- choose a software system that will be responsible for the virtual environment itself and will allow recording the data that is generated when a patient uses the system.

3.2.1 Choice of a haptic device

A haptic device is a tool used to manipulate objects in the virtual environment. There is a variety of haptic devices available. In general, they can be categorized into two types:

- a ”CyberGlove” type that allows a user to touch and manipulate objects in virtual environment;
- a robotic arm type that allows feeling the texture of the objects in the 3d virtual world.

Besides, the robotic arm devices can be classified by the degree-of-freedom, operational space, maximum force that can be applied within developed haptic environment, stiffness, and cost (Kadlecek, 2010). A Phantom Omni (Figure 3.1) was used for this work because of the following reasons:

- it is relatively cheap;
- it has an enough range of motion for a patient to perform an exercise in the virtual environment.

Figure 3.1: Phantom Omni haptic device

The Phantom Omni is a portable haptic device with six Degrees of Freedom (DoF) developed by Sensable Technologies. The workspace of the Phantom Omni is 16 cm x 12 cm x 7 cm (width x height x depth) and can provide force feedback up to 3.3 N. It has a nominal position resolution of around 0.055 mm. The main technical characteristics of the Phantom Omni are presented in Table 3.1. Based on the specification Phantom Omni could be used as a manipulator for a haptic virtual environment. Due to its size and weight, it is portable and can be used in the home environment for rehabilitation.

The Phantom is only actuated in the first three joints, which provides the ability to generate haptic forces at the tip or end-effector the patient's finger interacts (Figure 3.1). A forward kinematic model of position (Equation 3.1) that establish the relations between the position and orientation of the end-effector and the joint coordinates (Figure 3.2) can then be expressed as

$$\begin{aligned} x_p &= -\sin\Theta_1(L_2\sin\Theta_3 + L_1\cos\Theta_2) \\ y_p &= L3 - L_2\cos\Theta_3 + L_1\sin\Theta_2 \\ z_p &= -L_4 + \cos\Theta_1(L_1\cos\Theta_2 + L_2\sin\Theta_3) \end{aligned} \tag{3.1}$$

where

$L_1 = L_2 = 135mm$, $L_3 = 25mm$, $L_4 = 170mm$ (Silva et al., 2009). x_p, y_p, z_p are the

Table 3.1: Specifications of Phantom Omni

Force feedback workspace	160Wx 120 H x 70 D mm.
Footprint	168Wx 203 D mm.
Weight	1.36kg
Range of motion	Hand movement pivoting at wrist
Nominal position resolution	0.055 mm.
Backdrive friction	0.26 N
Maximum exertable force at nominal position	3.3 N
Continuous exertable force (24 hrs.)	0.88 N
Stiffness	X axis >1.26 N/mm Y axis >2.31 N/mm Z axis >1.02 N/mm
Inertia (apparent mass at tip)	45 g
Force feedback	x y z
Position sensing [Stylus end-effector]	x, y, z (digital encoders) Pitch, roll, yaw (linearity potentiometers)
Interface	IEEE-1394 FireWire

coordinates of the point P (Figure 3.2). It is noted that the Phantom Omni has a built in software system for forward kinematics and kinetics, which means that the interacting force between the tip and the finger is calculated by the software system.

3.2.2 Framework for design of a haptic virtual environment

One of the main challenges of the work is the design of a haptic virtual environment, and this challenge includes the following issues:

- the designed system should be simple and flexible enough so that it can be modified in the future according to the patient's needs;
- how to design an assistive system with the following criteria:

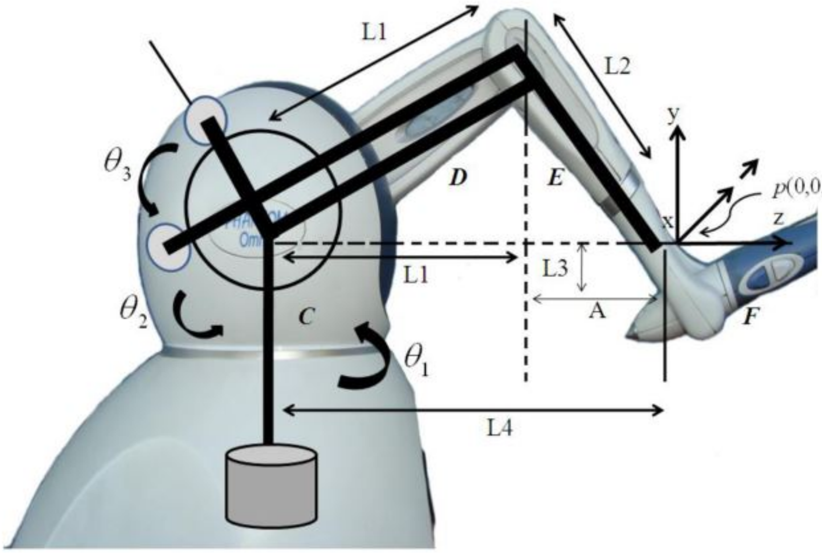


Figure 3.2: Phantom Omni Kinematic Model from Silva et al. (2009)

  - an assistance should be limited. A patient's efforts cannot be replaced by a machine.
  - the amount of assistance should be flexible. Even though machine does not replace a human, level of assistance should be adjusted according to the patient needs.

- the system should be able to record the biomechanics data of the rehabilitation process for determining the patient's performance and further analysis.

There are few available frameworks for design of a haptic virtual environment. Kadlecek (2010) gave a comparison and an overview of the APIs (application program interfaces) available. OpenHaptics, CHAI3D, H3D API, and others were compared based on different parameters, including available knowledge for development, the number of supported devices, and available support. For today, one of the most available tools for the haptic development is H3D API that allows quickly prototyping a haptic virtual environment. H3D API allows a developer to define the whole virtual environment scene with a camera set, lights, primitive objects, complex meshes, textures within XML nodes. Such simplicity in the development allows quickly developing an environment with a variety of tasks.

Comparison of H3D API with other frameworks presented in the Table 3.2. An H3D API was chosen as a framework for developing a haptic virtual environment, because it is open-source, which contributes to the final cost of the project. Moreover, it easily allows recording the data from the Phantom Omni device.

Table 3.2: Comparison of the most popular haptic development framework

	Chai3D	H3D API	OpenHaptics
OpenSource	Yes	Yes	No
Cross Platform	Yes	Yes	Yes
API manual	Yes	Yes	Yes
Examples	Yes	Yes	Yes
Haptic device data logging support	No	Yes	Yes

H3D API uses XML formatting with X3D for the creation of haptic simulations. X3D is a standard XML-based file format for representing 3D computer graphics. H3D API allows setting up a virtual environment scene with a variety of objects. These objects have "physical" parameters that can be adjusted according to the needs. H3D API libraries allow using the Phantom Omni device. The objects and forces that are generated within the haptic virtual environment can be defined and customized within XML document. It should be noted, that the kinematics of the Phantom Omni device (Equation 3.1) has already been built-in in the H3D API libraries.

3.3 Design of the assistive environment for the exercise of following circle trajectory

In rehabilitation, a patient has to do the task that will lead the patient to the increase of the motor function of the paralyzed limb. To exercise, the patient will need to perform rotational movements that will eventually result in the recovery of the wrist function. A "follow a circle trajectory" (Figure 3.3) task was chosen for this work without loss of generality of the work. In this task, a patient has to follow a circle path with a virtual end-effector of the Phantom Omni in the virtual environment.

Design of a virtual haptic environment using the H3D API consists of few steps. The first

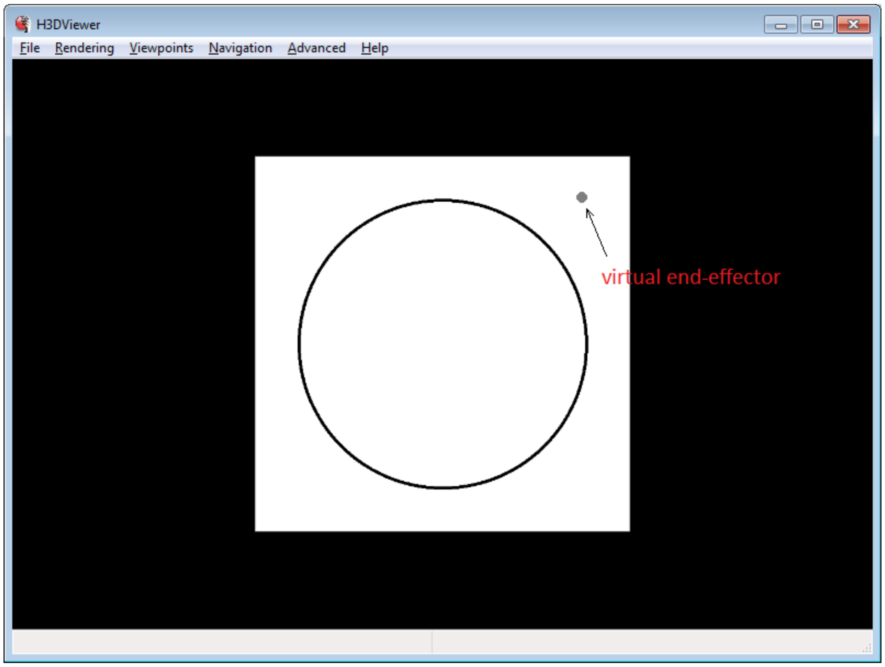


Figure 3.3: A circle trajectory in the haptic virtual environment

step is to create an object in the virtual environment. In this thesis, the object is a virtual surface with a circle trajectory on it.

Figure 3.4 shows a process of initializing a haptic virtual environment. In this process, a general virtual environment is initialized. Then a surface with a circle trajectory on it is created. With all that, a user of the system can perform an exercise. Also, the information from Phantom Omni such as position, speed, force is recorded for further analysis. Depending on the preferences, the information can be logged to a binary or ASCII format file at a set frequency.

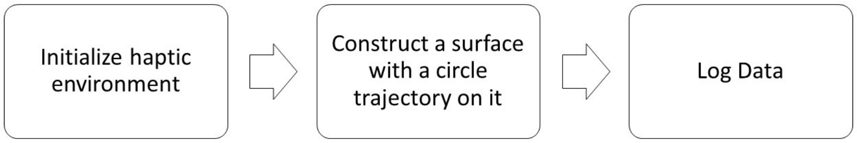


Figure 3.4: Flow chart for unassisted haptic virtual environment

Figure 3.5 shows the work of the Patient Assistive System (PAS). First, a virtual envi-

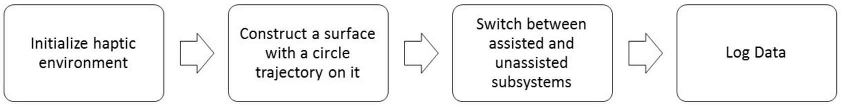


Figure 3.5: Flow chart for assisted haptic virtual environment

ronment is initialized. In the virtual environment a surface with a circle trajectory on it is created. While the user performs an exercise in the haptic virtual environment, the PAS assists the user to bring the end-effector to the circle trajectory. It should be noted that the PAS is active only specific amount of time. Thus, the system does not motivate the user to slack over the course of exercise. During the whole exercise, the information from Phantom Omni is recorded for further analysis.

To verify the hypothesis of this thesis, an assistive haptic virtual environment has been constructed with a simple task to be performed by a participant. To give assistance to the patient during an exercise a force field (Figure 3.6) was generated that returned the virtual end-effector of the Phantom Omni to the initial circle trajectory.

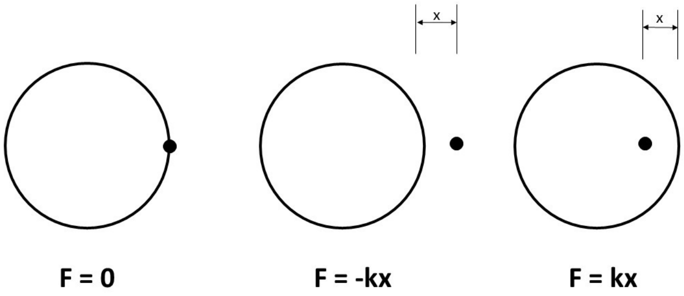


Figure 3.6: Force field generated during exercise

Over the course of the exercise, the participant receives a limited assistance to be able to complete the task (Figure 3.7). The assistance for the exercise consists of the force field that exists in the environment and brings the tip of the virtual end-effector of the haptic device

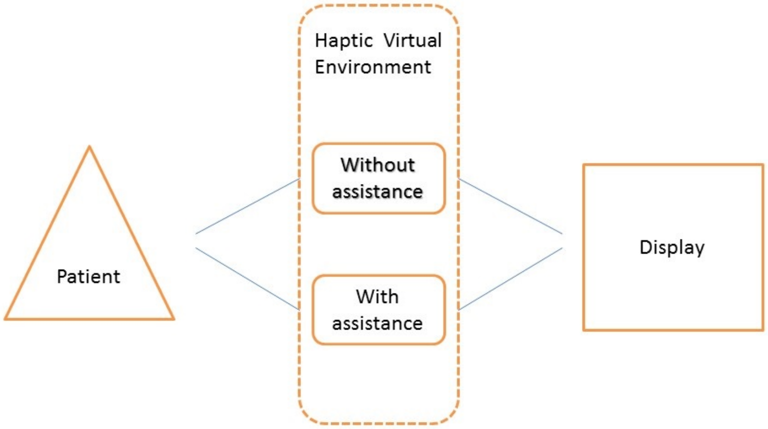


Figure 3.7: Assistive system diagram

back to the circle trajectory 33% of the time of the designed exercise (Figure 3.8). Thereby, the participant is still capable of completing the task, and the process is not disturbed by the machine.

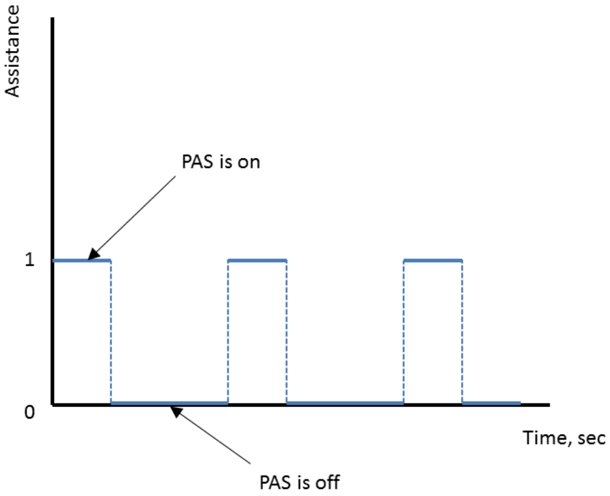


Figure 3.8: Work of the assistive system diagram

A rationale for choosing the amount of assistance is that the system will be verified with healthy group of people. Therefore, the level of assistance set to the constant value. In the real rehabilitation process the value will be adjusted with respect to the assessed condition of a patient, his performance over an exercise, and defined goals.

It is noted that once a Phantom Omni is initialized the tip of its virtual end-effector is presented in the virtual environment. Therefore, the user can easily understand what actions to perform in the virtual environment. The complete code for the designed haptic virtual environment is presented in Appendix B.

3.4 General metrics to evaluate participants' performance in the experiment

To assess the work of the designed Patient Assistive System (PAS), two sets of data were gathered through the experiment. The first set provides the performance metrics such as the number of circles drawn, mean velocity of drawing, the error of following the trajectory (movement accuracy) and force that is applied to the virtual surface (mean force). These metrics can be derived from the data obtained through the Phantom Omni device.

The number of circles drawn inferred for each participant using a Matlab is script presented in Appendix D. Mean velocity is determined by

$$V_{mean} = \frac{\sum_0^n V_i}{n}, \tag{3.2}$$

where $V_i = \sqrt{V_x^2 + V_y^2 + V_z^2}$. The movement accuracy is determined by

$$MA = \frac{\sum_0^n R_i}{n}, \tag{3.3}$$

where $R_i = \sqrt{(}Position_x^2 + Position_y^2) - R$, R is a radius of circle trajectory in the virtual environment. Force is determined as

$$F_{mean} = \frac{\sum_0^n F_i}{n}, \tag{3.4}$$

where F_i is the measured force in the y direction.

The second set of data is the aggregated result from the Intrinsic Motivation Inventory (IMI) which is a multidimensional measurement tool. The IMI intends to assess participants subjective experience related to a target activity in laboratory experiments. IMI has been used by many researchers (Ryan, 1982) and for the work IMI is adapted from Popović et al. (2014) work.

The Intrinsic Motivation Inventory (IMI) is a multi-dimensional measurement system that can be used to assess participants' individual experience related to a variety of activities within experiment settings (Plant & Ryan, 1985). It consists of a multi-item questionnaire evaluating the following parameters while performing a given exercise:

- participant's interest/enjoyment,
- perceived competence,
- effort,
- value/usefulness,
- felt pressure and tension,
- perceived choice.

In the IMI, the interest/enjoyment subscale is considered a self-report measure of intrinsic motivation. The perceived choice and competence parameters obtained my means of IMI are considered as a positive predictor of intrinsic motivation. The pressure and tension is theorized to be a negative predictor of intrinsic motivation.

The full version of the IMI consists of 45 questions and 7 subscales. The 26 questions questionnaire with 6 subscales tailored for the evaluation of the intrinsic motivation of the post-stroke patients was successfully used by Colombo et al. (2007). Each question in the IMI can have a score from 1 to 7. In addition, some questions coded with R. To calculate the results from the IMI questions coded with R are reversed by subtracting the question response from 8 and using the result as the item score for that item. The subscale scores are calculated by averaging the items scores for the questions on each subscale. The results of two questionnaire for each participant are be compared to observe changes in motivation after use of the Patient Assistive System. The IMI questionnaire adapted for the experiment in this thesis is presented in Appendix A.

3.5 Summary

This section provided an description of the design of a patient assistive system that could be used by post-stroke patients in the home setting. The system allows performing an exercise in the designed haptic virtual environment. The performance of the patient during the exercise can be recorded and can be analyzed to make adjustments in the rehabilitation plan. The level of assistance in the system is limited and set to the fixed value to avoid any voluntarily slacking of the patients to the assistance from the machine.

Chapter 4

Experiment

4.1 Introduction

The chapter presents an experiment of the test-bed as developed in Chapter 3. The experiment is to test the hypothesis of this thesis, namely the partial assistance to post-stroke patients, as designed in Chapter 3 is useful to increase a patient's motivation in the rehabilitation process. Section 4.2 introduces task to be performed in the designed Haptic Virtual Environment. In Section 4.3, the static design of the experiment is presented. In Section 4.4, the experimental result is presented along with discussion. Finally, in Section 4.5, conclusions are drawn.

4.2 Proposed task

The PAS, when active, adjusted the position of the tip of the virtual end-effector of the Phantom Omni haptic device closer to the defined circle trajectory. The assistive system was being active 33% of the time over the course of exercise. In order to eliminate any effect on the results of the experiment the level of assistance will remain constant for the whole experiment. Moreover, to avoid possible slacking from the participants, thus, affecting on the overall performance of the process the level of assistance remains constant over the course of exercise (Marchal-Crespo & Reinkensmeyer, 2009). It is noted, that by design the value can be adjusted according the needs and desire of the post-stroke patient. Thus, the haptic VR helps the patient to visualize the task the patient was performing, and the flexibility of the virtual environment enabled the customization of the process that corresponded to the patients' needs.

The following a circle trajectory task was chosen to make the wrist of the experiment participant to move only in two directions - vertical and horizontal. Thus, the wrist's extension, flexion, radial and ulnar deviation will be exercised, which is beneficial towards the goals of the rehabilitation practice. Drawing a spacial figure in the virtual environment would induce a motion in the elbow which is not required.

4.3 Statistical design of the experiment

To verify the use of the designed test-bed I designed an experiment. In the experiment a group of people have to perform an exercise without and with use of a Patient Assistive System. There is one factor in this experiment, that is the assistance to the patients. This factor has two levels: on and off. The participants were asked to perform tasks on the test-bed with on and off status of the assistance. The task performance data of the participants was recorded. After each task the participants were asked to fill out an IMI for further inferring the subjective experience with the designed system.

In the human behavior experiments the statistical power should be higher than 80 % (Cohen, 2013), and a sample size must be determined for a within-subject experiment. In order to determine the sample size, the methods of power analysis had to be used (Rosner, 2006). With the power of 80% at a 5% significant level Equation 4.1 gives 12 samples.

$$N = \frac{\sigma^2(z_{1-\beta} + z_{1-\alpha})}{(\mu_0 - \mu_1)^2} \tag{4.1}$$

The experiment assumed that the samples were randomly selected from the population, and the population was normally distributed. In addition, the experiment used a within-subject design in order to accommodate fewer participants. Because all participant are healthy the fatigue does not infer their performance when they do the exercise. In addition, to eliminate the effect of fatigue to the results of the experiment, the participants get an enough time interval to rest between any two exercises.

Before the start of the experiment participants got enough time to familiarize themselves with the designed system. This allows to eliminate performance increase during a second exercise when the participants got more familiar with the system.

This experiment was approved by the Ethics Committee in the University of Saskatchewan. The certificate of approval is attached in Appendix D.

In total 14 participants, including 7 males and 7 females, were recruited from the University of Saskatchewan campus. The participants' age ranged between 18 and 35 years old, all of them claimed to be physically and mentally healthy at the time of the experiment. Further, no one among the participants indicated having any experience with the haptic virtual environment in the past.

Since none of the participants had prior experience with the haptic virtual environment (HVE), they were given an introduction on the experiment settings, its overall purpose and the following procedure. Each participant had time to familiarize himself/herself with the use of the PhantomOmni haptic device and the designed HVE. Once a participant indicated that he or she was ready to start an exercise, he/she was asked to start following a circle trajectory in the HVE by a tip of the end-effector of the haptic device and continue doing the exercise for 2 minutes. Then, the participant was given an IMI questionnaire to fill out, and had a pause for a break. After the break, the participant was asked to complete the same task in the HVE with Patient Assistive System (PAS) for 2 more minutes, and then another IMI questionnaire was handed out for completion.

The designed system followed the requirements that were proposed in Chapter 3 and tracked the following parameters:

- the number of circles drawn during the exercise,
- the speed of the virtual end-effector in the virtual environment,
- the force applied to the virtual plane in the HVE, and,
- the overall accuracy of following the circle trajectory.

4.4 Results

Over the course of the experiment each participant performed a task with the PAS being on and off. For each task raw data containing information about position, speed, and force of the virtual end-effector of the Phantom Omni was recorded. The biomechanical data was recorded every 500 milliseconds during 2 minutes task. After each task each participant fill out IMI questionable that consists of 26 questions. As described in Chapter 3, the obtained biomechanical and IMI data was processed to infer the participants' performance and motivation without and with use of the Patient Assistive System.

The performance characteristics for each participant obtained from the raw data such as the number drawn circles, mean velocity, movement accuracy, and mean force as suggested in Chapter 3. Matlab scripts for preprocessing the data is provided in Appendix D. The results of the IMI were aggregated using the methodology provided in Chapter 3. A summary of the aggregated data is provided in Appendix C.

For the summarized performance and intrinsic motivation characteristics a paired t-test was performed to determine if the use of PAS significantly influenced the participants' inartistic motivation and performance.

4.4.1 Intrinsic Motivation Inventory Analysis

As shown in Figure 4.1, interest to the exercise without and with PAS remained at the same level among the participants. The given Box-and-Whisker Plot shows the median value (red line) of the interest/enjoyment level during both parts of the experiment, and represents minimum and maximum values of the interest/enjoyment.

A paired t-test was performed to determine if the use of PAS influenced the interest of participants to the task. For the t-test a $H_0 : \mu = 0$ and $H_a : \mu \neq 0$ hypothesis were tested. There is an evidence that there is no significant interest to the exercise ($M = 0.1857, SD = 0.8169, N = 14$), $t(13) = 0.8505$, two-tail $p = 0.4104 > 0.05$. Since p is higher than the significance level $\alpha = 0.05$, this provides an evidence that the use of the PAS as it is now does not affect on the interest/enjoyment of the participants on the task.

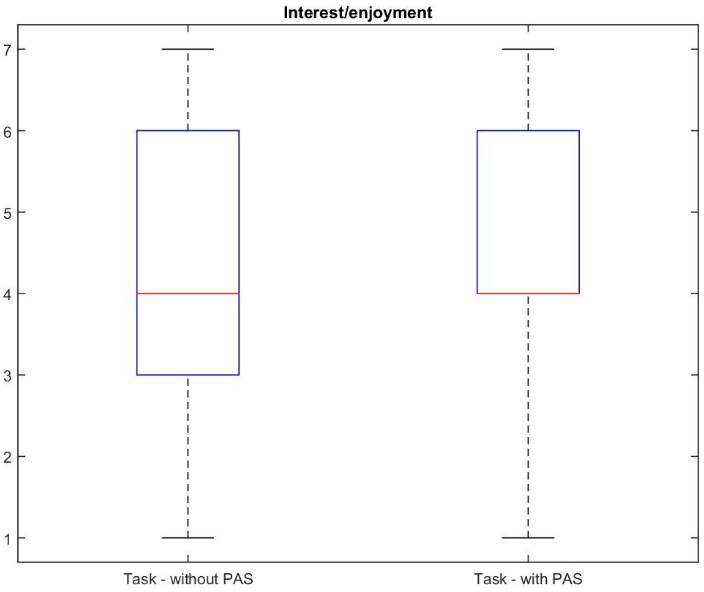


Figure 4.1: Interest/enjoyment

The perceived competence experienced over the course of the experiment is presented in Figure 4.2.

A paired t-test was performed to determine how use of PAS affects on the perceived competence. For the t-test a $H_0 : \mu = 0$ and $H_a : \mu \neq 0$ hypothesis were tested. There is an evidence that the participants did not gain any significant competence ($M = 0.2678, SD = 1.1285, N = 14$), $t(13) = -0.8880$, two-tail $p = 0.3906 > 0.05$, providing evidence that the use of the designed PAS as it is now does not affect on the perceived competence of the participants on the task.

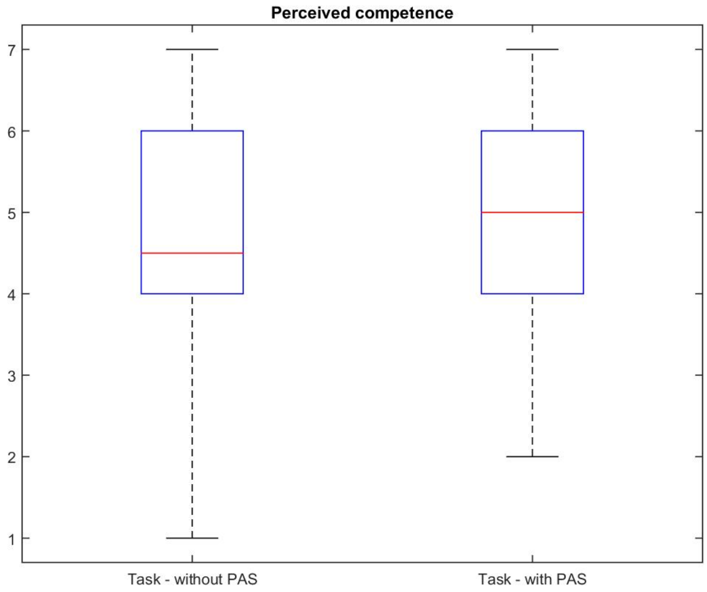


Figure 4.2: Perceived competence

Figure 4.3 shows efforts spent on the exercises.

A paired t-test was performed to determine how use of PAS affects on the perceived competence. For the t-test a $H_0 : \mu = 0$ and $H_a : \mu \neq 0$ hypothesis were tested. There is an evidence that the participants did not spend significantly more efforts on the exercise when PAS was on $(M = 0.0357, SD = 0.5081, N = 14)$, $t(13) = 0.2629$, two-tail $p = 0.7967 > 0.05$.

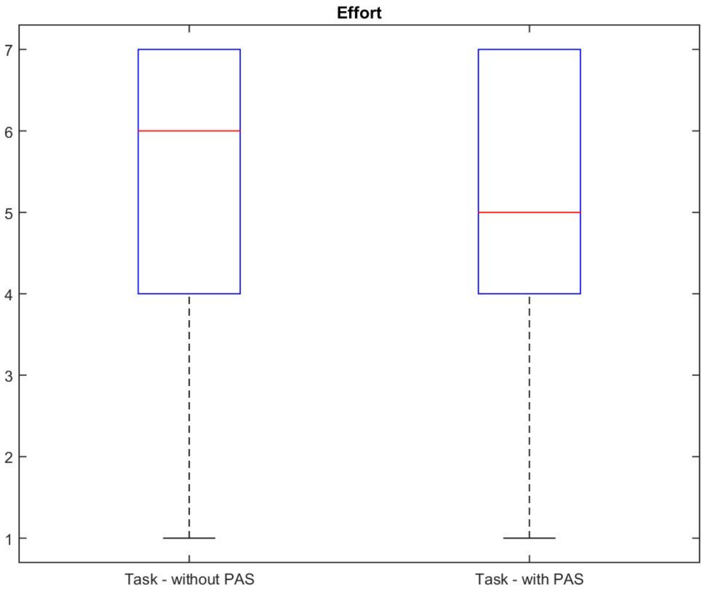


Figure 4.3: Effort

Figure 4.4 demonstrates how participants evaluated the value of the exercise.

A paired t-test was performed to determine if there is a significant difference between values during the experiment. For the t-test a $H_0 : \mu = 0$ and $H_a : \mu \neq 0$ hypothesis were tested. There is an evidence that the participants think that the value of the task with and without PAS are the same $(M = -0.2714, SD = 0.9302, N = 14)$, $t(13) = -1.0917$, two-tail $p = 0.2947 > 0.05$.

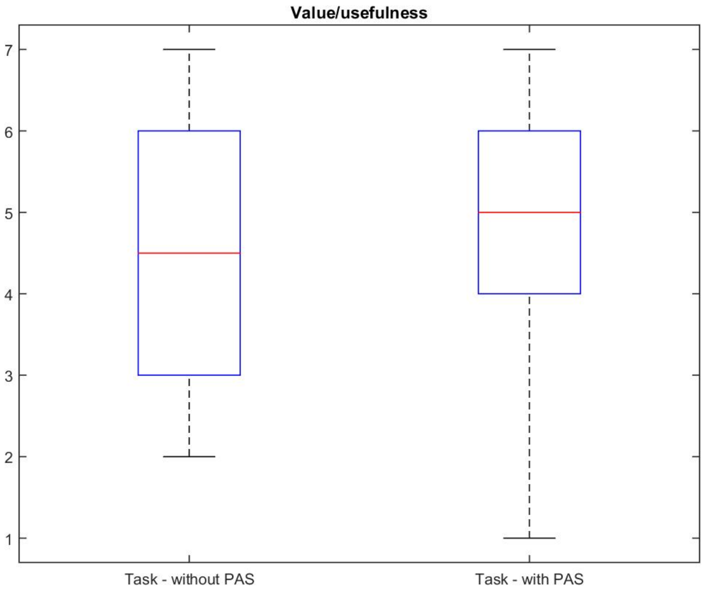


Figure 4.4: Value/usefulness

Figure 4.5 shows perceived choice during the exercises.

A paired t-test was performed to determine how use of PAS affects on the perceived choice. For the t-test a $H_0 : \mu = 0$ and $H_a : \mu \neq 0$ hypothesis were tested. There is an evidence that the participants did not developed any significant sense of choice ($M = -0.3928, SD = 1.0593, N = 14$), $t(13) = -1.3875$, two-tail $p = 0.1885 > 0.05$, providing evidence that the use of the designed PAS as it is now does not affect on the perceived choice of the participants on the task.

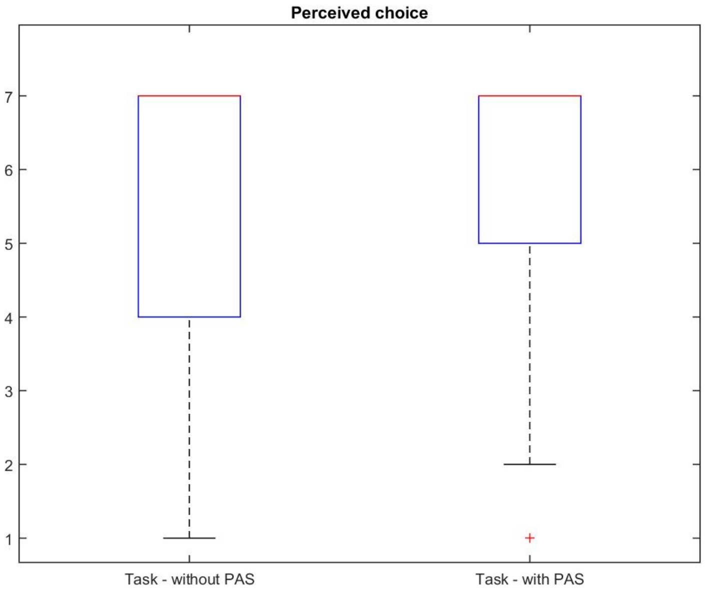


Figure 4.5: Perceived choice results obtained from IMI analysis

Figure 4.6 shows if the participants felt pressure or tension during the two exercises.

A paired t-test was performed to determine if the participants felt pressure or tension while doing a task without and with the PAS. For the t-test a $H_0 : \mu = 0$ and $H_a : \mu \neq 0$ hypothesis were tested. There is an evidence that there is no significant difference between how the participants felt pressure and tension while doing a task without and with PAS $(M = -0.125, SD = 1.1126, N = 14), t(13) = -0.4203$, two-tail $p = 0.6810 > 0.05$, providing evidence that the use of the designed PAS as it is now does not put any additional pressure on the user of the designed system.

4.4.2 Performance data analysis

The goal was to infer the following performance metrics from the participant's exercise:

- number of circles drawn;
- mean velocity;
- error of following the trajectory, or movement accuracy; mean distance $MD = \sum_{i=1}^{n} |di|/n$, where di is a distance between each point of the path and the origin trajectory;

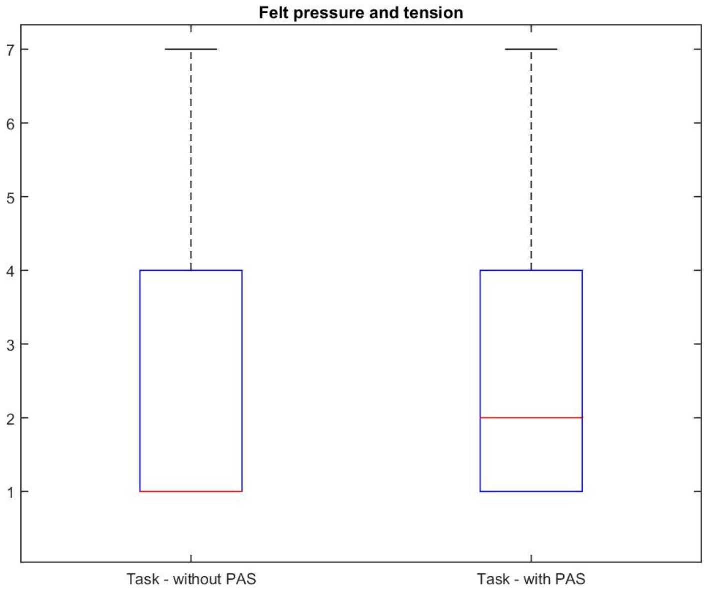


Figure 4.6: Felt pressure and tension

- force applied to the virtual surface, or mean force.

Figure 4.7 presents a comparison of the number of circles drawn by the participants without and with the PAS.

A paired t-test was performed to determine if there is a significant difference between the number of circles drawn by the participants over the course of the experiment.

For the t-test a $H_0 : \mu = 0$ and $H_a : \mu \neq 0$ hypothesis were tested.

There is an evidence that there is no significant difference between the numbers of circles drawn by the participants $(M = -0.5714, SD = 6.3332, N = 14)$, $t(13) = -0.3375$, two-tail $p = 0.7410 > 0.05$, providing evidence that the use of the designed PAS does not affect on the performance parameter.

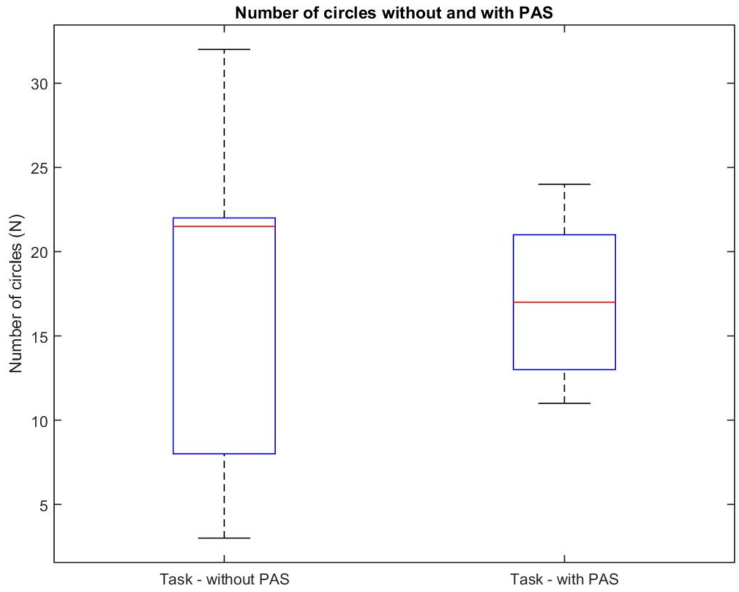


Figure 4.7: Number or circles drawn without and with PAS

Figure 4.8 shows the average force applied to the drawing plane in the HVE. It is observed that in the HVE with PAS the participants were able to spend less efforts on putting pressure to the virtual drawing plane.

A paired t-test was performed to determine if there is a significant difference between amount of force applied on the virtual plane over the course of the experiment.

For the t-test a $H_0 : \mu = 0$ and $H_a : \mu \neq 0$ hypothesis were tested.

There is an evidence that there is no significant difference between the numbers of circles drawn by the participants ($M = 0.0663, SD = 1.2035, N = 14$), $t(13) = 0.2063$, two-tail $p = 0.8397 > 0.05$, providing evidence that the use of the designed PAS does not affect the performance parameter.

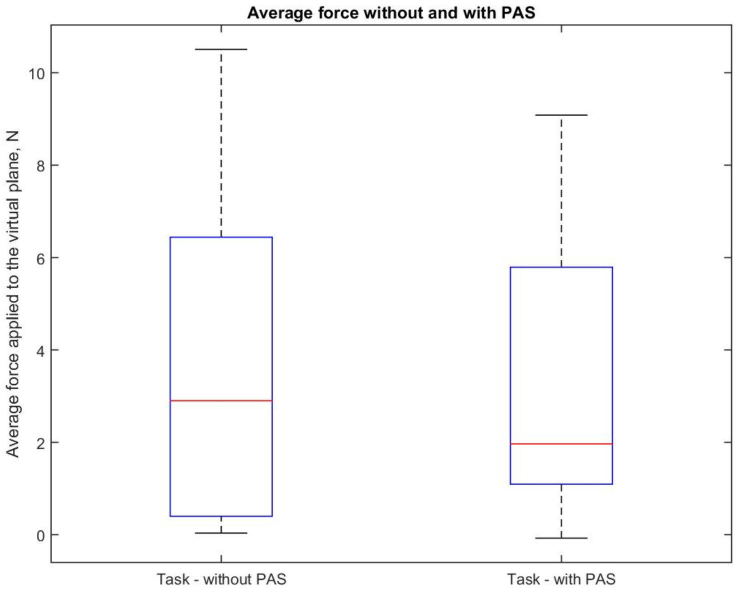


Figure 4.8: Average force without and with PAS

Figure 4.9 shows the average speed of following trajectory in the virtual space.

A paired t-test was performed to determine if there is a significant difference between measured speed of the tip of the end-effector over the course of the experiment.

For the t-test a $H_0 : \mu = 0$ and $H_a : \mu \neq 0$ hypothesis were tested.

There is an evidence that there is no significant difference between the numbers of circles drawn by the participants ($M = 0.0663, SD = 1.2035, N = 14$), $t(13) = -0.9347$, two-tail $p = 0.3669 > 0.05$, providing evidence that the use of the designed PAS does not affect the performance parameter.

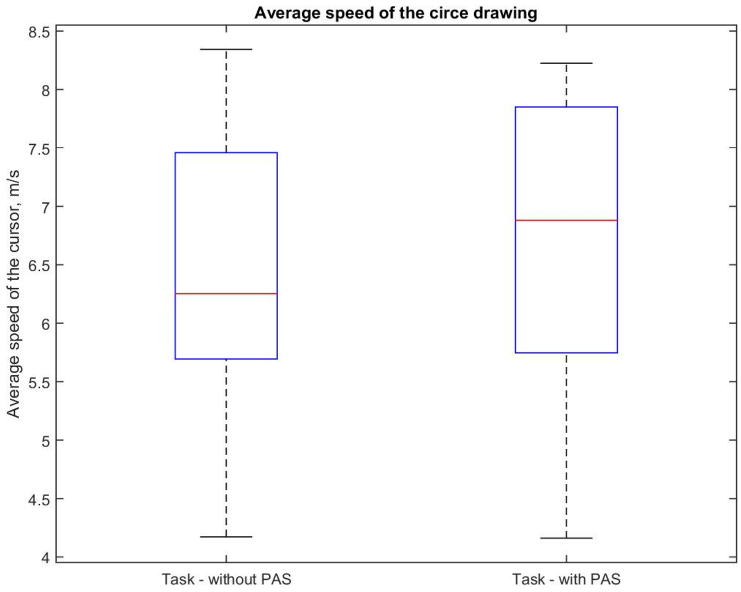


Figure 4.9: Average speed without and with PAS

Figure 4.10 shows the mean error for two exercises in HVE. In this box-and-whisker plot the data outliers are plotted individually using the '+' symbol.

A paired t-test was performed to determine if there is a significant difference between mean distance over the course of the experiment.

For the t-test a $H_0 : \mu = 0$ and $H_a : \mu \neq 0$ hypothesis were tested.

There is an evidence that there is a significant decrease of mean distance when PAS is on $(M = 0.0053, SD = 0.0081, N = 14)$, $t(13) = 2.4313$, two-tail $p = 0.0302 < 0.05$, providing evidence that the use of the designed PAS increase accuracy of the task execution.

4.5 Conclusion

In the experiment I evaluated how use of a patient assistive system would affect the performance and intrinsic motivation of patients.

First of all, the use of a Phantom Omni device with a haptic virtual environment allowed to measure the performance characteristics of the participants on the experiment. With the use of the patient assistive system participants did not show significant gain of performance in the proposed exercise. The only performance parameter that significantly changed is the

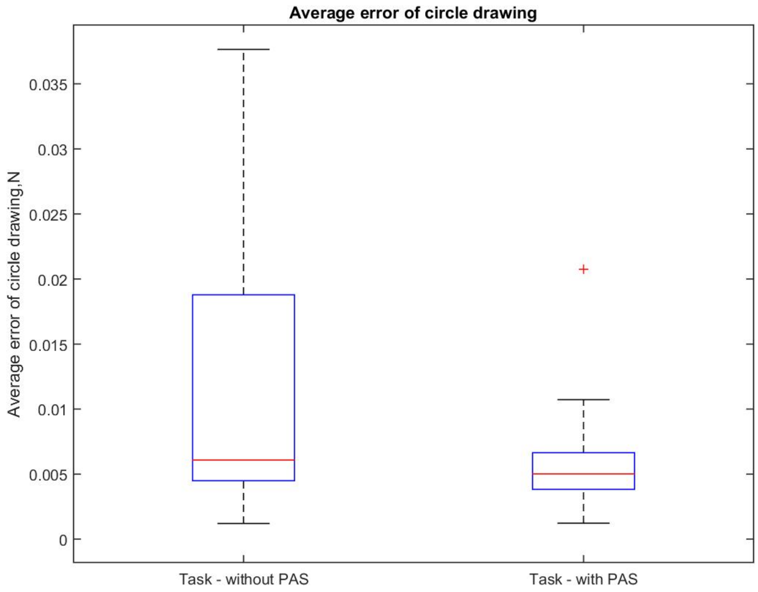


Figure 4.10: Average error without and with PAS

number of circles drawn during the experiment.

The results of the IMI questionnaire show that the use of a patient assistive system does not lose interest with the participant to the exercise. Participants did not gain any competence while performing the exercises without and with the patient assistive system. Participant are spending the same amount of efforts to do the exercise with and without the rehabilitation system. No change in the pressure or tension was discovered when participants were using the designed system.

CHAPTER 5

CONCLUSION

5.1 Overview

The research in this thesis aimed at tackling the issue of the partial assistance to the patient from a device's side. Particularly, it was revealed how partial assistance in a haptic virtual environment could affect the performance and intrinsic motivation of a healthy person. The research in the thesis proposed a new active assistance. The assistance offered by the device at the minimal level to let the user of the rehabilitation system to proceed with a recovery exercise. Still, the assistance does not make the user of the system slack during the exercise. This thesis proposed a hypothesis that is the proposed level of partial active assistance would not change the performance and would not reduce the motivation towards an exercise as well. Due to the difficulty in finding a proper number of patients, the study was conducted on healthy people.

This thesis described the design and implementation of the proposed method for active assistance and the experiment to test the hypothesis. The motivation of the patient was inferred from the analysis of the Intrinsic Motivation Inventory and the performance of the participants of the experiment was measured by the task completion attributes: (1) mean velocity of the exercise , (2) the movement accuracy, and (3) number of circles drawn during the exercise. The research in the thesis concluded the following: (a) use of the designed Patient Assistive System does not affect the motivation of the healthy people to discontinue the exercise; (b) overall, the healthy people draw significantly more circles in the haptic virtual environment with the use of the system; (c) use of the system makes the healthy people spend the same amount of efforts as for an exercise without assistance.

Use of a haptic virtual environment (HVE) and a small/inexpensive haptic device provides certain benefits for the home-based rehabilitation because of several factors. First, the HVE robotic system is cost-effective with the use of computing and software technology. Second, the HVE robotic system is more agile and portable the therefore suitable to the home-based rehabilitation approach. Third, as compared with real robotic systems, the HVE robotic system offers a more flexible possibility for assigning tasks or exercises to patients towards the activities of daily living.

However, the conclusions presented above cannot be extended to patients. For patients, the assistance system may significantly improve the task performance of patients, and thus the assistance system may actually improve the motivation of performing the task.

This thesis presented the results of the preliminary design of a haptic virtual reality rehabilitation system for recovery of a post-stroke patient with hemiplegia of upper-limb. Also, a hypothesis about effects of the use of such system was tested using the IMI framework and performance characteristic obtained in the experiment.

5.2 Contributions

The thesis developes a new active assistance approach to upper limb rehabilitation in the haptic virtual environment. The design is based on a Phantom Omni haptic device and the H3D API framework. The assistive component of the system was verified in an experiment where a group of healthy participants did a series of exercise with the use of the patient assistive system and without it. A difference in the performance during the experiment was inferred in terms of biomechanical parameters and results of the IMI questionnaire.

The proposed approach has been proved useful, through in a preliminary experiment. To the best of my knowledge, the proposed approach has never been done by others in literature in the context of HVE.

Another contribution of the thesis is the provision of a pilot study on how the assistance to the healthy people in rehabilitation would affect the motivation of the patient. It is noted that the motivation of doing exercise is one of the most important variables to a successful recovery of the function loss of the post-stroke patient.

As the experiment demonstrated, a small assistance from the machine leads to nonsignificantly fewer efforts on completing an exercise in the haptic virtual environment usage. Overall, the use of a PAS allowed participants (healthy people in this case) to execute a designed exercise faster. The use of a PAS did not decrease interest of participants to the exercise. The results inferred from the IMI suggest that the participants acknowledge that exercising with a PAS made them feel more confident but not significantly. But a care must be taken that the result of this study is on healthy people and for patients, the result may be different.

5.3 Future work

Nowadays, the virtual reality technologies are progressing especially fast. Most major technological companies either announced or released devices that allows the use of virtual reality in various aspects of our life. It becomes easier to apply the latest technological achievements in rehabilitation engineering.

There are some limitations with the current work than can be addressed in the future. First, the experiment is only performed on healthy people instead of patients. This can greatly compromise the accuracy of the result. It may be true that this limitation is responsible for a surprise in the experiment that the motivation of the participants remains the same with the proposed assistance. For the future research work, the experiment should be considered for a more extensive clinical study that involves post-stroke patients, and the designed system is tested over a prolonged period of time.

Second, in this thesis only one exercise related to the wrist coordination function is considered. This will certainly compromise the reliability of the experimental result. In the future, a variety of tasks should be considered especially with reference to a particular clinical assessment framework.

Last, the level of assistance should be made individually different. But currently, this point has not received sufficient attention. Individually-tailored rehabilitation therapy is certainly a future direction and thus worthy of study.

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APPENDIX A

INTRINSIC MOTIVATION INVENTORY (IMI)

The following statements express certain thoughts, beliefs, and feelings concerning the exercise you have been doing. Please indicate how true each statement is for you, using the following scale as a guide:

1. Not at all true
2.
3.
4. Somewhat true
5.
6.
7. Very true

(1) I enjoyed doing this activity very much.
(2) I think I am pretty good at this activity.
(3) I put a lot of effort into this.
(4) I did not feel nervous at all while doing this. (R)
(5) I thought this was a boring activity. (R)
(6) I believe this activity could be of some value tome.
(7) After exercising for a while, I felt pretty competent.
(8) I believe I had some choice about doing this activity.
(9) I did not try very hard to do well at this activity. (R)
(10) I think that doing these exercises might be useful for recovery of my hand/arm movements.
(11) This activity did not hold my attention at all. (R)
(12) I felt very tense while exercising.
(13) I felt like it was not my own choice to do these exercises. (R)
(14) I thought this activity was quite enjoyable.
(15) I would be willing to do this again because it has some value to me.
(16) I am satisfied with my performance at this task.
(17) I think this is important to do because it can help me grasp desired objects more easily.
(18) It was important to me to do well at this task.
(19) I did this activity because I had no choice. (R)
(20) I was anxious while exercising.
(21) While I was exercising, I was thinking about how much I enjoyed it.
(22) I did this activity because I wanted to.
(23) This was an activity that I could not do very well. (R)

(24) I did not put much energy into this. (R)
(25) I felt pressured while doing these.
(26) I think doing these exercises could help me to recover faster.

The six subscales include the following questions:
Interest/enjoyment subscale: 1, 5, 11, 14, 21
Perceived competence subscale: 2, 7, 16, 23
Effort subscale: 3, 9, 18, 24
Value/usefulness subscale: 6, 10, 15, 17, 26
Perceived choice subscale: 8, 13, 19, 22
Felt pressure and tension subscale: 4, 12, 20, 25.

To score the results from the questionnaire I reverse items 4, 5, 9, 11, 13, 19, 23, 24 by subtracting the item response from 8 and using the result as the item score for that item. Then calculate subscale scores by averaging the items scores for the items on each subscale.

APPENDIX B

HAPTIC VIRTUAL ENVIRONMENT CODE

Task - without PAS

```
<!--Create a Virtual Environment-->
<Scene>
  <Shape>
  <!--Create a surface with a circle trajectory on it-->
        <Appearance>
          <Material DEF='M' />
          <ImageTexture url="1.png"/>
          <SmoothSurface stiffness="1.0" />
        </Appearance>
        <Box size="0.3 0.3 0.1"/>
  </Shape>
  <!--Log the data from Phantom Omni-->
        <DeviceLog
         url='c:\\experiment\\task1_log.txt'
         frequency='500'
         deviceIndex='0'
         logBinary='false'
         logData='ALL' />
</Scene>
```

Task - with PAS

```
<?xml version="1.0" encoding="utf-8"?>
<X3D profile='Full' version='3.2'>
  <head>
    <meta name='title' content='Switch.x3d'/>
    <meta name='description' content='X3D Switch, TimeSensor and
        IntergarSequencer example.'/>
    <meta name='Dmitriy Chesnakov' content=
     'Haptic VR assisted experiment'/>
  </head>

  <!--Create a Virtual Environment-->
  <Scene>
  <!--Define trancition between Assisted and Unassisted VR-->
    <Viewpoint position='0 0 0.6' />
    <Switch DEF='S' whichChoice='0'>
      <Inline url='nomagnetic.x3d' />
      <Inline url='magnetic.x3d' />
```

```
    </Switch>

    <TimeSensor DEF='T' enabled='true' loop='true'
     cycleInterval='25' />
    <IntegerSequencer DEF='I' keyValue='0 1' key='0 0.60' />
    <ROUTE
        fromNode='T' fromField='fraction_changed'
        toNode='I' toField='set_fraction' />
    <ROUTE
        fromNode='I' fromField='value_changed'
        toNode='S' toField='whichChoice' />
        <!--Log the data from Phantom Omni-->
        <DeviceLog
        url='c:\\experiment\\task2_log.txt'
        frequency='500'
        deviceIndex='0'
        logBinary='false'
        logData='ALL' />
  </Scene>
</X3D>
```

magnetic.x3d

```
<Scene>
  <DynamicTransform DEF="D" angularMomentum="0.0 0.0 0.0">
      <Shape>
        <Appearance>
          <Material transparency="1"/>
          <MagneticSurface  staticFriction='0.0'
                                   dynamicFriction='0.0'
                            stiffness='0.4' damping='0.4'
                            snapDistance='0.01' />
        </Appearance>
        <Sphere radius='0.125' />
      </Shape>
          <Shape>
                <Appearance>
          <Material DEF='M' />
                  <ImageTexture url="1.png"/>
                  <SmoothSurface stiffness="1.0" />
        </Appearance>
        <Box size="0.3 0.3 0.1"/>
          </Shape>
  </DynamicTransform>
</Scene>
```

nonmagnetic.x3d

```
<Scene>
  <Shape>
        <Appearance>
          <Material DEF=’M’ />
          <ImageTexture url=”1.png”/>
          <SmoothSurface stiffness=”1.0” />
        </Appearance>
        <Box size=”0.3 0.3 0.1”/>
  </Shape>
</Scene>
```

Appendix C

Data obtained over the experiment

Table C.1: Summary of data for part 1

Participant	Interest/enjoyment	Perceived competence	Effort	Value/usefulness	Perceived choice	Felt pressure and tension	Force	Mean distance	Number of circles	Speed
1	4.8	4.5	5.5	5.4	6	4.5	10.50	0.0058	23	6.15
2	4.4	4.5	5.25	5.8	6.5	1.75	0.40	0.0079	32	5.94
3	4.6	4.5	7	2.8	6.25	1.5	3.76	0.0051	23	8.08
4	3.4	3.25	6	4.6	5	3.75	6.98	0.0188	22	7.95
5	5.6	6.25	3.75	6.8	3.5	1	0.10	0.0376	10	6.36
6	5.4	4.25	5.5	4	5.75	1	0.72	0.0012	3	5.96
7	4.4	4.5	4.25	3.8	6.25	2.5	5.07	0.0198	21	7.38
8	6.4	3.25	5.5	6.4	6.25	2.5	1.03	0.0031	5	5.69
9	3.6	5.25	3.25	4	6	1.25	2.05	0.0045	19	5.16
10	4.2	4.75	7	3	5.5	1	7.03	0.0064	22	8.34
11	2.2	3.75	6.25	2.8	2.25	5.5	3.91	0.0028	8	7.46
12	3.2	5.75	6.25	5.6	6	2.5	0.14	0.0163	5	7.30
13	5.8	5.75	4.25	6	6.5	3	6.44	0.0047	22	4.17
14	4.2	4	4.5	5.2	5.75	2.25	0.04	0.0300	22	5.23

Table C.2: Summary of data for part 2

Participant	Interest/enjoyment	Perceived competence	Effort	Value/usefulness	Perceived choice	Felt pressure and tension	Force	Mean distance	Number of circles	Speed
1	4.2	4.75	5.5	5.6	5.5	4.5	9.08	0.0049	21	6.06
2	5.2	5.25	4	5.4	6	1.5	1.09	0.0054	24	8.22
3	3.6	3	7	2.8	7	2.75	2.94	0.0038	17	6.28
4	4.4	3.75	6	4.8	5	2.25	7.13	0.0061	17	7.96
5	4	7	3	7	5.5	2.5	2.26	0.0107	11	7.29
6	6.2	5	6	5.6	5.75	1	1.30	0.0012	13	5.75
7	4.6	4	4.5	4.6	5.75	3.5	5.48	0.0097	24	7.55
8	6.4	5.5	5.5	4.6	6.25	2.5	1.09	0.0034	14	6.48
9	4.4	5.75	4	5	7	1	0.82	0.0066	13	5.25
10	4.2	5	7	4	7	2.5	5.79	0.0042	19	8.19
11	3.4	5	6.25	4.6	4.5	3.25	1.67	0.0051	12	7.58
12	3.6	3.5	6.5	5.6	5.25	3.75	1.59	0.0032	17	7.85
13	5.6	5.5	4.5	5.6	5.5	2.5	7.08	0.0042	22	4.16
14	5	5	4	4.8	7	2.25	0.07	0.0208	21	5.59

Appendix D

Experiment data processing scripts

```
%% Import data from text file.
%% Initialize variables.
filename = './experiment data/task2_log.txt';
delimiter = ' ';
startRow = 2;
%% Open the text file.
fileID = fopen(filename,'r');
%% Read columns of data according to format string.
dataArray = textscan(fileID, formatSpec, 'Delimiter', delimiter,...
'MultipleDelimsAsOne', true, 'HeaderLines' ,startRow-1,...
'ReturnOnError', false);
%% Close the text file.
fclose(fileID);
%% Post processing for unimportable data.
%% Allocate imported array to column variable names
TIME = dataArray{:, 1};
Position1 = dataArray{:, 2};
Position2 = dataArray{:, 3};
Position3 = dataArray{:, 4};
ORIENTATION1 = dataArray{:, 5};
ORIENTATION2 = dataArray{:, 6};
ORIENTATION3 = dataArray{:, 7};
VELOCITY1 = dataArray{:, 8};
VELOCITY2 = dataArray{:, 9};
VELOCITY3 = dataArray{:, 10};
FORCE1 = dataArray{:, 14};
FORCE2 = dataArray{:, 15};
FORCE3 = dataArray{:, 16};
%% Cut off data before the drawing starts
[N1,locs] = findpeaks(Position1,'MinPeakDistance',...
800,'MinPeakHeight',.05);
FORCE2 = FORCE2(locs(1):end);
VELOCITY1 = VELOCITY1(locs(1):locs(end));
VELOCITY2 = VELOCITY2(locs(1):locs(end));
VELOCITY3 = VELOCITY3(locs(1):locs(end));
Position1 = Position1(locs(1):locs(end));
Position2 = Position2(locs(1):locs(end));
%% Clear temporary variables
```

```
clearvars filename delimiter startRow formatSpec...
 fileID dataArray ans;
%% Rounding up very small acount to zero
FORCE1(abs(FORCE1)<1e-3)=0;
FORCE2(abs(FORCE2)<1e-3)=0;
FORCE3(abs(FORCE3)<1e-3)=0;
TORQUE1(abs(TORQUE1)<1e-3)=0;
TORQUE2(abs(TORQUE2)<1e-3)=0;
TORQUE3(abs(TORQUE3)<1e-3)=0;

%% Getting performance values for the task

% Force
 F2_avg = mean(FORCE2);
 F2_sd = std(FORCE2);

% Momement accuracy, or mean distance from the origin circle
R = 0.1150; %radius of original circle in VR
 Raduis = sqrt(Position1.^2 + Position2.^2); %Distance ...
%from the origin circle
MD = mean(abs(Raduis - R));
 MD_sd = std(Raduis - R);

% Mean Velocity
 Velocity = sqrt(VELOCITY1.^2 + VELOCITY1.^2 + VELOCITY1.^2);
 V_avg = mean(Velocity);
 V_sd = std(Velocity);

% Number of circles drawn
 findpeaks(Position1,'MinPeakDistance',1400,'MinPeakHeight',.05);
N = numel(findpeaks(Position1,'MinPeakDistance',1400,...
 'MinPeakHeight',.05))
```

Appendix E

Certificate of ethics approval for the experiment

UNIVERSITY OF SASKATCHEWAN

Behavioural Research Ethics Board

Certificate of Approval

PRINCIPAL INVESTIGATOR
Chris Zhang

DEPARTMENT
Mechanical Engineering

BEH#
16-34

INSTITUTION(S) WHERE RESEARCH WILL BE CONDUCTED
University of Saskatchewan

STUDENT RESEARCHER(S)
Dmitriy Chesnakov

FUNDER(S)
UNFUNDED

TITLE
Patient Assistive System with Virtual Environment for Home-Based Rehabilitation

ORIGINAL REVIEW DATE	APPROVAL ON	APPROVAL OF:	EXPIRY DATE
09-Feb-2016	24-Feb-2016	Application for Behavioural Research Ethics Review Consent Form Recruitment Poster Intrinsic Motivation Inventory	23-Feb-2017

Full Board Meeting ☐ Date of Full Board Meeting:

Delegated Review ☒

CERTIFICATION

The University of Saskatchewan Behavioural Research Ethics Board has reviewed the above-named research project. The proposal was found to be acceptable on ethical grounds. The principal investigator has the responsibility for any other administrative or regulatory approvals that may pertain to this research project, and for ensuring that the authorized research is carried out according to the conditions outlined in the original protocol submitted for ethics review. This Certificate of Approval is valid for the above time period provided there is no change in experimental protocol or consent process or documents.

Any significant changes to your proposed method, or your consent and recruitment procedures should be reported to the Chair for Research Ethics Board consideration in advance of its implementation.

ONGOING REVIEW REQUIREMENTS

In order to receive annual renewal, a status report must be submitted to the REB Chair for Board consideration within one month prior to the current expiry date each year the study remains open, and upon study completion. Please refer to the following website for further instructions: *http://research.usask.ca/for-researchers/ethics/index.php*

Vivian Ramsden, Chair
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Behavioural Research Ethics Board

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