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Stratégie de contrôle haptique pour la réhabilitation du membre supérieur atteint de l'enfant hémiplégique

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Résumé

L'hémiplégie est une préoccupation mondiale pour la santé; C'est une partie de la Paralysie Cérébrale (PC) où une moitié verticale du corps est affectée. Cela peut avoir un impact significatif sur le niveau du handicap. Les déficiences motrices concernant les membres supérieurs, sont fréquentes chez les personnes hémiplégiques. Ces handicaps surviennent en raison de la perte de la communication entre le cerveau et le côté affecté du corps. Dans cette thèse, une stimulation visuelle, audio et tactile a été fournie aux patients pour une réhabilitation de ces membres affectés. La stratégie de contrôle haptique a été développée en utilisant des dispositifs haptiques, qui sont moins coûteux. Des scénarios de Réalité Virtuelle (RV) pour la thérapie haptique-RV, ont été développés afin de s'assurer la cohérence entre les flux visuels, audio et tactiles. Un dispositif haptique à 3 degrés de liberté (DDL) (Novint Falcon) que nous avons associé à un dispositif de rotation avec 1 DDL, que nous avons réalisé, a été utilisé pour appliquer cette stratégie de contrôle en mode-actif. La stratégie développée fournit des trajectoires libres dans des scènes RV et force feed-back dans d'autres directions, autrement dit modèle 'résistant aux besoins'.

Deux méthodes ont été développées pour évaluer les performances des membres supérieurs ciblés. La première méthode a été développée en utilisant une kinect^{TM} pour Windows. Cet appareil a été choisi et utilisé dans notre système en raison sa portabilité, de son espace de travail, de sa facilité d'utilisation et de son prix bas. Le but principal de cette méthode d'évaluation est de valider la relation entre les différents scénarios de RV et le type de mouvement effectué par les membres supérieurs affectés des enfants. La deuxième méthode d'évaluation a été développée en utilisant les données collectées du système lui-même afin de fournir aux thérapeutes la qualité et la quantité de performance à chaque type de mouvements. Cette méthode a été construite en utilisant l'approche de la logique floue.

Enfin, trois expériences ont été réalisées. Deux expériences de thérapie et une expérience d'évaluation. Les résultats illustrent la faisabilité de notre approche. Des perspectives ont été données en vue d'une validation au près d'un groupe d'enfant hémiplégique plus important dans l'avenir. Ce travail nécessite une préparation importante et une coordination sur le très long terme avec le corps médical et les familles des enfants atteints.

Summary

Hemiplegia is a global concern for health; it is a part of Cerebral Palsy (CP) where a vertical half of the body is affected. This can have a significant impact on the level of disability. Upper extremity motor impairments are common in hemiplegic patients. These disabilities occur because of the loss of communication between the brain and the affected side of the body. In this thesis, visual, audio and tactile stimulation was provided to patients for rehabilitation of these affected limbs. The haptic control strategy has been developed using haptic devices, which are less costly. Virtual Reality (VR) scenarios for haptic-VR therapy have been developed to ensure coherence between visual, audio and tactile flows. A 3-degree-of-freedom (DOF) haptic device (Novint Falcon) which we have associated with a rotation device with 1 DOF, which we have realized, has been used to apply this active-mode control strategy. The developed strategy provides free trajectories in VR scenes and forces feedback in other directions, 'resistant when needed' model.

Two methods have been developed to evaluate the performance of the targeted upper limbs. The first method was developed using a kinect^{TM} for Windows. This device was chosen and used in our system because of its portability, workspace, ease of use and low price. The main purpose of this evaluation method is to validate the relationship between the different VR scenarios and the type of movement performed by the affected upper limbs of children. The second evaluation method was developed using the collected data from the system itself in order to provide the therapists with the quality and the quantity of the performance for each type of movements. This method was constructed using the fuzzy logic approach.

Finally, three experiments were carried out. Two therapy experiments and one evaluation experiment. The results illustrate the feasibility of our approach. Prospects have been given for validation with a larger group of hemiplegic children in the future. This work requires considerable preparation and coordination over the very long term with the medical profession and the families of affected children.

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General Introduction

Hemiplegia is a global health concern; it is a part of Cerebral Palsy (CP) where one vertical half of the body is affected (the paralysis) see Fig.1. It causes a significant impact on the level of the disability. Motor impairments, which include upper limb disabilities, are common following hemiplegia. Postures patterns, that are already stored in motor memory, are used to perform tasks of Activities of Daily Living (ADL). The problem with those children is that, they have a lack of those stored postures patterns for their affected upper limbs, because they most likely use the unaffected side of the body to perform activities even for those which require the use of the affected side. They might use their affected side, but with different joint recruitment.

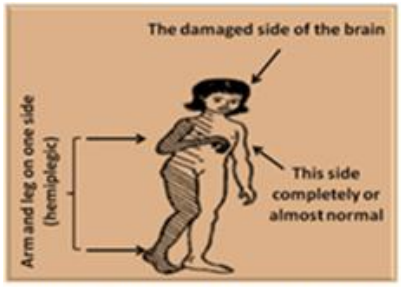


Figure 1: Child with hemiplegia [2]

The existing interventions strategies to encourage the activities with the affected upper limbs of children with hemiplegia use one of the following techniques: 1) Motivating Virtual Environments (VE) with defined challenges are used to increase the interest and the implication of patients (like in Fig.2). Those VE systems show significant improvements in upper limb functions, but require good motor functions to complete tasks, which may be an issue for children with hemiplegia. Because of that, children with hemiplegia usually have difficulties in joint coordination and motor functions. 2) Robotic devices are used to guide the affected limb and perform specific tasks as in Fig.3. Those robotic devices are used to carry out a mechanical interaction between patients and VE in pre-defined scenarios. However, these devices are mostly used in clinics and their cost is quite high compared to their limited functionalities. Also, there are almost not using at homes. 3) Haptics guidance to encourage movements' learning as can be seen in Fig.4. Those haptics seem to be a potential solution for upper limbs therapy; especially when VE is integrated.

Different aspects need to be taken into account when developing such systems like functionality, accuracy, portability, accessibility, work-space, safety, eases of use, and cost.



Figure 2: VR therapy [49]



Figure 3: Robotics therapy [62]



Figure 4: Haptic therapy [74]

Objectives

In this thesis, a therapy which combines haptic feed-back techniques and a serious game in a VE has been developed. The high level haptic controller modifies the visco-elastic behavior of the haptic device according to different virtual reality scenarios. This technique is new because it tries to constraint targeted joints of the affected upper limb to perform movements and guide it through privileged directions, while interactions with a VE are enabled. Virtual reality scenarios have been developed to stimulate joints of upper limbs to practice activities that are needed in ADLs. In this thesis, eleven virtual reality scenarios were developed and integrated with the haptic device to fulfill this need. Given the random demographic distribution of the population, which reduces the possibility of having a center of therapy near to all of those people, the application has been designed to be used at home with therapeutic-like exercises.

Performance metrics when using the developed haptic application is another important aspect which has been considered in this work. The therapists use well known assessment methods and/or devices which enable them to evaluate and validate the progress of the therapy. These methods require the presence of the therapists and specialists. In our proposed therapy, we have developed two evaluation methods. The first one uses the Kinect™ device because of its portability, work-space, ease of use, and low price. This assessment technique allows us to validate the relation between the different virtual reality scenarios and the type of movement performed by the affected upper limbs of children. The gathered data from the Kinect™ was used to adapt the scenarios and/ or change the position of the haptic device to make the scenario targets the movement correctly. The second evaluation method was developed by using the collected data from the system itself in order to provide the therapists with quantified and

qualified performance metrics for each programmed movement. In this method, different evaluation metrics have been considered such as the consumed time to perform a movement, the number of collisions, and the number of collected objects during each attempt. These data are used to calculate the degree of affiliation of that movement to each evaluation category. So, the results, which will be in percentage, explain to the therapists the quality and the quantity of the performance during the movements.

In this PhD thesis the following scientific questions have been taking into account when developing the strategy and answered:

- **How do we constrain the targeted joint(s) to recruit normally during a rehabilitation program, despite the complexity of the upper limb?**

  Develop a scenario or more for each joint to enable that joint to perform movements that are related to it, as well as develop scenarios which target more than one joint to stimulate the movements which are needed in activities of daily lives.

- **Does the resistive force improve the motor learning in children with hemiplegia?**

  Children with hemiplegia can move their affected upper limbs, but they perform those movements with different joint recruitment comparing with healthy subjects. So, the force feed-back (resistive force) help hemiplegic children relearning and reusing their affected upper limbs with normal joint recruitments.

- **Does the use of the possible different sensation helps with the recovery process?**

  The use of the visual and audio stimulation coming from the virtual reality scenarios along with the tactile stimulation coming from the haptic device in conjunction encourage the brain of the children with hemiplegia to transmit its instructions to the joints of the affected upper limbs in order to perform the assigned tasks.

- **Is the potential of the therapy fully used?**

  The work presented in this PhD thesis clearly point out the potential for the use of serious games combined with haptic devices for hemiplegic children. The full considerations, of all children who have used the system, were on the virtual scenarios and not on the real movement of the upper limb. In meanwhile, the haptic device is used to constrain the joints of those upper limbs to follow the pre-prepared trajectories. But the system was less useful for creating meaningful movements which stimulate movements of activities of daily living like wearing clothes.

- **How can the rehabilitation system give a reliable assessment to therapists on the basis of the collected data by the system itself?**

  Identify the collected data which are related to the quality of the movement and those related to the quantity of the movement in order to provide the therapists with reliable performance metrics.

- **What are the advantages of the system?**

  As a result of the configuration of our system, the following advantages are provided:

  1. Enables Home-Based rehabilitation
  2. Provides therapists with the history of the performance automatically
  3. Is not expensive

Thesis organization

The thesis is organized into 4 chapters which are summarized as follows:

Chapter 1

The first chapter briefly reviews different types of rehabilitation devices and techniques. First, VR based therapies which use of virtual world to enable children to navigate through digitally created environments and complete specially designed tasks often tailored to treat a specific ailment. Second, Robotic based therapies which include robotic devices tailored for assisting different sensorimotor functions such as arm, hand, and development of different schemes of producing therapeutic training; here, robots are used mainly as therapy aids instead of assistive devices. Finally, Haptic based therapies which implement resistive therapeutic training and combines haptics and VR applications. Results and discussions on the use of those systems are presented in order to establish the foundation for the understanding of our work.

Chapter 2

This chapter presents the methodology of using a haptic device in upper limb therapy, and describes the evaluation method that has been suggested for home-based therapy. Examples of devices and applications which are closest to our methodology are presented. Sensory control strategy used in the system is explained. Then, both assessment methods are introduced.

Chapter 3

The development of the system is explained in this chapter. The operational workflow of the system is illustrated. Then, the control strategy as well as angles estimation are explained. The different scenarios and their corresponding mathematic equations are developed. Finally, the developments of the two assessment methods are detailed.

Chapter 4

This chapter illustrates the protocol and the experiments that have been conducted using the developed system. Conclusions, discussions and future work are presented for each experiment. Those experiments explain and criticize the functionality, usability, and repeatability of the system.

Scientific productions

International refereed journals:

- Mohammed Elsaeh, Philippe Pudlo, Mohamed Djemai, Mohamed Bouri, Andre Thevenon and Isabelle Heymann (2017) "Strategie de controle haptique pour la rehabilitation du member superieur atteint de l'enfant hemiplegique", *Actualites en Medecine Physique et de Readaptation*, jan-fev-mars 2017, pp. 28-29

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International conferences:

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Chapter 1. Introduction and State Of the Art

This chapter presents the definition of the hemiplegia, different types of therapy systems, the need for upper limb rehabilitation for hemiplegic children, and the research objectives, challenges, questions, scope, and organization of the thesis.

1.1 Problem statement

1.1.1 The burden of hemiplegia with children

Hemiplegia appears in about one third of cerebral palsy children (CP), and cerebral palsy prevalence in Europe was estimated between 2 and 3 in 1000 live births. [1]. Cerebral palsy is usually accompanied with motor dysfunction and sensation deficits at lesion location [2]. As a result, cerebral palsy affects multi-joint coordination in both upper and lower extremities: it may affect activities of daily lives (ADLs) or decrease critical child activities like playing [3, 4]. Various ability weaknesses have been reported as consequences of CP by different authors [5, 6]. In fact, the causes of hemiplegia in children can be attributed to a perinatal period stroke, which develops between 28 weeks of gestation and 1 month of age, or later on between 30 days and 18 years of age as a result of childhood stroke [7]. Cognitive and movement discords are usually shown with children with hemiplegia [8]. Around half of hemiplegic children suffer from their impaired upper extremity functions [9]. Furthermore, children with hemiplegia have: upper limb spasticity, muscle weakness, problems with motor control, and impaired sensory mechanisms [10, 11]. These impairments prevent those children from performing ADLs. Many hours are spent on hemiplegic rehabilitation to improve their function, decrease impairment, and increase the independency. A major part of this rehabilitation focuses on motor function; because of that 95% of hemiplegics have sensory and motor deficits that result in serious disabilities [12].

The severity of the disability intensifies whenever the patient's age increased [13], so the appropriate age to start the therapy is limited to between 4-10 years old. But there are several elements that might reduce the access to hemiplegic rehabilitation. These possibly consist of a not equal and fair distribution of resources, insufficient health insurance coverage, lack of sufficient time for parents and therapists, or parent’s unreliability of the potential gain of rehabilitation. Not equal and fair distribution of resources might be due to locations especially

for those who live in the suburban or remote locations. Experts may be also limited due to a scarcity of qualified hemiplegic therapists. These lead to limit hemiplegic's therapy in terms of duration and frequency.

1.1.2 Rehabilitation therapy

Rehabilitation therapy showed a significant improvement of upper limb (UL) functions. For example, task-oriented arm training has significantly improved functional activities of the affected upper limb and reduced its dysfunction [14]. Caregivers reported significant increase in frequency and quality of movement of limb use for children with hemiplegia [15]. Actually, various occupational therapies have shown wide improvements in functions of affected ULs [16, 17]. Different interventions (e.g., helping upper limbs to make correct movements such as reach-to-touch) are carried out by therapists in hospitals or their clinics. Now therapy usually consists in repeating precise movements and the schedule of therapists may interfere with intensive rehabilitation program with patients. High cost of this type of therapy limits the number of hemiplegic children who benefit from it and decreases the potential of success. The repetitive aspect of physical therapy exercise limits the overall period of time. So proposing exercises with increased interest and challenge may attract the patient's attention, and increase the consumed time in therapy.

Virtual reality (VR) meets these requirements, especially for children. Virtual reality technology has been recently used to accomplish intensive therapy practices with children. Individual treatments can be achieved by applying motivating environment of VR, and increase the intensity of the therapy [18]. The use of VR with children increased play-participation, and encouraged the need to practice more [19, 20]. Significant improvements in postures and movements could be gained from intensive training when using VR [21]. But VR systems normally require good motor functions in order to complete the demanding tasks, and that may be an issue for hemiplegic children [22].

Specific robotic systems can be used with virtual environments to ease the interaction with VR systems [23]. Robotic therapies with VR on UL movements and functions have been tested with hemiplegic children with cerebral palsy, and these therapies resulted in improvements in UL quality and motor performance [24, 25, 26, 27].

1.1.3 Rehabilitation haptics – possible solution?

Robotic devices are usually used in therapy to maximize the number of repetition, patients' attention, and needed effort [28]. In that field, robotic devices were used as haptic interfaces to perform activities in virtual reality environment, with a high-level control strategy called haptic stimulation control strategy [29]. In addition, continuation of therapy increases the potential of success [30], and home-based therapy is the most successful therapy in terms of continuation [31]. But in order to produce a successful therapy, an acceptable device for rehabilitation in terms of precision (resolution, DOF...) and with a reasonable cost needs to be used.

Clinical acceptance of a haptic rehabilitation device may also be related to haptic capabilities and features such as exact repetitive movements, system able resistance, objective evaluation, and movement sensing capabilities. These categories would theoretically increase clinical acceptance. Although haptics will likely never replace therapists, they may be useful in aiding therapists or extending rehabilitation to remote locations or at homes.

1.1.4 Assessment

The efficiency of a rehabilitation process is mainly based on the results which normally derived from impairment and functional assessment. The therapists use these results to build their decisions about the upcoming treatment plan, as well as judging the usability of a certain treatment. Those decisions mostly depend on the improvement level that has been noticed by using different assessment methods. In fact, there are wide methods of assessment such as Performance Measures which contains of (Action Research Arm Test (ARAT), Box and Block Test (BB), Chedoke Arm and Hand Activity Inventory (CAHAI), Jebsen-Taylor Hand Function Test, Nine-Hole Peg Test, and Wolf Motor Function Test (WMFT)), and Self-Rep ort Measures which contains of (Motor Activity Log (MAL) and Stroke Impact Scale) [32]. A performance measure is a method in which the therapists' rate and/ or time a certain set of upper limb (UL) actions which normally perform by patients. Whereas, self-rep ort measure is a method in which, patients need to answer a set of questions which pre-prepared by the therapists. These methods are based on the experience of the therapists, and require the presence of those therapists to make the decision. But those therapists have indicated that they prefer to have a core set of measurement instruments which require less user intervention, instruction, and interpretation

[33]. The routine of the assessment of impairments and performance improvement are critical for the therapists for decision making [34, 35]. There are many rehabilitation processes, which have used haptic devices as based equipment for the rehab [36, 37, 38], however, most of those devices are used to help patients to complete the desired tasks. Despite the fact that these systems have illustrated promising results for UL rehabilitation, most of those systems are unable to determine the level of difficulty and the level of enhancement, which the patients have achieved, of the rehab exercise; instead the therapists use the other assessments methods.

Continuation of the rehabilitation process increases the potential of success [39], home-based rehabilitation is considered as the most successful type of rehabilitation in terms of continuation. To ensure that this type of rehabilitation will be available for the majority of patients, the price element needs to be considered. However, performance or self-report measures, which assess the progression of patients, are mostly performed by the therapists regularly at a certain amount of time. These assessments provide the therapist with the meanwhile range of motion, not the overall progression of the patients during all sessions of the therapy. This makes the judgment of the outcome of the therapy such hard work.

Estimating the success of a therapy usually requires assessing the joints' range of motion (ROM). Additionally, there are other methods available to evaluate the level of motor function such as occupational therapy assessment tools (with manual muscle testing), Brunnstrom method, stroke impairment assessment set, or use measurement devices, but these assessments are largely based on therapist's or expert's observations. Another approach is to measure, analyze, and evaluate the patient's performance in objective and quantitative terms. The result here depends on the quality of therapy and gives the possibility to notice the changes in ROMs of the ULs of children with hemiplegia.

1.2 Objectives

The main objective of this research is to develop a portable rehabilitation system aimed at:

- Constrain the target upper limb of a hemiplegic child to perform oriented movements while avoiding abnormal joint recruitment.

- Allow the therapist to evaluate systematically and quickly the child performance during the rehabilitation program, and provide them with the history of patients' performance.

To meet these stated objectives, a program of work has been organized for each stage of each objective separately, and an appropriate program language has been chosen for each developing stage as can be seen in chapter 2.

1.3 Scientific research questions

This research will attempt to answer the following questions:

- How do we constrain the targeted joint(s) to recruit normally during a rehabilitation program, despite the complexity of the upper limb?
- How can we develop a VR scenario(s) for each type of movement?
- How therapists can chose the appropriate rehabilitation scenario for a particular patient based on the patient needs?
- How can the rehabilitation system give a reliable assessment to therapists on the basis of data collected by the system itself?

1.4 Challenges

- Upper limb rehabilitation is a complicated process regarding to the complex chain setup of the arm, forearm, and hand during movements.
- The functional interactions between the affected upper limb of patients and the rehabilitation device are critical for any rehabilitation program, especially when targeting particular joints.
- Performance of an upper limb depends on various categories, especially in functional assessment of performance.

1.5 User centered design

In order to develop a future home-based rehabilitation system (HBRS), it is essential to obtain an understanding of what kind of movements do therapists desire?, what their patients would use?, and why the currently available systems are not commonly used. Developing a usable HBRS must address the needs of therapists as well as the abilities of patients; therefore, end users must be considered. User centered design is a technique that concentrates on the users' needs, wants, and abilities, of using a system [40]. User-centered design can be identified as a multi-step process to solve a problem. This system is not only requiring developers to analyze and imagine how patients most likely would use that system, but also test and enhance their suggestions regarding to patients' behaviors to minimize the overall time of the development process [41].

1.6 Background

Various therapy interventions for children with hemiplegia had been performed. Haptic systems for upper-limb rehabilitation therapy had been also developed by researchers and some of them have been later on evaluated by clinicians. While the overall discussions of those researches were promising, various aspects are yet need to be considered. The upper-limb therapy interventions described below do not include all the upper-limb therapies' types in the literature. But they give the general idea about the usable upper limb therapies devices nowadays.

In order to better understand the advantages and relatively the disadvantages of current upper limb rehabilitation systems, a literature search was done mainly on Google Scholar, IEEE, and Medline. The terms of the search were limited to children with hemiplegia, and cerebrovascular accident. The search for solutions was then pointed to articles concerning the following categories: upper limb, arm, or upper extremity. This search was finally again limited to articles which contain devices with end-effector for upper limb rehabilitation. Devices that have been clinically tested and used were choosing in this search. According to this search, articles which include haptic devices and robot devices that work based on haptic feedback and virtual reality were deeply reviewed.

1.6.1 Virtual reality therapy

Various occupational therapies have shown wide improvements in functions of affected ULs [42, 43]. Different interventions (e.g., helping upper limbs to make correct movements such as reach-to touch) are carried out by therapists in hospitals or their clinics. This therapy usually consists in repeating precise movements, but the schedule of therapists may interfere with intensive rehabilitation program with patients. High cost of this type of therapy also limits the number of hemiplegic children who benefit from it, and this decreases the potential of success.

To achieve the repetitive aspect of physical therapy exercise, it is important to propose exercises with increased interest and challenge which may attract the patient‘s attention, and increase the consumed time in therapy. Virtual reality meets these requirements, especially for children. Virtual Reality (VR) technology has been recently used to accomplish intensive therapy practices with children. Individual treatments can be achieved by applying motivating environment of VR, and increase the intensity of the therapy [44]. The use of VR with children increased play-participation, and encouraged the need to practice more [45, 46]. Significant improvements in postures and movements could be gained from intensive training when using VR [47]. The VR systems described below are not the only systems that have been used in the rehabilitation therapies, but they give the wide use of this technology in rehabilitation.

1.6.1.1 “Orbosity” VR application

1.6.1.1.1 Description

The 1996 patented Mandala1 Gesture Xtreme (GX) technology developed by Vivid Group Inc from Toronto was used and applied on three CP children. This system uses a video camera as a capturing and tracking device to put the user inside VR experiences. With the GX technology, the user is at the centre of the action, inside a computer world. Users do not have to wear Head Mounted Displays (HMD), Data Gloves, or other devices that bound them to the computer. In fact, users do not have to wear, touch, or hold anything, leaving them free to actively move about in the real world while they use their entire body to interact with the computer [48]. Through the use of the system’s `video gesture’ capability, the movements (e.g. reaching, bending) trigger

visible or invisible icons to score points, and manipulate animations (e.g. playing a virtual drum kit, playing volleyball) as can be seen in figure [1.1].

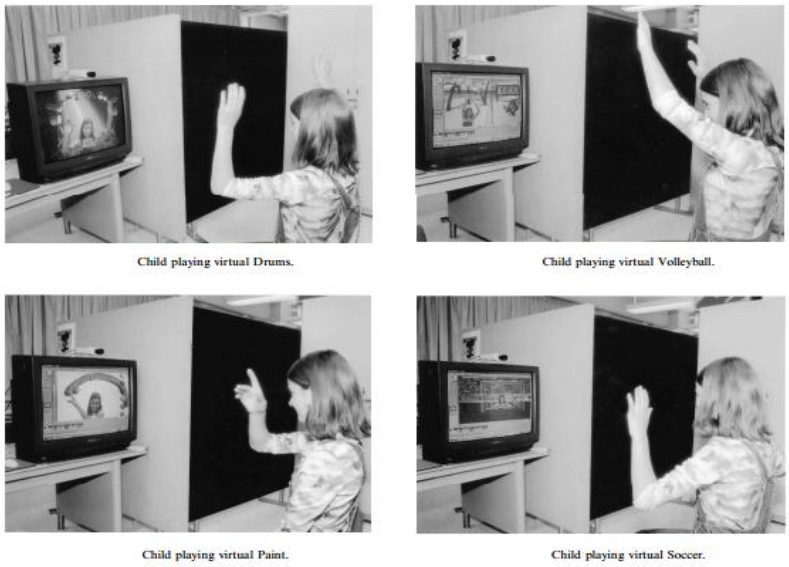


Figure [1.1]: different upper body movements using Orbosity application

1.6.1.1.2 Conclusion

This pilot study suggests that a virtual play environment provides children with an opportunity to interact with virtual play activities that are enjoyable and non-threatening. This opportunity allows for increased play engagement and an opportunity to exercise control over their actions. This overall experience enables the development of a sense of mastery or greater self-efficacy feelings.

1.6.1.2 Bird–ball, conveyor, soccer VR applications

1.6.1.2.1 Description

Three virtual environments were interfaced with the bird–ball, conveyor, and soccer exercise games. This system was performed by 8-year-old male who has hemiparetic cerebral palsy. These tasks were designed to improve the development of different motor skills, with each game programmed to exercise one of the aspects of the affected upper extremity movement with emphasis on intensive, repetitive range of motion, mobility, and strengthening in the shoulder,

elbow, and wrist movement. For example, the bird–ball exercise simulates functional reaching and touching motor tasks [49]. As can be seen in Fig [1.2]



Figure [1.2]: (a) Virtual reality experimental set-up; (b) bird–ball; (c) conveyor; (d) soccer.

1.6.1.2.2 Conclusion

VR therapy produced measurable neuroplastic changes, and the changes seem to associate closely with enhancement of age-appropriate motor skills in the affected limb. The results showed that the child was able to perform spontaneous reaching, self-feeding, and dressing, which were not possible before the intervention. Further development may reduce the cost of VR therapy. This study invites further investigations to compare whether the effectiveness and related neuroplastic changes after VR therapy are unique or comparable with those of other neurorehabilitations.

1.6.1.3 Maze and Koos Block Design VR application

1.6.1.3.1 Description

The aim for the child in VE version of this task was to move through a maze to reach a tree [50]. The VE task used a version of the maze, the child's 'point of view' moving within the virtual maze via mouse operation as can be seen in Fig [1.3. a]. The virtual viewpoint moved

only in the horizontal plane, just below the upper edge of the maze walls. The target tree, which was lower than the walls, could be seen only from short distance, when not hidden by the walls.

For the Koos Block Design Test in Fig [1.3. b], on the right hand side of the screen the child saw a test figure constructed of three types of square wholly white, wholly red, or divided diagonally into white and red halves. The same squares were represented at the bottom of the left half of the screen. The aim of the task was to move these squares to the top left corner of the screen and assemble them to create the test figure shown on the right.

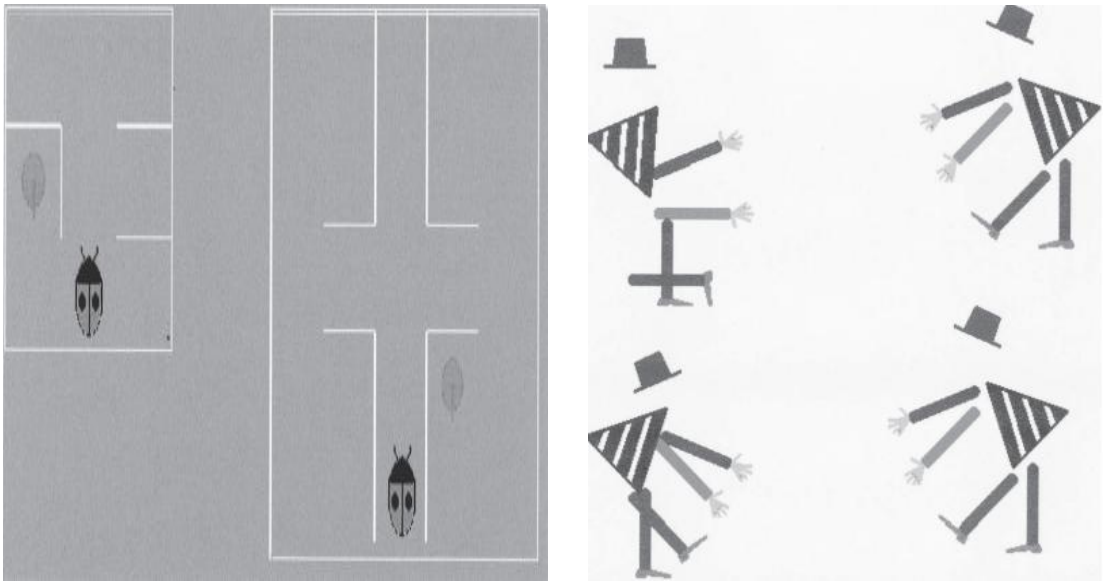


Figure [1.3]: a) Maze application; b) Koos Block Design test

1.6.1.3.2 Conclusion

The scores of the measures used for pre- and post training assessment were normalized, based on the distributions of pretraining scores. The normalized scores were averaged separately for pre- and post training assessments and these scores were used in the analysis. The scores were subjected to two (time/test sessions). This assessment shows a significant main effect for time (F(1.19) = 5.0, p 5 0.05). But the majority of the children who have very poor initial skills did not benefit from the treatment. This observation was also consistent with teachers' subjective estimations of quality of lessons with these children.

1.6.1.4 The volleyball VR application

1.6.1.4.1 Description

Johnny, 10-year-old boy with spastic quadriplegic cerebral palsy who sat in a manual wheelchair was participated in this study [51]. He remained in his wheelchair for the duration of the VR session. The activities chosen for the VR environment were sport activities like volleyball as in Fig [1.4].

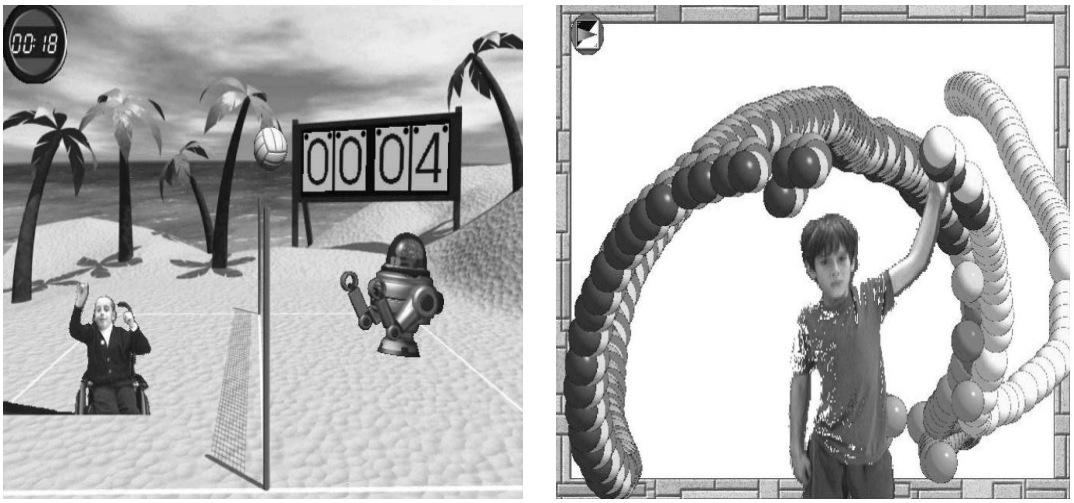


Figure [1.4]: The volleyball VR application

1.6.1.4.2 Conclusion

Johnny had some difficulties in managing a ball in the real physical environments. He was unable to retrieve a ball or run and hit a ball in most instances. Therefore, he remained usually an observer to games of baseball, soccer and other ball games. The VR applications that were used with Johnny allowed him to see himself inside the specialized soccer or volleyball VE. The authors concluded that, in order to engage in play, there must be a fit between the child's abilities and the challenges of the activity.

But VR systems normally require good motor functions in order to complete the demanding tasks, and that may be an issue for hemiplegic children [52].

1.6.2 Robotic therapy

Specific robotic systems can be used with virtual environments to ease the interaction with VR systems [53]. Robotic therapies with VR on UL movements and functions have been tested with hemiplegic children with cerebral palsy, and these therapies resulted in improvements in UL quality and motor performance [54, 55, 56, 57]. Robotic devices are usually used in therapy to maximize the number of repetition, patients‘attention and needed effort [58]. In that field, robotic devices were used as haptic interfaces to perform activities in virtual reality environment, with a high-level control strategy called haptic stimulation control strategy [59].

1.6.2.1 T-WREX Robot therapy

1.6.2.1.1 Description

Wilmington Robotic Exoskeleton (T-WREX) is a five DOFs robot which provide passive arm movement in order to be used by those who have critical arm weakness. This robot gives the opportunity to perform intensive arm movement training, and has sensors for each joint to evaluate arm positions [60]. Furthermore, it can be integrated with VE to enable users to interact with virtual games Fig [1.5].



Figure [1.5]: T-WREX Robot

1.6.2.1.2 Conclusion

For the 23 subjects who had performed the experiment sessions. They have benefited from the use of this robot, especially in the time needed to complete tasks. But by comparing the experiment group with the control group, they have found that, no significant differences were found. Only for the assessment that has been done based on fugl-meyer clinical assessment, some important differences have been noticed for the experiment group.

1.6.2.2 Wrist-Robot therapy

1.6.2.2.1 Description

The two DOFs therapy robot is an end-effector type of robot. The user's forearm places on a support platform which linked to the end-effector. This allows users to move in transverse plane by using their shoulder and elbow joints to perform activities which are presented in VE [61]. This robot has been enhanced later on to support wrist movement and has grasp sensors [62, 63]. This robot has three modes: resisted mode in which the robot provides a certain resistance in the opposite direction of the user movement, active mode in which the robot provides movements in the same direction of the user's movement, and passive-mode in which the robot does the movement and the user's arm is passively guided.

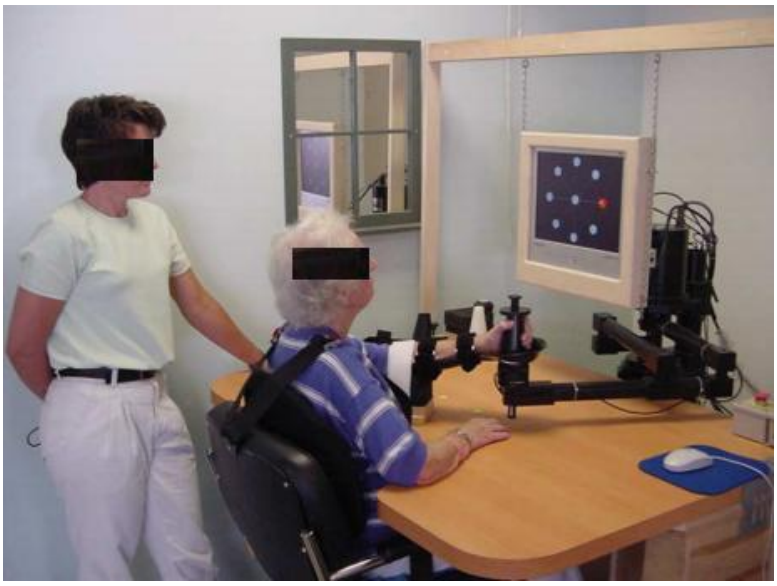


Figure [1.6]: Wrist-Robot

1.6.2.2.2 Conclusion

The use of this robot has shown a statistically significant improvement in impairment at the shoulder and elbow which were the targeted joints in the exercise. But no changes have been noticed at the wrist and fingers.

1.6.2.3 iPAM Robot therapy

1.6.2.3.1 Description

Intelligent Pneumatic Arm Movement (iPAM) is a therapy robot which has two pneumatically actuated arms, and each actuated has three DOFs [64]. This robot is a gravity compensated, so the upper limb is placed in pressure cuff as can be seen in Fig [1.7]. This robot allows the interaction with VEs, so by using this system, users can perform activities in VR environments.

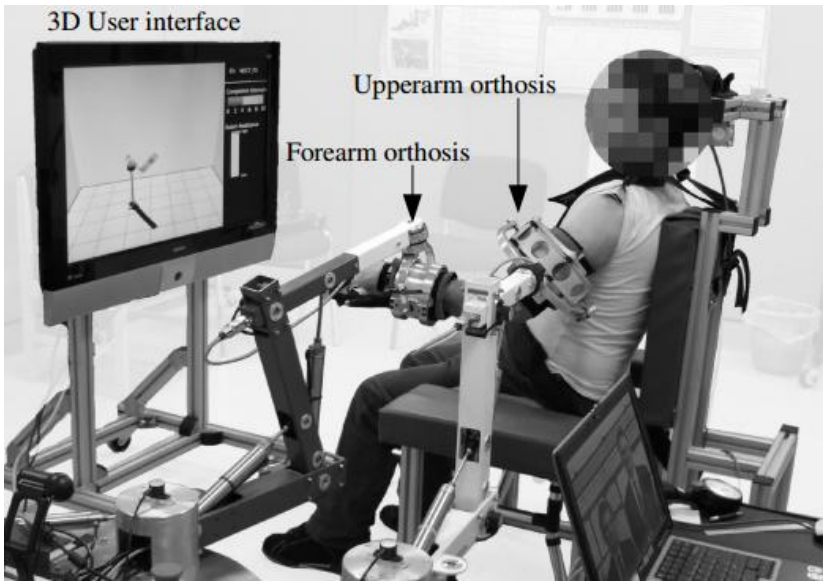


Figure [1.7]: iPAM Robot

1.6.2.3.2 Conclusion

Six hemiparetic subjects have performed different reach movements by using iPAM robot with VE, and they have concluded that the movements were not difficult. Improvements in the impairment were not measured, because this study has used qualitative date to assess the performance of the subjects.

1.6.2.4 REHAROB Robot therapy

1.6.2.4.1 Description

The affected arm is placed in the REHAROB robot in order to perform passive physiotherapy (including the movements of the shoulder and the elbow) [65]. This robot consists of two robots which can be control by the physiotherapist (PT) as can be seen in Fig [1.8]. First, the PT "teaches in" the robot some exercises. "Teaching in" means that the PT performs some movements, and then the robot apply these movements on the affected arm of the patient. The PT can change the type, amplitude, and the speed of the movement.



Figure [1.8]: REHAROB Robot

1.6.2.4.2 Conclusion

The subjects (four healthy and eight hemiparetic), who have participated and used this robot, have shown an increase in functionality and a decrease in spasticity. This robot performs the exercises according to the directions of the PT.

1.6.2.5 Braccio di Ferro Haptic Robot therapy

1.6.2.5.1 Description

Haptic end-effector system called (Braccio di Ferro) is two DOFs with a large space, and it can generate big forces [66]. This robot allows patients to perform movements in horizontal plane as can be seen in Fig [1.9]. By using this robot, patients can perform VE activities which present to them in the screen.

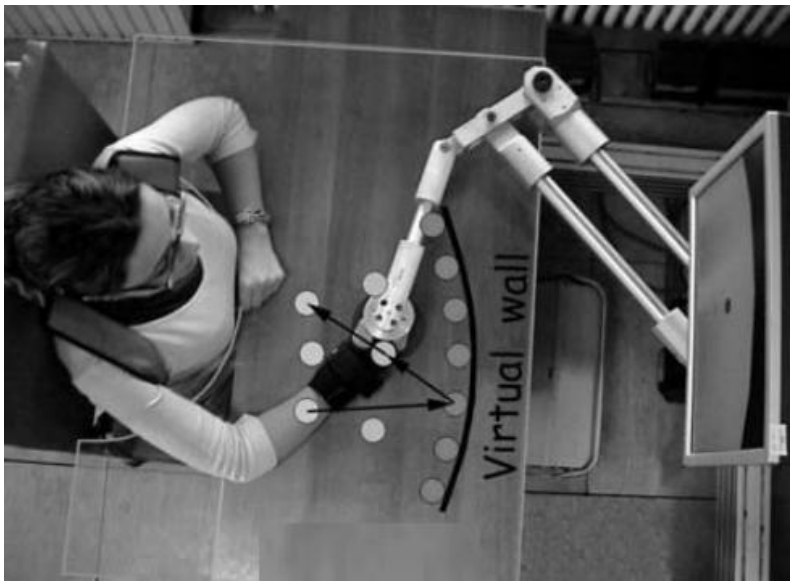


Figure [1.9]: Braccio di Ferro Haptic Robot

1.6.2.5.2 Conclusion

The subjects who have participated and using this robot in a pilot study have shown a decrease in the impairment scores. Also, a decrease in the level of assistance has been noticed.

To conclude, continuation of therapy increases the potential of success [67], and home-based therapy is the most successful therapy in terms of continuation [68]. But the above VR, and robot therapies require the presence of therapists and/ or experience people in order to enable patients to perform those therapy processes. Furthermore, the cost of some of those systems, especially robot systems, is high for home-based therapy. In order to produce a successful home-based therapy, which enables patients to have the maximum number of repetition, an acceptable device for rehabilitation which needs to include good precisions (resolution, DOF...) and a reasonable cost needs to be chosen.

1.6.3 Haptic therapy

Haptic interaction is considered as an important element on the motor learning and development especially for children [69]. Infants until 5 months use their hands to understand and perceive the physical objects around them [70]. Also, haptic sense is essential for the sensory

integration that is needed for the sensory information use in daily life [71]. This haptic sense is the only sense which allows people to interact physically with the world [72]. So, it is important to investigate the role that the haptic interaction applies in motor learning, and find out which kind of haptic interaction can enhance learning and for which motor task?

1.6.3.1 WAM Arm haptic device

1.6.3.1.1 Description

Sixty participants with average age 21.9 were participated in this case study [73]. Each participant has to grasp the end-effector of the WAM Arm and track a green dot that was displayed on the visual screen as a circle of 0.2 cm radius and moved along a predefined 2D trajectory as can be seen in Fig [1.10].



Figure [1.10]: WAM Arm haptic device

1.6.3.1.2 Conclusion

It has been found that the more haptic guidance is provided the tracking accuracy is getting better. And the results suggest high potentials for haptic disturbance to be a general strategy for expediting the motor learning process.

1.6.3.2 The Phantom® Omni® haptic device

1.6.3.2.1 Description

Two children at the age of 7, diagnosed with dystonia and dyskinesia, respectively were used the phantom omni haptic device to perform the writing tasks that were displayed to them in VE [74]. The virtual hand writing training system was built to enable the subjects to use the handler of the haptic to practice the writing. They have used the haptic device which was put on the table as can be seen in Fig [1.11].



Figure [1.11]: The Phantom ®Omni® haptic device

1.6.3.2.2 Conclusion

The writing time and the path length have been reduced through repeated practices by the two subjects. Also, they show a better sense of handwriting. The authors have also concluded that the use of haptic feedback appears to be a useful approach to improve CP children's handwriting skills.

1.6.3.3 Haptic Guidance

1.6.3.3.1 Description

Three training methods have been used to compare the relation between the feedback and learning as can be seen from Fig [1.12]. The methods are visual training (V), haptic guidance (H), and haptic along with vision (HV) [75]. The user observes the end-effector which moves through the ideal motion in the screen. And then he holds the end-effector by their hand and he will be guided by the haptic without screen. Finally, he observes the motion while being guided by the haptic device.



Figure [1.12]: Visual (left), haptic (center), and haptic + visual (right) feedback

1.6.3.3.2 Conclusion

The 36 right handed participants have shown statically performance improvement. The measurement of position accuracy was in its high level with (VH) training. The findings from this study indicate that haptic guidance can be benefit performance. And most importantly, haptic guidance might provide us with benefits similar to physical practice.

1.7 Discussion

There are many systems for upper limb therapy. In those systems, there are many categories that need to be considered in order to use those systems such as the usability, the functionality, the cost constraints, the safety, the portability, the continuity (the in-home use possibility) and the inclusiveness in terms of the performance evaluation.

The previous review illustrates that there are many upper limb therapy systems which have been already developed. The VR systems show significant upper limb functional improvements for those who can already recruit their joints to perform good motor functions. These systems can be performed at homes and they are not expensive. But, VR systems require good motor functions to complete tasks, and children with hemiplegia usually have difficulties in terms of joint coordination and motor functions which may be an issue for children with hemiplegia [52].

Robotic therapies are used to facilitate the interaction between patients and VR scenarios [53]. These robotics systems have been used with cerebral palsy children and showed improvements in upper limb functions [53-57]. However, there are few commercially available robotics and few of them are used in clinics [76] due to the high cost and limited functionality. Also, there are almost not using at homes [77].

Haptic therapy could be viewed as a solution for upper limbs therapy, especially when it integrates with VR, in order to provide visual, audio, and tactile feedback. Functionality is an important category in upper limb therapy systems. By using haptics with VR, many different functions, that stimulate ADLs, can be developed for upper limbs. Furthermore, those systems can be created to be established as tele-rehabilitation because of the following features: portability, accessibility as tele-rehabilitation, relatively small work-space, safety, eases of use, and with really low cost.

1.8 Scope of research

The main focus of this research is to develop a haptic control strategy for upper limb rehabilitation of children with hemiplegia that ensure the safety and usability, and evaluate the performance of the upper limbs systematically in cadre of tele-rehabilitation.

1.9 Organization of thesis

Chapter 2 explains the methodology of using a haptic device in upper limb therapy, and describes the evaluation method that has been suggested for home-based therapy. Chapter 3 gives the development process of the system. Chapter 4 illustrates the protocol and the experiments that have been done with the system and its results along with conclusions, and discusses future works.

1.10 Conclusion

In this chapter, hemiplegia is defined; and different rehabilitation therapies for this type of illness are described. Also, the objectives of this thesis are determined. Furthermore, the state of the art related to this work is described. In fact, the following therapy systems are investigated: VR based therapy, robotic based therapy and haptic based therapy. A discussion of those systems is done to determine the strong points and weak points for those systems; and then specify the proposed therapy system based on these points. Finally, scope of the research and organization of the thesis are illustrated.

Chapter 2: The proposed Haptic-Virtual reality game therapy for upper limbs of children with hemiplegia

In this chapter the proposed Haptic-Virtual reality game therapy for affected upper limbs of children with hemiplegia is presented. It consists of two main modules (VR, and haptic) as shown in Fig. 2.1. This system is described as following:

- Virtual reality multimodal scenarios which provide multi-scenarios depend on the desire upper limb movement
- The haptic device which enables the targeted children to interact with VR scenarios
- Algorithms which consist of: An algorithm which provides the visual, audio, and tactile feed-back in conjunction. And another algorithm which provides an evaluation decision, about the performance of the upper limbs, to the therapists.

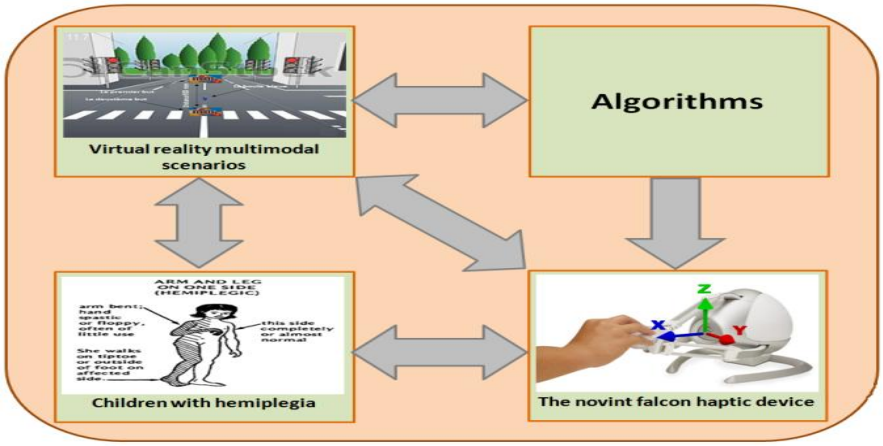


Figure 2.1: Functional schema of the proposed haptic-VR system

2.1 Devices and applications

There are different types of therapy that can be given to the patients in order to decrease the level of disorders of the affected upper limbs such as conventional therapy, robot-aided therapy (active, and passive), sensory integration therapy, constraint-induced movement therapy (CIMT), and modify constraint-induced movement therapy. All of these types have the potential to be used as a process of upper limb therapy. In this project, the aim is to develop a strategy for haptic control for upper limb rehabilitation, so the suitable types among the existing types are the robot-aided therapy (passive), or the sensory integration therapy. These two types of therapy provide the possibility of using the needed haptic feed-back to be used in the strategy. Types of

assistance and resistive in rehabilitation have been determined [78]. Table 2.1 illustrates the different types of existing therapies.

Term	Description
Active device	A device able to move limbs. Under such condition, this device requires active actuators which may increase the weight. It may also apply to subjects completely unable to move their limb.
Passive device	A device unable to move limbs, but may resist the movement when exerted in the wrong direction. This type of device may only be used for rehabilitation of subjects able to move their limbs. It is usually lighter than active device since it possesses no actuators other than brakes.
Haptic device	A device that interfaces with the user through the sense of touch. In most cases it provides some amount of resistive force, often also some other sensation (e.g. vibration). It is sometimes also able to generate specific movements. However, the force it generates is usually small. Haptic devices are commonly used in rehabilitation settings with virtual environments.
Coaching device	A device that neither assists nor resists movement. However, it is able to track the movement and provide feedback related to the performance of the subject. As haptic devices, coaching devices are also commonly used in rehabilitation settings with virtual environments.
Active exercise	An exercise in which subjects actively move their limb, although some assistance of the device may be provided. Such type of the exercise may be performed using any of the above listed types of devices.
Passive exercise	An exercise in which the subject remains passive, while a device moves the limb. This type of exercise requires an active device. Continuous passive motion (CPM) training is an example of passive exercise with active devices.

Table 2.1: The terms concerning types of assistance and resistive therapy

Children with hemiplegia can move their upper limbs but with different joints recruitment compared with healthy ones [79], which leads to avoid the first type of devices (active devices), because this type of devices can be used with subjects who cannot move their UE. Furthermore, the strategy here is to constrain the upper extremity to apply normal joint recruitments and to correct its trajectory during the movements, so devices that use the tactile feedback might be the best in order to achieve this objective. So, haptic devices seem to be the most appropriate type of devices that have been illustrated in table 2.1. Hence a compatible exercise of the possible exercises available needs to be chosen in order to work with the device, active exercise which require active action or movement from the subject to be applied to the haptic device is the suitable exercise.

2.1.1 Control strategy:

The available control strategies for the rehabilitation process have been determined [78]. These strategies are listed in table 2.2 along with its descriptions.

Term	Description
High-level control strategy A control strategy with control algorithms explicitly designed to induce motor plasticity.	
Assistive control	A "high-level" control strategy in which a device provides the physical assistance to aid the patient in accomplishing an intended movement.
Challenge-based control	A "high-level" control strategy in which a device challenges the patient to accomplish an intended movement.
Haptic stimulation	A "high-level" control strategy in which a robotic device is used as a haptic interface to perform activities in virtual reality environment.

Couching control	A “high-level” control strategy in which a robotic device neither physically assists nor resists the movement of the subject. It only quantifies and provides feedback (visual, acoustic or other) concerning the performance of the subject during exercise.
Low-level control strategy A control strategy considered in the implementation of the “high-level” control strategy in a device by appropriate control of the force, position, impedance or admittance.	
Admittance control	A “low-level” control strategy in which the force exerted by the user is measured, and the device generates the corresponding displacement.
Impedance control	A “low-level” control strategy in which the motion of the limb is measured and the robot provides the corresponding force feedback.

Table 2.2: The different control strategies of robots for rehab process

The most important terminology of control strategies are introduced in table 2.2. Each strategy might be used with one or many types of robots depend on its mechanism. The proposed device for rehabilitation is haptic device. Furthermore, in order to provide children with hemiplegia with the possible sensation which are visual, audio and tactile feedback, the system is built to respect the following concept: the haptic device that is responsible to provide the tactile feed-back needs to be controlled using VR scenarios which will provide the visual and audio feed-back. According to these requirements, haptic stimulation control strategy seems to be the option that will meet these requirements. Also haptic stimulation strategies enable the use of haptic devices, which has been chosen above, to give tactile sensation according to virtual reality objects. Training of the most popular ADLs such as reach-out, or reach-up can be easily supported by using this easy and quick set-up strategy. By using VR, alternate tasks in many environments could be provided and attention of the subjects would be attracted.

2.1.2 Haptic Device:

A haptic device is a device which simulates various aspects of touch, and provides a force feed-back to the users. This is usually a 3 dimensional system based on the x, y and z axes. So a device which has a 3 DOF is appropriate to represent movements in such systems, but there are other specifications need to be investigated in order to determine which device can fit the needs based on the requirements of the system. So a comparison between available haptic devices shown in table 2.3 would leads to the answer.

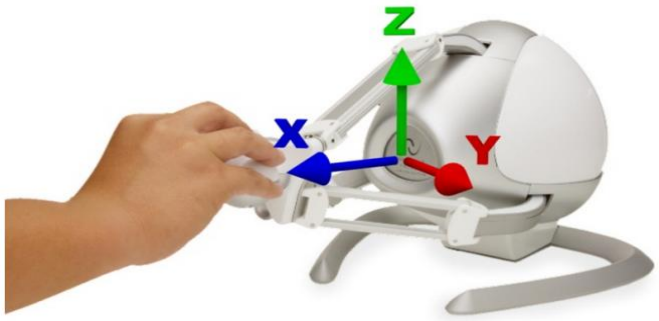
Model	Area (cm)	Resolution (mm)	Force (N)
sigma.7 [80]	19 x 13	0.0015	20.0
omega.3 [81]	16 x 11	0.01	12.0
omega.6 [82]	16 x 11	0.01	12.0
omega.7 [83]	16 x 11	0.01	12.0
delta.3 [84]	40 x 26	0.02	20.0
delta.6 [85]	40 x 26	0.02	20.0
Virtuose 3D [86]	20 x 20 x 20	n/a	3
Phantom omni [87]	16 x 12 x 7	0.055	3.3
Novint falcon [88]	10 x 10 x 10	0.049	10

Table 2.3: The comparison between the different available haptic devices

As can be seen from the table 2.3, this comparison includes devices with different (DOF), but all of them designed for desktop usage. In our case 3 DOF is suitable to assist subjects to apply the movements that will be suggested in the virtual reality, because every point in the space can be represented using (X, Y, and Z). Also the system should be simple scene to avoid subject's dispersion, so the needed resolution would not be too high. Also, subjects (children with hemiplegia) have a muscle deficit, so a reasonable force will fulfill its purpose as a force feed-

back. The strategy is to constrain the UE to apply a certain trajectories in VR scenarios, so there is no need for a huge work-space. The price column has been neglected because of the lack of trustable information given by different sources, but in general the novint falcon seems at low price comparing with the other haptic devices shown in the table.

However, there are not the only reasons for choosing the novint falcon as a haptic device in this upper limb rehabilitation, there are also some exercises which have been done using this device and showed a certain improvements. H H Le et al have used the haptic device (novint falcon) in a painting program, and concluded that the participants executed more movements while exploring the painting. It appears that the haptic painting paradigm encourages development of analytical skills, imagination, promotes spatial skills realization and enhances touch/hearing sensory channels. [89]. S.B. Nagaraj et al have also examined the effects of using haptic device on the UE, and found that the electromyographic (EMG) activity in upper limb increase significantly even for small changes in the low force feed-back from the haptic device. [90], they also suggested that haptic devices with low vibration force feedback can be used to develop rehabilitation programs. J. Sanchez et al haves tested the haptic device with blind people and came-up with that, the people correctly describe the textures and shapes used in the software by using the sense of feeling or touch provided by the haptic device. [91]. Based on the above evidences and these exercises, we suppose that people can learn and experience a new patterns and trajectories by using a proper haptic device (the novint falcon) shown in picture 2.1.



Picture 2.1: the novint falcon

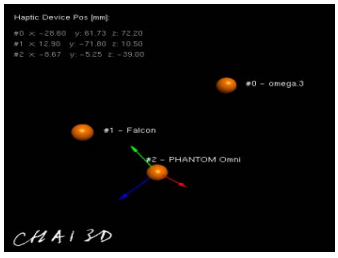
The specification of novint falcon:

The device's name	Novint falcon
DOF	3
Supported movements	Upper limb (R/L)
Main control inputs	End-point position and torque (Novint Falcon)
Actuators	Electric motors
Type	Stationary system (end-effector-based, using haptic device)
field of application	Fine motor upper limb therapy

Table 2.4: The Novint Falcon specifications

2.1.3 Virtual reality:

To ensure that visual, audio, and tactile feed-back are provided, integration between the haptic device and VR need to be done. However, a comparison between the available VR applications, shown in pictures 2.2.. 2.4, might help to chose the most powerful application that can support the haptic device and provide the different needed functionalities to the children with hemiplegia.



Picture 2.2: CHAI 3D



Picture 2.3: UNITY 3D



Picture2.4:UNREAL ENGINE

	Chai 3D [92]	Unity 3D [93]	Unreal Engine [94]
Languages	C++	C#, and Java	C#, and Java
Graphics	Non	Actors, Cameras and Lighting	Cameras and Lighting
Audio abilities	Non	All different types of sounds	All different types of sounds
Editor	C++ editor	Working with the panels, tabs and views of the Unity Editor	Key principles on how the editor works
Physics	Non	Actors, Cameras, and Lighting	Cameras, and Lighting
Architecture	Non	The ability of setting up the architecture of your project	Different types of components to be used as sub object with an Actor
Animations	Non	Provide a full diagram of animation	Provide a full diagram of animation

Table 2.5: The specifications of available virtual reality

From table 2.5, Chai 3D is an open source set of C++ libraries for computer haptics, visualization and interactive real-time simulation. Chai 3D has been developed mainly for haptic devices, and supports several commercially-available three, six and seven degree-of-freedom haptic devices, and makes it simple to support new custom force feed-back devices. Chai 3D is especially suitable for education and research purposes. But Unity 3D and Unreal engine seem to be more suitable than Chai 3D specially in using (visual and audio feed-back). Table 2.5 shows the advantages of these two applications (unity 3D, and unreal engine) over the third one (Chai 3D), but concerning the integration with the haptic devices, unity 3D has the potential to work with them more than unreal engine. As a result of this comparison, Unity 3D has been chosen as a VR tool in order to develop the game stages that will control the force feed-back of the haptic device, and enable the subjects to play the games.

Haptic device-virtual reality would be a modern method for upper limb's rehabilitation, by integrating the traditional sense of touch of haptic devices with virtual reality worlds. Virtual reality environment is used as a mean of visual and audio feed-back. Haptic devices provide sense of touch along with force feed-back coming from its actuators with different degrees of freedom (DOFs). Actually, any reach-to-touch movement of an upper limb will draw a trajectory in the virtual environment from the start point to the end point, also any point in this trajectory is a point in the space, and devices with 3 DOFs have enough degrees to represent these movements.

The Novint Falcon has three identical parallel kinematic chains which represent movements in X, Y, and Z axes, also there are four links for each kinematic chain, also linked to moving platform as can be seen in Fig 2.2. As a result of this configuration, the position of moving stationary in 3D space can be controlled by actuating only the lowest three joints, and then use its sensors to detect the angular positions of these three lower joints in order to control movements of moving platform according to trajectories that have been determined in virtual reality scenarios.

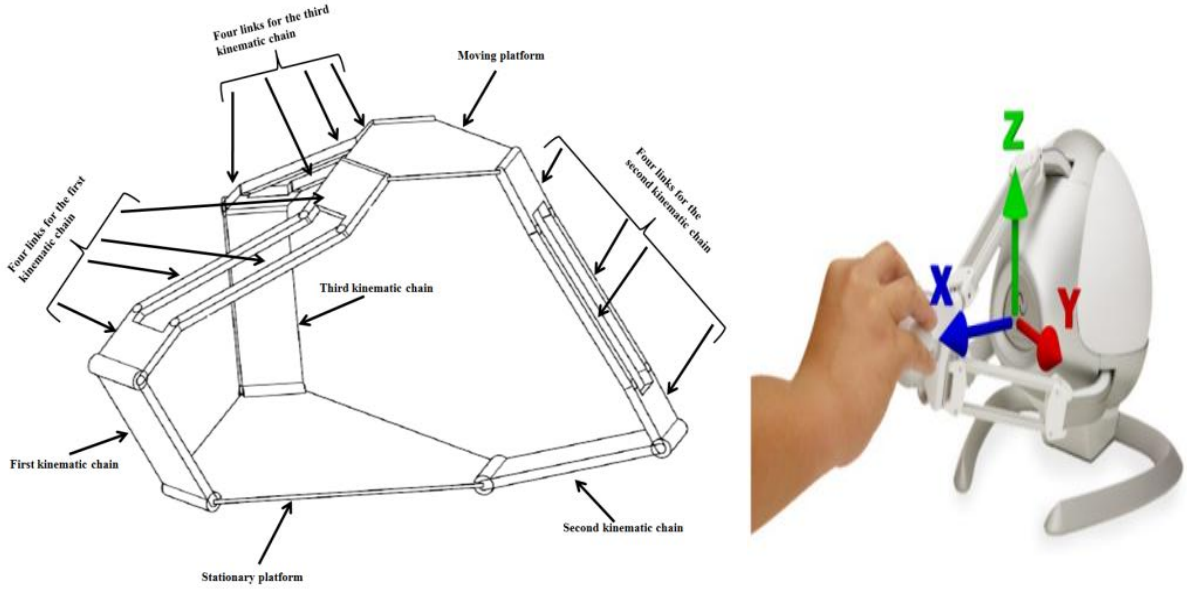


Figure 2.2: Mechanical schematic of novint falcon's configuration

Moving the handler of the Novint Falcon is performed by using the hand of the subjects, so its impact will be directly applied on the hand and the wrist joint of the upper limb. However, Jorge Ambrosio et al have concluded that efficiency of hand positioning is in large part achieved by the combined motion of the shoulder and elbow mechanisms [95]. So, the hand position will be controlled by the force feed-back coming from Novint Falcon in order to improve the joints coordinate system (JCS) of the upper limb.

2.2 Biomechanical models and movement representation of upper limbs

In order to integrate the upper limb (UL) with the haptic device and VR, a good understanding of the UL and its references are needed. The determination of the most needed upper limb's patterns and its relations with upper limb's joints is necessary in order to produce the trajectories from the start position (upper limb initial pattern) to the end position (upper limb desired pattern). To do that an analysis of purpose-oriented movements should be carefully done because a motor task can be achieved by the musculoskeletal System in many ways by permitting the organism to adapt to different environmental conditions in order to select the desired trajectory and inter-joint coordination among many possible strategies to make goal-oriented movements [96]. And by comparing the patient's movements with health's movements, healthy subjects normally used elbow extension and shoulder flexion, scaled to movement distance whereas patients with hemiparesis use different patterns of joint recruitment with different scaling rules. Also patients with large degree of impairment compensated by recruiting extra degrees of freedom, particularly trunk bending [96]. From these evidences, it is worth to redirect joints of the upper limbs towards reproduce a normal joints recruitment and avoid compensation movements with special concentration on the degree of freedom needed to accomplish a movement pattern keeping into account the gradient in performance to avoid abnormal muscle tone.

Postures or patterns stored in the motor memory are used to select reaching movements and that cost of possible postures and postural transitions are taken into account in the selection process [97]. However, functional changes in muscle's patterns and upper limb's joint movement are essential to improve movement ability for children with hemiplegia [98]. So, repeatable movements between two or more patterns and joint movements of the upper limbs would

increase the possibility of storing these movements' patterns in the motor memory. In order to achieve these functions, targeted trajectory, based on the initial pattern and position as well as determine the goal point in the space in order to reach the desired pattern, needs to be applied. For a given reaching task, the final values of shoulder angle, elbow angle, and wrist were reproducible from attempt to another [99]. In fact, each target/reach movement needs a complex sequence of upper limb's segments coordinate which impose certain joint angles (shoulder, elbow, and wrist) flexion/extension or internal/ external rotations, to coordinate in a particular manner to achieve these trajectories of movements. However, in order to perform these needed patterns, understanding of both single angles behave and angle joint's coordinate is fundamental. And then work on the production of specific scenes by using virtual reality for the purpose of enabling them to make these effective patterns during their daily performance.

J. Ambrósio et al [95] have defined the model 1 as 4 rigid bodies – thorax, humerus, ulna and radius – and three anatomical articulations – glenohumeral (GH), humeroulnar (HU) and radioulnar (RU), as can be seen in fig 2.3. a. Upper limbs movement is developed in a 4 dimensional space (3 spatial dimensions and time dimension). As long as movement of a limb is applied, each part of that limb (segment) takes a particular orientation depends on the type of the movement each specific time (these orientations change from time to time).

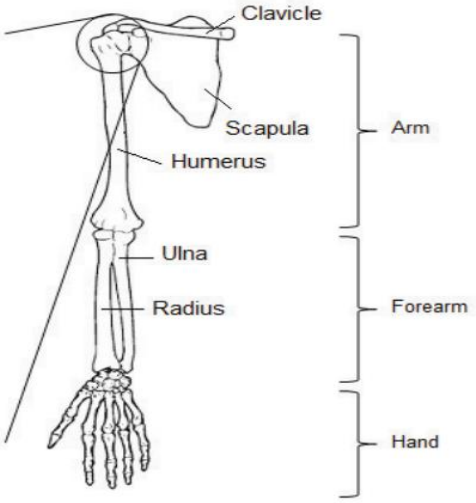


Figure 2.3: a) Bones of the upper extremity

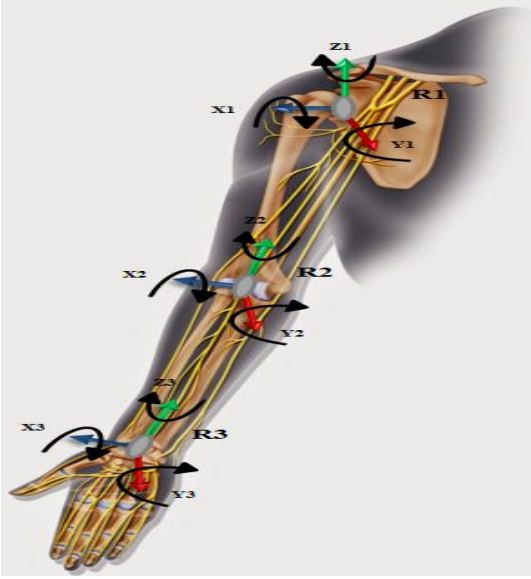


Figure 2.3: b) The upper limb kinematic based on its references R1, R2, and R3

Upper limbs movement representation would be described and discussed using the definition of the joint coordinate system (JCS) for the shoulder, elbow, and wrist [100]. Some simplifications have been done and discussed to describe the upper limbs models assumed as following:

1) Each upper limb joint defines through one articular centre, (shoulder joint, elbow joint, and wrist joint).

2) The forearm considers as a rigid body, so pronation-supination movements must be resigned to elbow joint.

3) The hand also considers as a rigid-body, and its movement allocates to the wrist joint. It will be considered as closed hand (the hand will hold the handle of the falcon to play).

By using this simplification, the movement of affected upper limb can be represented in seven essential movements: three rotations on shoulder, flexion-extension of elbow, forearm rotation, and two hand-wrist rotations are considered to complete the description. Now joint coordinate system (JCS) needs to be clearly determined in order to define the kinematic models, segments coordinates that would facilitate the movement representation [101], as can be seen from fig 2.3. b.

2.3 The method

Reach-to-touch tasks are assigned, in VR, to the subjects in order to enable them to apply the required posture patterns. In our active-constrained mode, the haptic device provides a free- pass in the directions of the desired movements, and applies a force feed-back in all other directions. The subject has to reach toward the goal object(s) which present(s) in the virtual reality scenarios as shown in Fig 2.4.

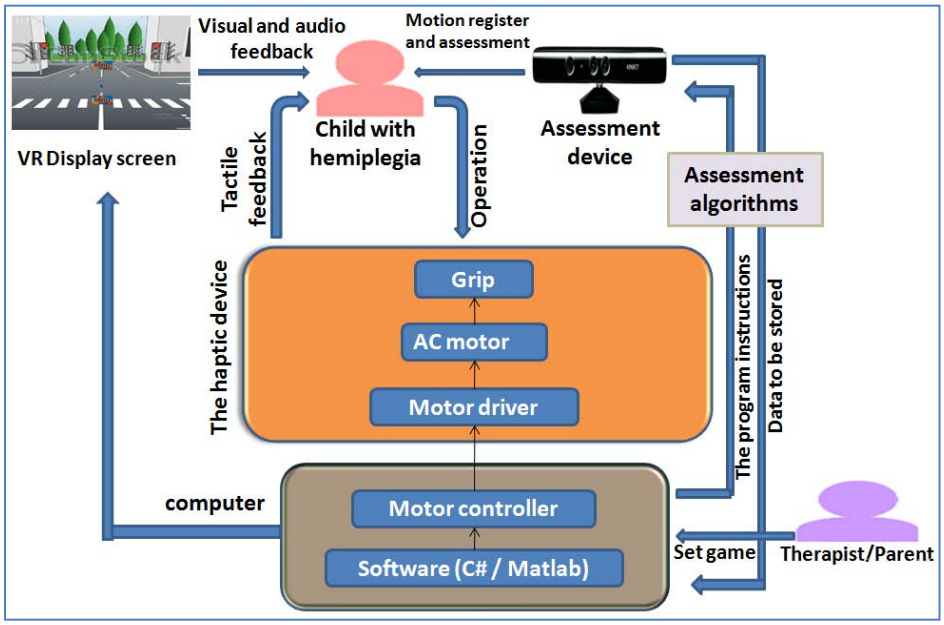


Figure 2.4: The set-up of the system

The subject exerts a force on the handler (grip) of the haptic device with the affected upper limb, in order to play the game suggested in VR scenario. The force feed-back comes from the haptic device is controlled by C# scripts according to shapes and trajectories in VR scenario. The blue ball in VR represents the handler of the haptic device, and adds the possibility to constrain the joints of ULs in order to avoid abnormal recruitments based on UL's references see section 2.2.

C# and MATLAB are used to build the assessment algorithms which count the number of triggered feedback reaction from the haptic device according to the virtual environment, measure the overall time consumed to complete a task, count the number of collected objects in each

scenario, count the number of completed tasks in a certain period of time, and compare the trajectories drawn by the subjects and the ideal trajectory.

2.3.1 Sensory control strategy

The human's brain has the ability of interpreting sensory information given by haptics, even if it is not real or showed in natural modality, this means blind people can describe textures and shapes presented in virtual reality correctly by receiving haptic stimulation on their skin [102]. The cross modal plasticity of the brain is the source of the sensory substitution [103]. It is started with the tactile vision substitution system (TVSS); this theory has been reviewed and confirmed the concept of sensory substitution [104].

The integration of possible sensory stimulus such as visual, audio, and tactile, can improve upper limb's functions in children with hemiplegia. Control strategies, which have been used with robots in therapy, have been classified into two main categories (high level, and low level). High-level control algorithms are designed to use motor plasticity whereas low-level strategies control the force, position, impedance or admittance factors of the high-level control strategies [105]. Haptic stimulation control strategy has been chosen in this work to ensure that all possible sensation will be provided, since this strategy is a high-level control strategy in which a robotic device is used as a haptic interface to perform activities in virtual reality environment.

Main difficulties which normally combined with haptic feed-back, when it is linked with visual and audio feed-back, are time delay, parameter uncertainties, and nonlinearities. In other words control the force feed-back to work within the whole system (visual, and audio) in conjunction, in order to stimulate the human sensory system to response according to scenarios provided in the technical system. Then, the objective here is to develop a high level control in which the human brain is stimulated by the visual, audio, and tactile sensation to transmit instructions to the affected upper limb's joints to response to actions proposed in the system.

In this work, integration between a haptic device and virtual reality environment based on upper limb's movement control has been done, in order to develop a control strategy that will invoke the brain of subjects to give instructions to joints of the upper limb, to act with the proposed scenarios in VR.

This control strategy is based on resistive force feed-back to be applied on the affected upper limb according to predefined trajectories in VR scenarios. The analysis of internal factors such as strength, flexibility, coordination, pain level, motivation, and cognition, are used to establish limitations of movements and its directions, by developing scenarios depending on the length of upper limb and the angle's value that needs to be applied, by asking patients to use the handle of the haptic device to interact with virtual objects presented in VR scenarios as can be seen in fig 2.5.

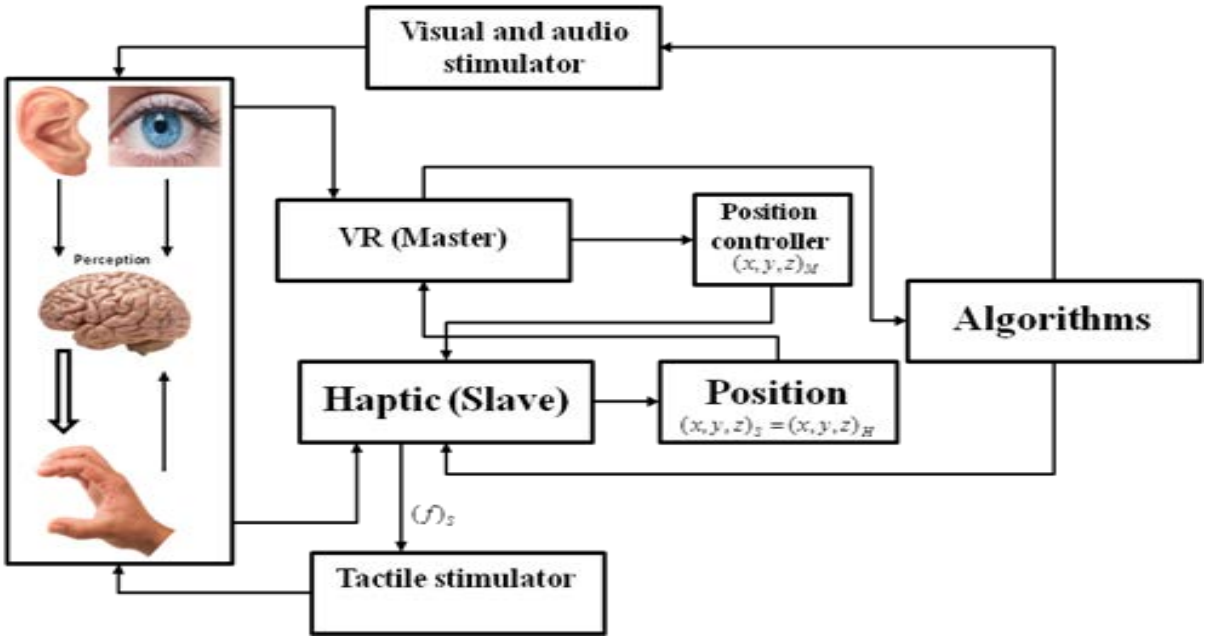


Figure 2.5: Manipulation with sensory substitution

This structure illustrates the bilateral control (haptic, VR) which ensures operations' stability, as well as provides the physical constraint to prevent abnormal joint recruitment during performing tasks. Based on the concept of sensory substitution, we develop a method of providing force feed-back that works depending on predefined VR scenarios. In this strategy, the haptic device (slave) transmits position of subjects' UL (x, y, and z) to VR (master) to interact with objects in the suggested games. Then, predefined trajectories will be applied by the master on these entered parameters and provides the slave with updates parameters (positions) depending on the scenarios. Finally, the slave applies its inverse kinematics on updates parameters in order to calculate angular positions to produce the forward kinematics which constrains UL's movements of subjects.

2.3.2 The assessment

2.3.2.1 The type of the movements' assessment

Upper limb's kinematics is different when the patients are attempting to point to an object comparing when they are grasping [106]. Three-dimensional analysis of ADLs has been made firstly for healthy subjects in order to evaluate their movements [107, 108]. But similar studies on cerebral palsy children has also been done and conclude that the measurement of the results of treatments is more accurate when using three-dimensional upper limb motion analysis than using current clinical methods [109]. So, Three-dimensional motion capture needs to be recorded. Kinect for windows device has met the clinical requirements when doing experiments [110]. Some comparisons between kinect and other 3D motion captures, such as Vicon and PhaseSpace, have been done [111, 112], and it has been found that the kinect system is a low-cost, home-based sensor, and can accurately measure the timing and gross spatial characteristics of clinically relevant movements, also the Kinect based measurement has been confirmed as a sufficiently accurate and robust for UE evaluation. Furthermore, the precision of the Kinect is, of course, less than other motion capture systems presented in this comparison, but the following criteria: price, portability, work-space, and marker-less make it the best choice for the assessment of the different types of the movements in home-based rehabilitation.

2.3.2.2 The quality and quantity of the movements' assessment

The efficiency of a rehabilitation process is mainly based on the results which normally derived from impairment and functional assessment. The therapists use these results to build their decisions about the upcoming treatment plan, as well as judging the usability of a certain treatment. Those decisions mostly depend on the improvement level that has been noticed by using different assessment methods. In fact, there are wide methods of assessment such as Performance Measures which contains of (Action Research Arm Test (ARAT), Box and Block Test (BB) Chedoke Arm and Hand Activity Inventory (CAHAI), Jebsen-Taylor Hand Function Test, Nine-Hole Peg Test, and Wolf Motor Function Test (WMFT)). And Self-Rep ort Measures which contains of (Motor Activity Log (MAL) and Stroke Impact Scale) [113].

A performance measure is a method in which the therapists rate and/ or time a certain set of upper limb (UL) actions which normally perform by patients. Whereas, self-rep ort measure is a

method in which, patients need to answer a set of questions which pre-prepared by the therapists. These methods are based on the experience of the therapists, and require the presence of those therapists to make the decision. But those therapists have indicated that they prefer to have a core set of measurement instruments which require less user intervention, instruction, and interpretation [114].

The routine of the assessment of impairments and performance improvement are critical for the therapists for decision making [115, 116]. There are many rehabilitation processes, which have used haptic devices as based equipment for the rehab [117, 118, 119], however, most of those devices are used to help patients to complete the desired tasks. Despite the fact that these systems have illustrated promising results for UL rehabilitation, most of those systems are unable to determine the level of difficulty and the level of enhancement, which the patients have achieved, of the rehab exercise; instead the therapists use the other assessments methods.

Performance or self-report measures, which assess the progression of patients, are mostly performed by the therapists regularly at a certain amount of time. These assessments provide the therapist with the meanwhile range of motion, not the overall progression of the patients during all sessions of the therapy. This makes the judgment of the outcome of the therapy such hard work.

In this work, we have developed an intelligent system which will use the possible collected data, time and number of contact with the force feed-back, from the haptic device to determine the range of difficulties and the enhancement level based on the proposed fuzzy approach, in order to provide the therapists with the information to help them making their decisions about the current level of rehab, and the potential next stage in the rehab process. Actually fuzzy approach has been used in various aspects of assessment, such as in perceptual image quality assessment [120]. It has been also used to provide a valuable information or assessment about the real behavior of a machine system [121]. And both of them have shown the reliability of using such approach.

We assume that; the application of this method will b e a helpful practice in terms of an aggregation of possible objective judgment, based on the experience of the specialists in

assessment field, and provide the therapists with the big picture of the quality and quantity of the movements.

In conclusion, this chapter describes the comparison processes that have been applied to choose the devices, the applications and the control strategy that are used in the system. Also, explains the methodology of the system which based on the use of the novint falcon haptic device along with unity 3D VR application in order to develop a system for upper limb therapy for hemiplegic children. Finally, illustrates the two evaluation methods which have been developed in order to enable therapists to evaluate the performance of the children with hemiplegia during the therapy process in cadre of Tele-Rehabilitation.

Chapter 3: The development of the system

The main features, of this proposed home-based therapy system, are: it offers, for both children with hemiplegia and therapists, interactive information to gain new insight in the therapy process. From the children's point of view, it provides a friendly, easy to understand, exciting, and immersive VR exercises that show in 3D environment; these exercises are integrated with the haptic device to add the tactile sensation to the visual and audio VR sensations. This configuration is made to enable the targeted children to practice the relevant movements to each upper limb joint. From the therapists' point of view, the system provides them with the statistical information about the performance of the children during the exercises. Furthermore, another novel contribution of the system is that it's capacity to judge the targeted upper limbs performance during different proposed tasks and provides the therapists with the line of performance decisions as a history of their performance.

3.1 The system workflow

The use of the system, in general, requires the following of the activities shown in Fig 3.1, which could be executed by three or four different actors. Some activities correspond to the plan of the therapy (blue), and the others to the execution of the therapy (green). With the respect to the protocol of the therapy see appendix A. First of all, the therapists and the developers discuss and make the VR scenarios which need to be assigned to the children. Each scenario targets on or two upper limb's joint(s) to encourage that joint(s) to perform its related movements in the ADLs. For example, for the shoulder joint, scenarios that stimulate the Flexion-Extension, Abduction-Adduction, and Internal-External rotation movements need to be developed. After that, the therapists assign the suggested scenarios to the children who will perform those activities. Both therapists and parents can monitor the children when they perform the activities. The system is built as a user centered design, so the therapists and the developers could re-discuss and adapt the system according to the needs of the children as can be seen in section 3.5. Finally, the system provides the therapists with the numeric evaluation along with the decision about the children's performance.

Concerning the execution of the different activities, the children use the haptic device to perform the proposed VR activities. The retrieved data are used by the system itself to make a reasonable decision about the enhancement and the level of impairment.

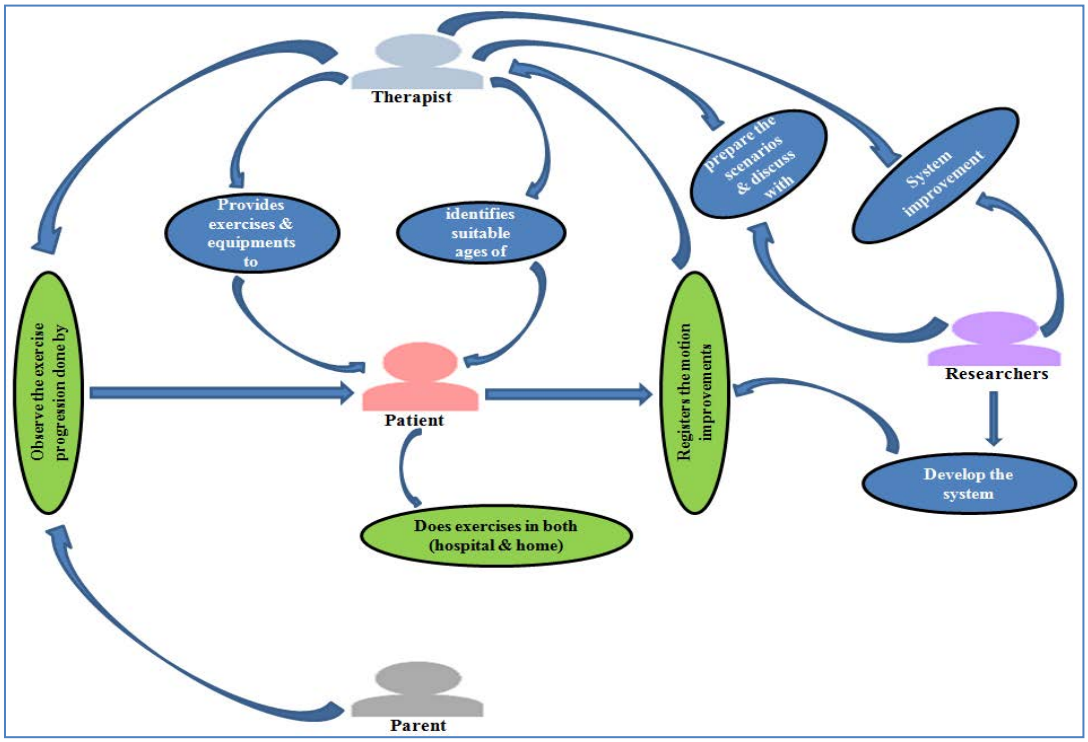


Figure 3.1: The interdependent network of behaviours

3.2 Control strategy

According to the explanation of the behavior of the system presented in chapter 2, section 2.3.1. The haptic control schema shown in Fig 3.2, illustrates the integration of the upper limb movements with the haptic device and VR scenarios. This integration allows us to control the behavior of the haptic device according to VR scenarios. This means that the haptic device provides free paths in VR scenarios and force feed-back in the other directions according to shapes and obstacles presented in the scene. In other words, resist when-needed model.

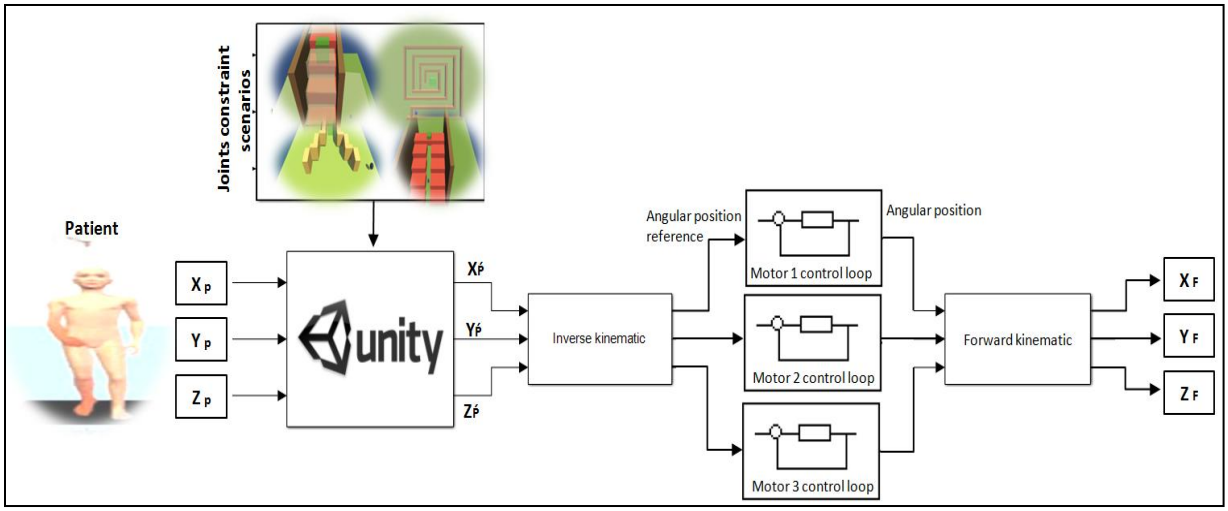
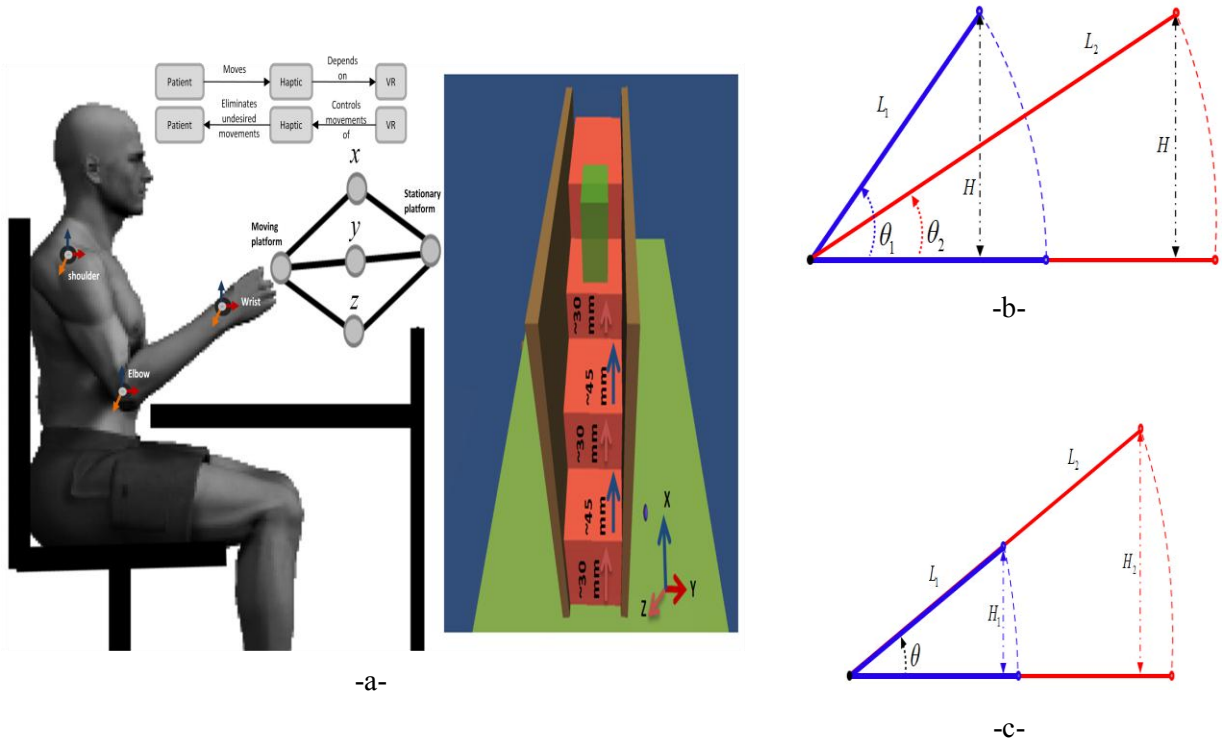


Figure 3.2: Haptic control schema for upper limbs

The child moves the handler of the novint falcon haptic device to play the proposed games in the VR environment. The haptic device (slave) transforms the position of the upper limb in the space (X_P, Y_P, Z_P) to the VR (master). Each VR scenario is built to constrain the joints of the upper limb to perform and repeat a certain movement, see section 3.5. So, C# scripts, which control the integration between the haptic and VR, compare this initial position with the pre-defined trajectory in the scenario. Now, if this initial position is within the trajectory, then the new position from the scripts will be the same which means the haptic will provide a free pass for this movement at this point. But if that initial position is not in the trajectories (the child is about to touch an obstacle presented in VR scenario), the scripts provides the haptic device with new position ($X_{P'}$, $Y_{P'}$, $Z_{P'}$). This new position will constrain the upper limb to stay within the illustrated trajectory. Then, the novint falcon applies its inverse kinematics to this new position in order to define its angular position and then applies the forward kinematics to produce the final position (X_F, Y_F, Z_F) which respects the VR scenarios.

Since the system uses limitation depend on the upper limb's length, so overload of ROM will be significantly avoided. However, different angles can be performed depending on the device's work-space and the length of the segment. These joint's angles can be predefined as can be seen in fig. 3.3.



-a-

-b-

-c-

Figure 3.3: The different angles with different segment's length of ULs

Whereas L_1 is the segment length of a subject, and L_2 is the segment length of other subject. And (θ, θ_1, and θ_2) are the angles that can be performed. (H , H_1, and H_2) are the highest which subjects can reach depending on the device's work-space and the limitation in VR. Based on this, scenarios can be building to constrain ULs to produce a certain angle even with different segment lengths fig 3.c, by determining the proper high for each segment length based as follows:

For the first segment length of patient1: $\theta = \sin^{-1}(\frac{H_1}{L_1})$, and for the second one $\theta = \sin^{-1}(\frac{H_2}{L_2})$

And in general for patient i:

$$\theta = \sin^{-1}(\frac{H_i}{L_i}) \qquad (1)$$

From this equation the proper high for each segment length can be found as follows:

$$H_i = L_i \sin(\theta).$$

In contrast, one predefined scenario or a particular work-space for a device can produce different joint's angles depending on segment lengths as follows:

For patient 1: $\theta_1 = \sin^{-1}(\frac{H}{L_1})$, and for patient 2: $\theta_2 = \sin^{-1}(\frac{H}{L_2})$, and in general for patient i:

$$\theta_i = \sin^{-1}(\frac{H}{L_i}) \quad (2)$$

However, shoulder and elbow joints' motion are mostly combined together to produce various movements, but each joint has certain movements related to it. So a strategy for each joint has been established.

3.3 Angles estimation

3.3.1 Flexion-Extension angles estimation

In the GUI, therapists determine the desired theta to be performed by the joints of the affected upper limb. Each scenario has its parameters like the length of the arm and forearm. Estimation of the needed work space in the haptic device and VR scenario needs to be calculating to produce the desired theta, as well as the overall thetas that will be produced in the proposed trajectory. However, the internal relation of the upper limb joints also needs to be considered in order to calculate the related joints thetas. For example, in the shoulder elbow Flexion-Extension scenario the therapists need to determine the desired shoulder theta and the length of the upper limb. And then estimation of the needed work space to produce this theta needs to be calculated from the initial position to the final position as can be seen in Fig. 3.4.

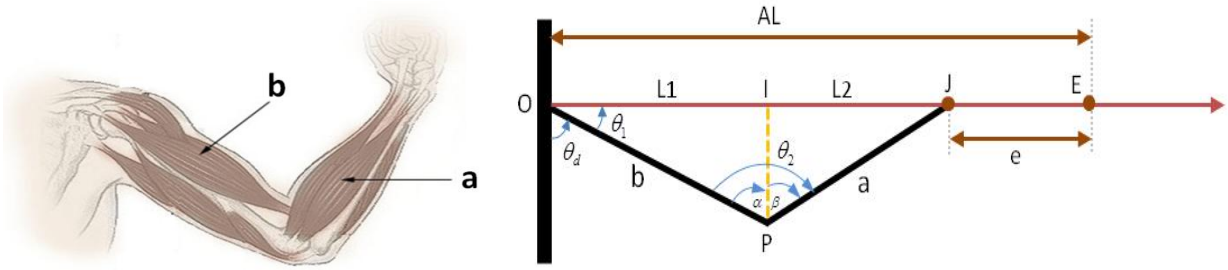


Figure 3.4: Geometric formulation of Flexion-Extension movement

The following geometric representations illustrate the possible chooses to respond to the estimation problem. The desired mechanical equation can be found from the obtained triangles:

From the left triangle (OIP) we have:

$$(OP)^2 = (OI)^2 + (IP)^2$$

$$\cos(\theta_1) = \frac{OI}{OP}$$

$$OP = \frac{OI}{\cos(\theta_1)}$$

From the right triangle (JIP) we have:

$$(PJ)^2 = (IJ)^2 + (IP)^2$$

$$\sin(\beta) = \frac{IJ}{PJ}$$

$$PJ = \frac{IJ}{\sin(\beta)}$$

Now the required displacement in the haptic device work space (e), which will constrain the shoulder angle to apply the desired angle, needs to be counted:

$$\theta_1 = 90 - \theta_d$$

$$L_1 = b\cos(\theta_1)$$

$$IP = \sqrt{b^2 - L_1^2}$$

$$L_2 = \sqrt{a^2 - (IP)^2} = \sqrt{a^2 - b^2 + L_1^2}$$

$$e = AL - (L_1 + L_2) = (a+b) - (b\cos(\theta_1) + \sqrt{a^2 - b^2 + b^2\cos^2(\theta_1)})$$

$$e = (a+b) - (b\cos(\theta_1) + \sqrt{a^2 - b^2\sin^2(\theta_1)}) \qquad (3)$$

Now an estimation of all possible angles that would be performed by the shoulder and the elbow, from the initial position to the final position, needs to be done, in order to provide the therapists with the whole angles that have been performed to help them make their decisions about the next step in the therapy process. In order to compute the shoulder and elbow angles from the measurement of the wrist position, which is obtained from the falcon position, at any point within the displacement (e). We consider the inverse problem as follows:

$$AL - e_x = L_1 + L_2 \qquad x \in \{1, 2, 3, \ldots\}$$

And from the law of cosines:

$$\cos(\theta_{1x}) = \frac{b^2 + (L_1 + L_2)^2 - a^2}{2b(L_1 + L_2)} \qquad (4)$$

$$\theta_{dx} = 90 - \theta_{1x}$$

$$\cos(\theta_{2x}) = \frac{a^2 + b^2 - (L_1 + L_2)^2}{2ab} \qquad (5)$$

3.3.2 Abduction-Adduction angles estimation

The purpose of this movement is, in fact, to allow the patient to exert a vertical movement considering 90 ° as the basic or initial angle of movement. This configuration can be also considered as a guideline for the designers of the system to mathematically provide a general mechanical equation to meet the needs of the attending physician. The work-space of the haptic device must be taken into account in this calculation. Fig 3.5 illustrates the geometric translate of the problem, and then the analytic by the equations.

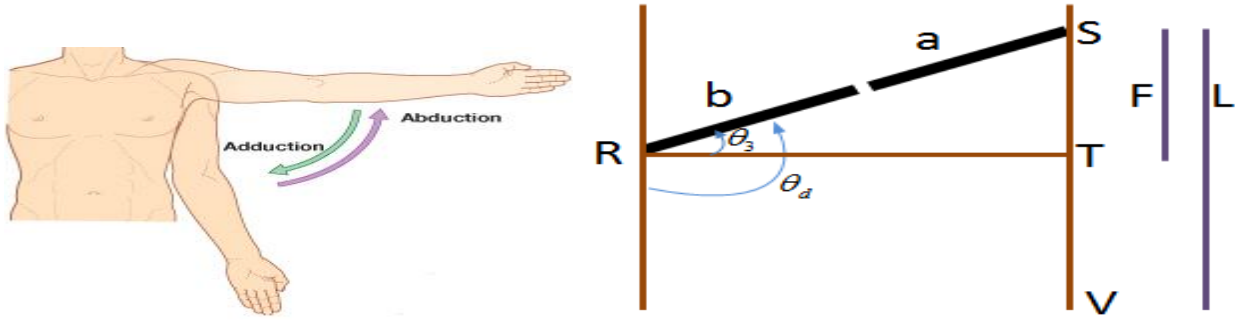


Figure 3.5: Geometric formulation of the Abduction-Adduction movement

The above figure is used to adopt the situation of our movement. To this end, the solution to the problem posed will be to determine the desired displacement in the work-space F as a function of the desired θ_d and Lb which equal to $a+b$.

The analysis of the possibilities allowing us to give the mechanical equation of the motion and obliges us to consider the triangle (RTS).

The use of $\sin(\theta_3)=\frac{ST}{RS}$ immediately gives us F, because ST = F, RS = Lb, and $\theta_3+90^0=desired\theta_d$ then $\theta_3=\theta_d-90^0$.

Hence the following mechanical equation: $F=Lb*\sin(desired\theta_d-90^0)$ (6)

3.3.3 Elbow Pronation-Supination and Shoulder Internal-External angles estimation

The proposed novint falcon in this system is 3 DOF haptic device, so it allows for movements in the space that related to its work-space. But it does not support the rotation movements such as Elbow Pronation-Supination, and Shoulder Internal-External rotations. These movements are the most needed movements to be enhanced for children with hemiplegia. So, we have developed a translator device (from the rotation movements to a movement to Y axis). This device allows us to add two degree of freedom to our haptic device as can be seen in the following explanation:

3.3.3.1 The schematic representation of the operational area of work

This architecture shown in Fig 3.6 makes it possible to highlight the desired scenario, in all logic, in order to arrive at the calculations of the angles related to the degrees of freedom (movement) considered

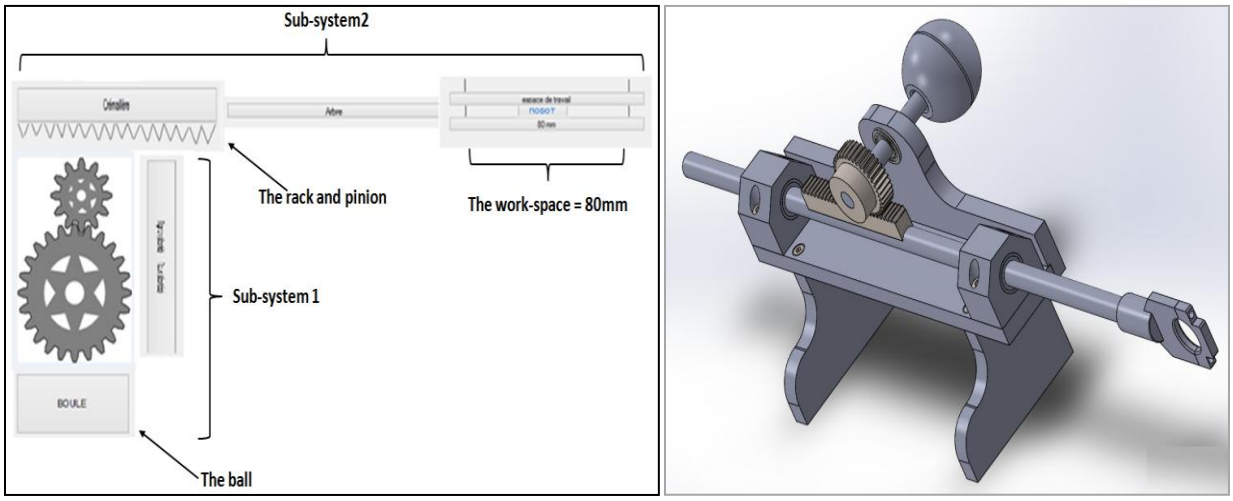


Figure 3.6: Architecture of the overall system

As illustrated above the architecture consists of two sub-systems each assuming a role to achieve the desired end goal as following:

- Sub-system 1: This sub-system consists of a ball by which the hemiplegic children will move with the robot from his wrist; either he will exercise Elbow Pronation-Supination or Shoulder Internal-External rotation movements. The two toothed organs (wheel and pinion) will mechanically enter Transmission (rotation) when either pronation or supination is realized.

- Sub-system 2: This sub-system is constituted of a rack which serves to initiate the translational movement caused by the rotation of the pinion. It is connected to a shaft which is connected to the intelligent robot which will move strictly and accordingly in the work-space.

3.3.3.2 The geometric formulation of the problem

Fig 3.7 illustrates the translation from the rotation movements to a movement in a unique axis as following:

- (C1) the circle, it is related to the system of gear (wheel + pinion), with center A and radius [AB] representing the state of equilibrium of the movement.
- The segment [BE], it is related to the length L = 80 mm of the work-space, tangent to (C1).
- The robot is linked to a material point, this point has moved along the work-space until reaching a point D belonging to the segment [BE], when the patient performs the rotation movement.
- The final $\theta = 270^0$, because of that this degree is the maximum degree that can be performed when trying to do any pronation, supination, or rotation movement. Therefore, the final relation to calculate the radius of the circle is:

For the general case: Perimeter of $(C_1) = 2\pi AB = L.$ So, $AB = \frac{L}{2\pi}$

For our case: Perimeter of $(C_1) = \frac{270}{360} * 2\pi AB = L.$ So, $AB = \frac{L}{270}$

Then, the desired workspace is: $$desired_L = \frac{desired\theta * L}{270} \quad (7)$$

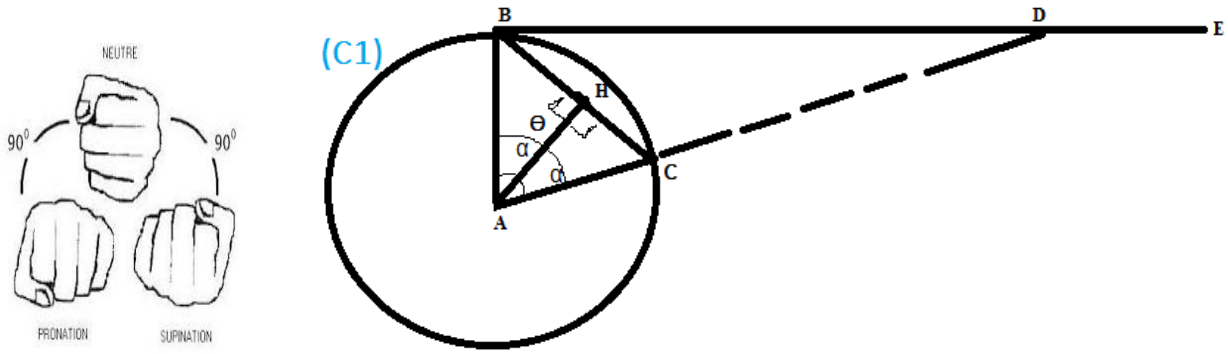


Figure 3.7: The translation of the geometric formulation of the system

3.4 The configuration of the system

The efficiency of hand positioning is in large part achieved by the combined motion of the shoulder and elbow mechanisms [95]. In each reach to touch process, the ideal joints recruitment is that shoulder flexion and elbow extension [96]. So, the hand position will be controlled by the haptic device and VR in order to improve the JCS of the UE as can be seen in Fig 3.8.

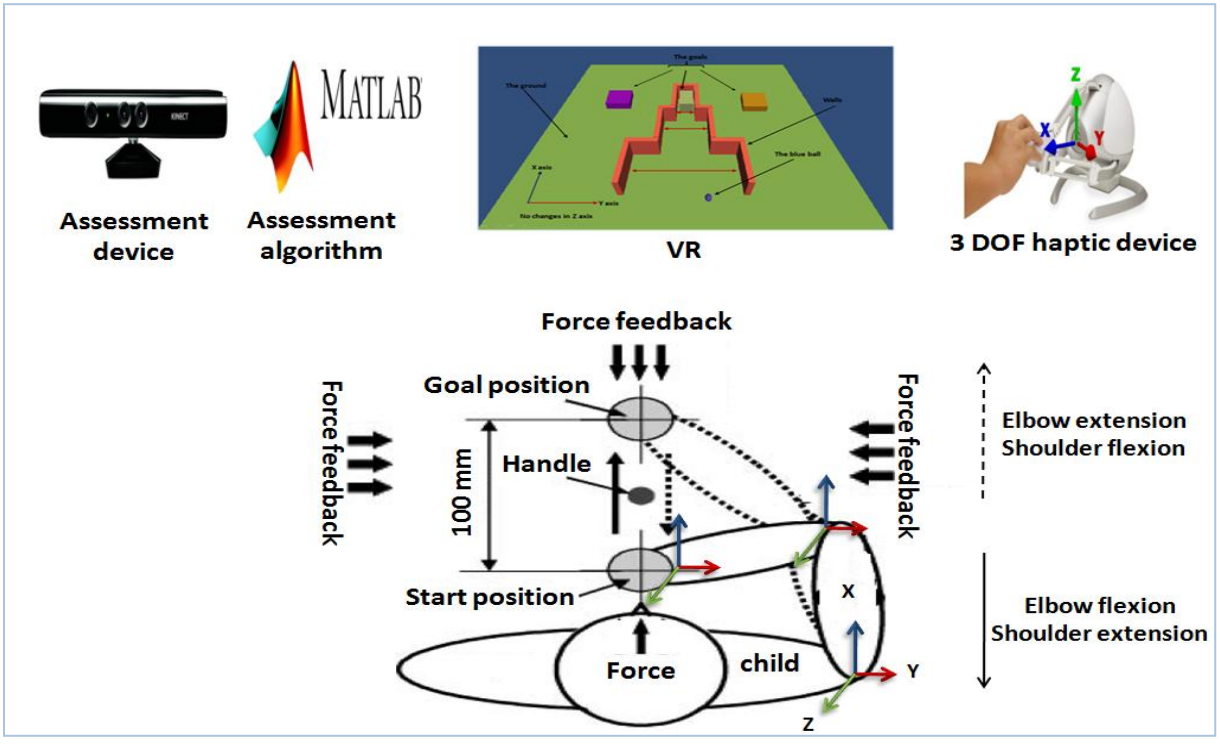


Figure 3.8: The configuration of the system

- Use the movement representation (x, y, z) of each joint as a based to constrain the upper limb's movement.
- integrate the references of the UE with the (x, y, z) of the haptic device and VR in order to:
    - Develop the VR game.
    - Constrain the UE joints based on its references:
        - High (Z axis)
        - Low (Z axis)
        - Sides spaces (Y axis)
        - Forward (X axis)
        - Backward (X axis)
- Work in anterior and lateral positions by changing the position of the haptic device.
- Muscles strength.

3.5 Virtual reality-Haptic scenarios

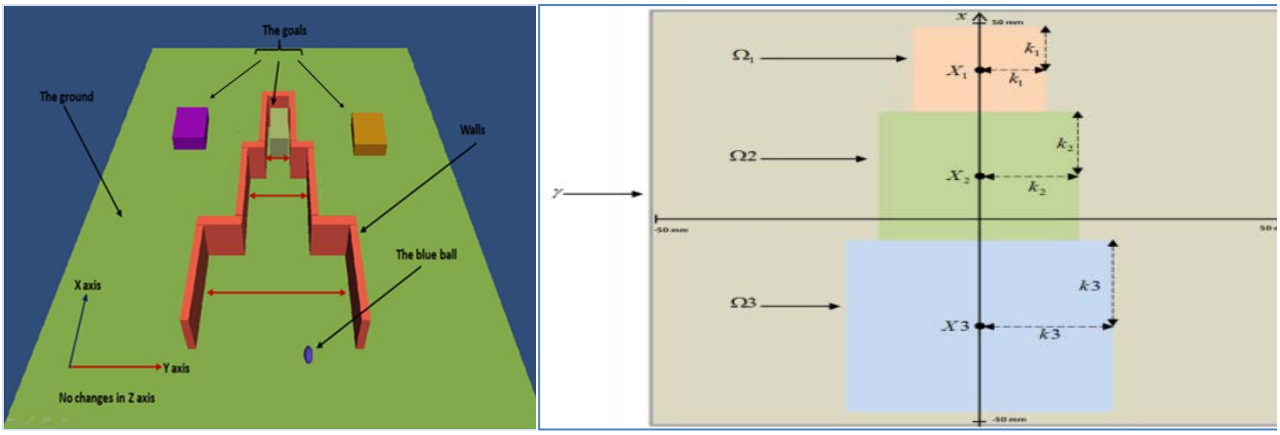
This section shows the different VR scenarios that will control the haptic device to constrain the upper limb joints to perform the desired movements as following:

3.5.1 Flexion-Extension movement

3.5.1.1 Multiple goals reach

The purpose of multiple goals reach simulation is to improve bilateral shoulder and elbow movements, as well as reaching accuracy. The VR scenario shows a three-dimensional floor, and roads with different spaces. Although Z axis will be fixed at a certain value and remains constant during performing this task, but different values of Z axis can be identified by producing several scenes with different degrees of Zs. However, X axis and Y axis of the novint falcon allow joints to perform shoulder and elbow flexion/ extension movements. In addition, virtual obstacles make the trajectory towards the goal object more constricted by the time, so joints will be constrained

to coordinate in certain normal mechanism in order to reach the goal object and enhance reaching accuracy as can be seen in Fig 3.9.a.



a) Multiple goals reach scenario b) Flexion and extension strategy

Figure 3.9: Flexion-Extension movement

A commonly discussed strategy, about controlling trajectories during movements maintaining the posture of the upper limb in anterior and lateral positions, is the flexion and extension of joints. This strategy is mainly required changes in X axis of those joints, accompanied may be with changes in Y axis depend on the location of the target goal. So, to perform this strategy, subjects need to perform trajectories that require changes in these axes to be applied, as can be seen in Fig 3.9.b.

Let us define the work-space region γ as below:

$$\gamma = \left\{ X \in R^3 : \|X\|_\infty \leq \frac{w}{2} \right\} \qquad (8)$$

Where $X = \begin{bmatrix} x & y & z \end{bmatrix}^T$ is a vector that represents the position of the handler of the haptic device in VR scenarios, and w is the whole work-space length.

In this scenario possible movements that the haptic device can perform is limited in between:

$$\Omega = \Omega_1 \cup \Omega_2 \cup \Omega_3$$

But there are limitations of Y axis at different levels of X axis in order to make trajectories stricter in terms of orientation by the time as following:

$$\Omega_1 = \left\{ X \in \gamma_{xy} : \left\| X - x_1 \right\|_\infty \le k_1 \right\}$$

$$\Omega_2 = \left\{ X \in \gamma_{xy} : \left\| X - x_2 \right\|_\infty \le k_2 \right\}$$

$$\Omega_3 = \left\{ X \in \gamma_{xy} : \left\| X - x_3 \right\|_\infty \le k_3 \right\}$$

Where γ_{xy} is the projection of the work-space γ onto the plane (x, y). All regions have to be placed within the work space. So the parameters $k_i, i = 1,2,3$ must respect the following constraint:

$$\sum_{i=1}^{3} k_i < \frac{w}{2}$$

And in general with n regions:

$$\Omega = \bigcup_{i=1}^{n} \Omega_i, \text{ whereas } \Omega_i = \left\{ X \in \gamma_{xy} : \left\| X - x_i \right\|_\infty \le k_i \right\} \quad (9)$$

3.5.1.2 Flexion-Extension scenario

In this scenario, each child needs to touch the goal object using the blue ball which represents the movement of the haptic device (Novint Falcon®). This goal object will be destroyed when it has been reached, and other goal object will be appears to encourage the child to move toward that object. By applying this movement, the child will perform the desired shoulder/ elbow flexion-extension. Any other compensation movement will be heavily reduced by the force feedback coming from the falcon, and this force works according to the virtual walls in the VR scenario as can be seen in Fig 3.10.

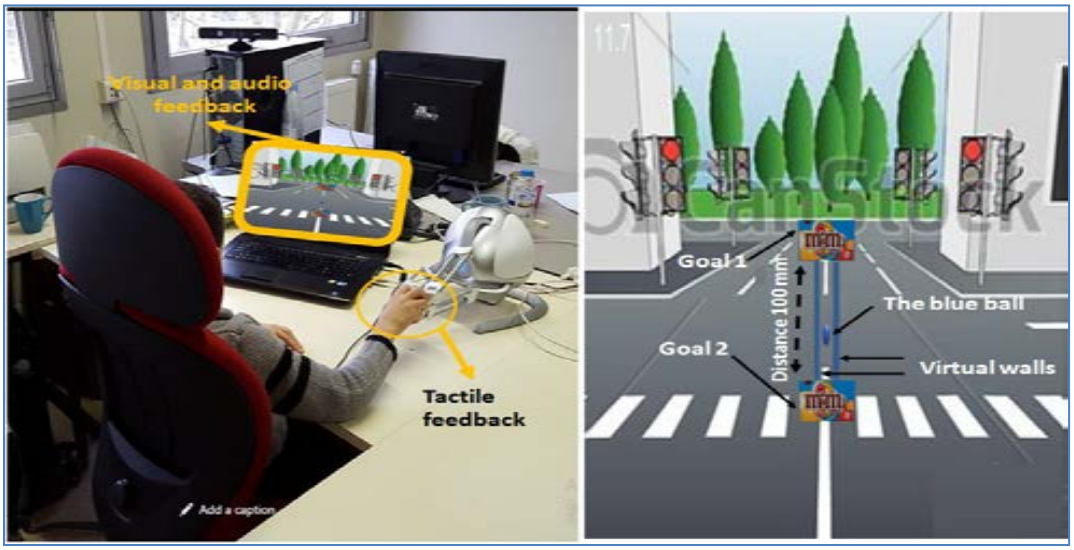


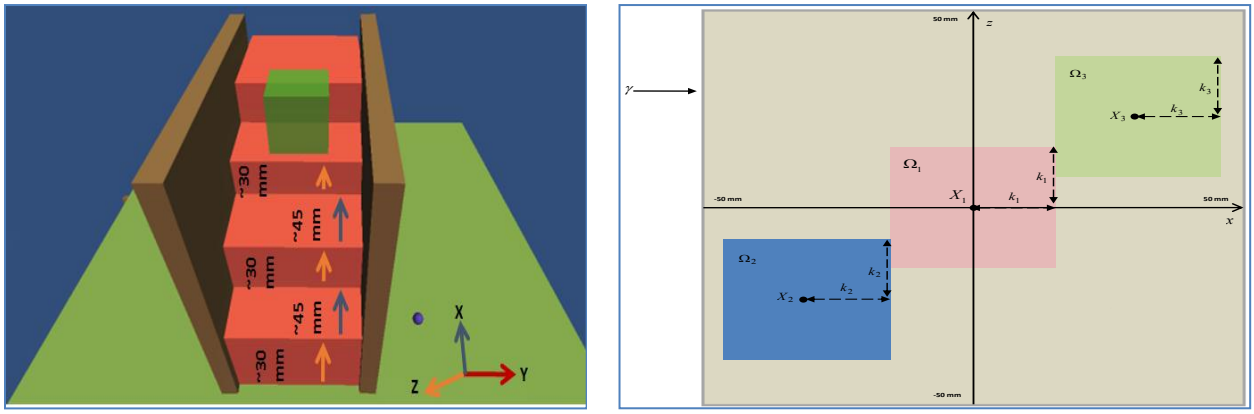
Figure 3.10: Flexion-extension scenario

3.5.2 Abduction-Adduction movement

3.5.2.1 Stairs climb

The main interest of stairs climb simulation is to improve shoulder lift and elbow extension joints' coordinate. As can be seen in Fig 3.11.a, subjects will practice shoulder lift and elbow extension by trying to move the blue ball to the goal object. However, all unwanted movements (abnormal joint recruitment) would be prevented by determined certain trajectory to reach the goal. This trajectory allows changes in (X, Y, and Z) axis of UL's joints. Virtual obstacles (stairs, walls, floor, and hidden sky) are developed to enable joints to move certain axis in each level of this scenario. Furthermore, climb a stair requires a successful shoulder/ elbow coordinate to

move the blue ball to the next level, this coordinate was required each climb attempt with different Z axis.



a) stair climb b) Abduction and adduction strategy

Figure 3.11: Abduction-Adduction movement

In children with hemiplegia, when shoulder strategy fails to control the movement that responsible to perform abduction or adduction, a compensation strategy, most likely recruiting extra degree of freedom of trunk pending, responses to that action. However, in our strategy, the trunk movements will be eliminated, and a combined control strategy, which supports the shoulder abduction and adduction movements as well as elbow flexion and extension, is developed as can be seen in Fig 3.11.b. Note that movements that require changes in X axis and Z axis are predefined to act as a movement's support.

The work-space of the haptic device is fixed, so as has been defined in (8).

The admissible regions of the handle of the haptic are defined with the same manner as in section (3.5.1.1)

$$\Omega = \bigcup_{i=1}^{n} \Omega_i \text{, whereas } \Omega_i = \left\{ X \in \gamma_{xz} : \left\| X - x_i \right\|_{\infty} \leq k_i \right\} \tag{10}$$

Where γ_{xz} is the projection of the work-space γ onto the plane (x, z) in order to have the abduction and adduction movements desired, and n=3 in this case. The parameters k_i must also respect the following constraint:

$$\sum_{i=1}^{n} k_i < \frac{w}{2} \tag{11}$$

3.5.2.2 Abduction-Adduction scenario

In this scenario, each child needs to touch the goal object using the blue ball which represents the movement of the haptic device (Novint Falcon®). This goal object will be destroyed when it has been reached, and other goal object will be appears to encourage the child to move toward that object. By applying this movement, the child will perform the desired shoulder/ abduction-adduction. Initial position and the scenario are presented as can be seen in Fig 3.12. So, shoulder abduction-adduction will be performed. And other compensation movements will be avoided.

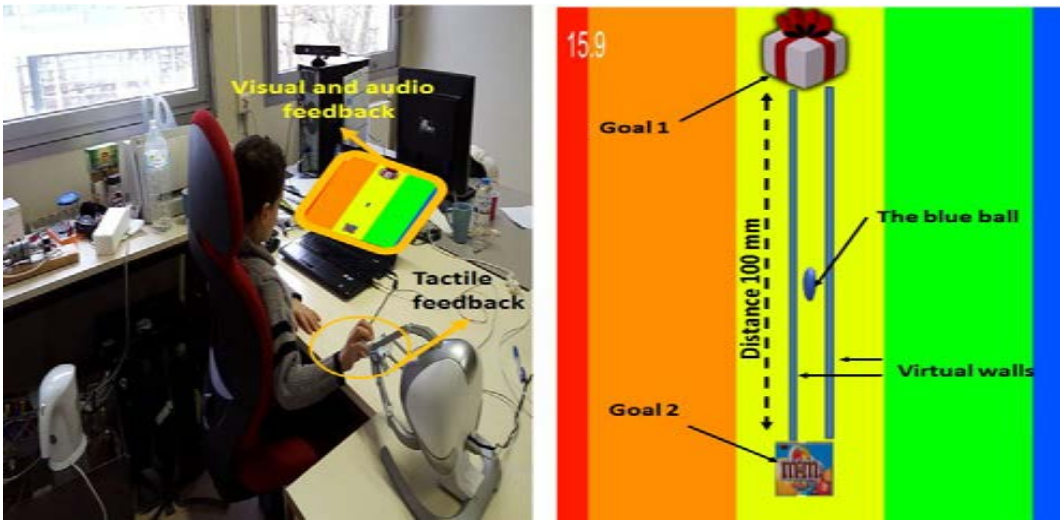
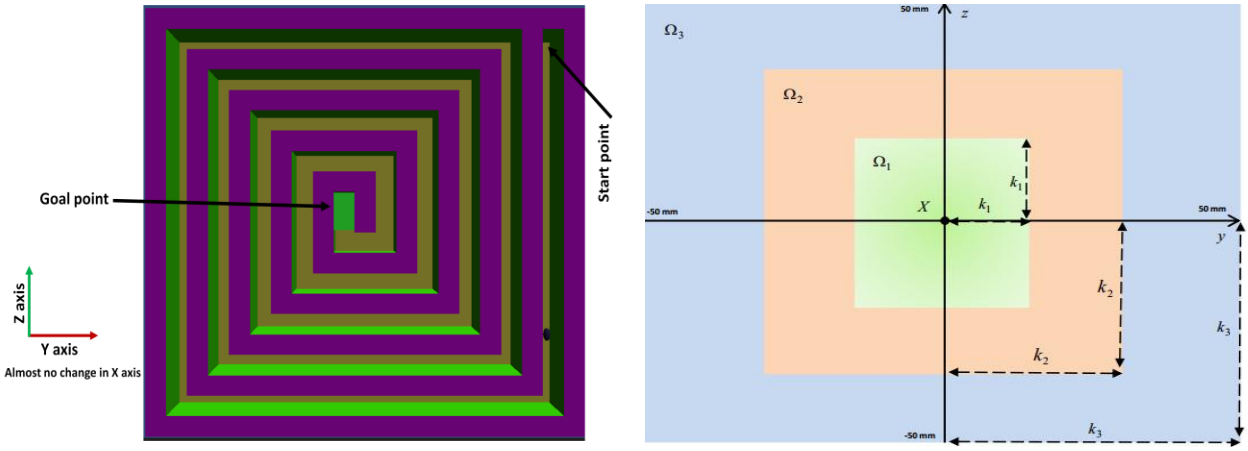


Figure 3.12: Abduction-Adduction scenario

3.5.3 Circumduction movement

In the circumduction strategy, shoulder and wrist joints can perform tasks, but only one joint can perform it each time. The possible movements are limited to Y axis and Z axis to enable circumduction strategy to be performed without changes in X axis as can be seen in Fig 3.13.a. The number of contacts between subjects and the haptic device are measured to figure out the level of independency of movements from trail to another.



a) External circumduction (outside→inside) scenario

b) Circumduction strategy

Figure 3.13: Circumduction movement

The limitations of Y axis at different levels of Z axis in order to make trajectories stricter as shown in Fig 3.13.b. this configuration constrains the movements of the target joint to perform the type of circumduction desired as following:

$$\Omega_1 = \left\{ X \in \gamma_{yz} : \|X\|_\infty < k_1 \right\} \tag{12}$$

$$\Omega_2 = \left\{ X \in \gamma_{yz} : k_1 < \|X\|_\infty < k_2 \right\} \tag{13}$$

$$\Omega_3 = \left\{ X \in \gamma_{yz} : k_2 < \|X\|_\infty < k_3 \right\} \tag{14}$$

However, in order to enable subjects to move from region to another, depend on the type of circumduction required, the next definitions need to be followed:

$$\Omega_1^1 = \left\{ X \in \gamma_{yz} : y = k_1, -k_1 \le z \le 0 \right\} \tag{15}$$

$$\Omega_2^1 = \left\{ X \in \gamma_{yz} : y = k_2, -k_2 \le z \le \frac{-k_2}{2} \right\} \tag{16}$$

Whereas $\Omega = \Omega_1 \cup \Omega_2 \cup \Omega_3 \cup \Omega_1^1 \cup \Omega_2^1$.

So internal circumduction (inside →outside), as well as external circumduction (outside→inside) will be performed.

$$\Omega_1^2 = \left\{ X \in \gamma_{yz} : y = -k_1, -k_1 \le z \le 0 \right\} \tag{17}$$

$$\Omega_2^2 = \left\{ X \in \gamma_{yz} : y = -k_2, -k_2 \le z \le \frac{-k_2}{2} \right\} \tag{18}$$

Whereas $\Omega = \Omega_1 \cup \Omega_2 \cup \Omega_3 \cup \Omega_1^2 \cup \Omega_2^2$

So internal circumduction (outside→inside), as well as external circumduction (inside →outside) will be performed.

The rest of circumduction movements are described in chapter 4, section 4.1.7

3.5.4 Pronation-Supination movement

In this scenario, each child needs to use the translator device shown in Fig 3.14. This device is responsible for converting the circular movement of the hand (elbow pronation-supination) to the straight movement in the Y axis in the VR as explained in section 3.3.3.

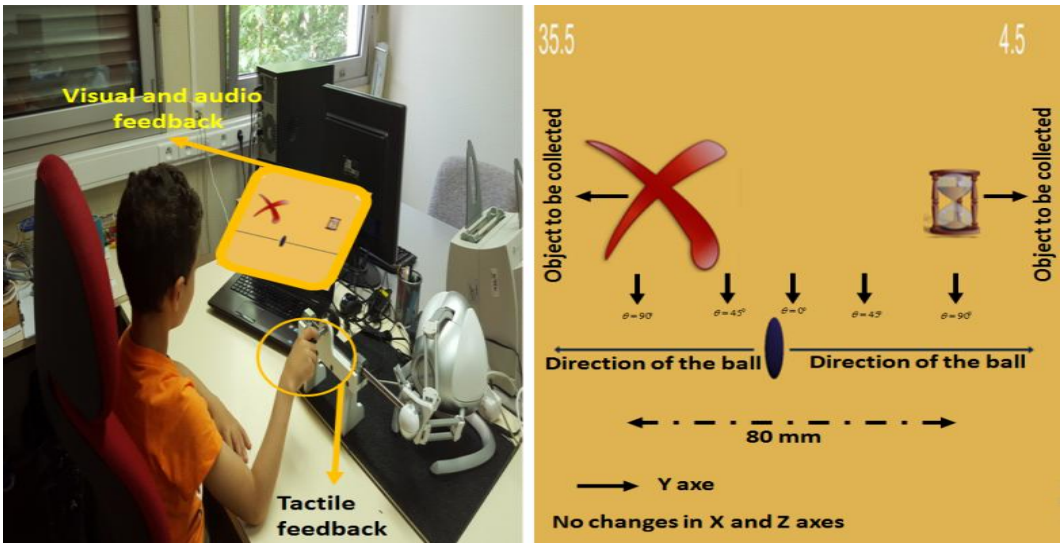


Fig 3.14: Pronation-supination scenario

In this scenario, there are multiple objects which will come-up in the scenario. Each object needs to be collected by the child, and those objects are positioned in the scenario to encourage

the child to make a certain pronation-supination angle. In other words, this configuration allows the children to perform the pronation-supination movements with different angles.

The other two scenarios which are made to do one movement by the time. Pronation scenario and Supination scenario are listed in appendix F.

In fact, there are other scenarios which have been made according to the needs of children and have been determined by the therapists. All of the developed scenarios are also listed in appendix F.

3.6 The assessment

Home-based therapy requires a full operation at home without the presence of the therapists. As a consequence, therapists have indicated that they prefer to have a core set of measurement instruments which require less user intervention, instruction, and interpretation [114]. In this work, we have developed two different assessment systems, which will fulfit the needs of the therapists, as following:

3.6.1 Three-dimensional analysis of the movement

VR provides visual and audio feedback to the patients; also it provides a useful data, about the activities that have been done by the patients, to the therapists [122, 123, and 124]. By using VR, patients can instantly see visual and audio feedback. Meanwhile, tactile feedback is provided by the haptic device, which will help them to recover functions of their upper limbs. But therapists need to know the data about the movement of the upper limb during performing tasks at home such as shoulder flexion-extension, shoulder abduction-adduction, shoulder rotation, elbow flexion-extension, and so on.

Inexpensive assessment device the Microsoft kinect^{TM} might be used in order to translate this information to the therapists. Kinect^{TM} is a promising solution for home-based assessment because of its portability, work-space, and price. In fact, this motion assessment device (kinect^{TM}) has been used in home-care: 1) To track the motion performance [125]. 2) In fall risk assessment at homes [126]. 3) To record posture and movements in 3D space to determine the risk of musculoskeletal injury in the workplace [127]. In these experiments, kinect^{TM} has been

used mainly to provide the position of the body joints in 3D according to the position of the kinect, and give the trajectories which have been made by each joint. Whereas the type of the movements along with thetas that have been made in each movement are needed by the therapist to observe the use of joint coordinate system by the hemiplegic children. For example, has the child make shoulder flexion-extension to perform certain movement that required flexion-extension? Or, has he performed other compensations like shoulder abduction-adduction to performed that movement?

There is a study which determines the type of shoulder movements and the thetas created during those movements [128]. They have used the circle which was created by the movement of the arm to determine the type of the shoulder movement (flexion-extension, and abduction-adduction) and the related theta. In this work, we have used the collected joints' data from the kinect™ to determine the type of the movements of all upper limbs segments and the related thetas to be given to the therapists of children with hemiplegia to enable them to judge the joint coordination system during movements for those children in home-based therapy.

3.6.1.1 The equipment

The Kinect consists of three sensors: a projector (an infrared IR emitter), a camera (a RGB color sensor), and an IR camera (an IR depth sensor) as in Fig 3.15. Body tracking is performed using the depth sensor, so the coordinates (X, Y, Z) of the body joints are correctly aligned with the depth frame only. The Kinect for Windows version 2 SDK 2:0 determines skeleton position information from the provided depth image. The result is Cartesian coordinates of joint positions related in meters with the Kinect depth sensor center as the origin. These skeletons acquire at a rate of about 20 to 26 samples per second [129].

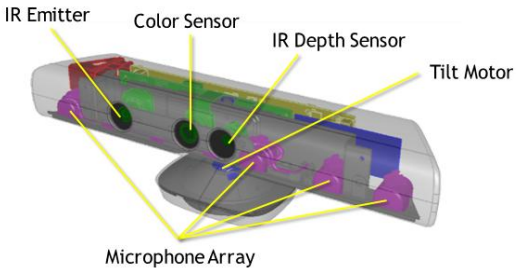
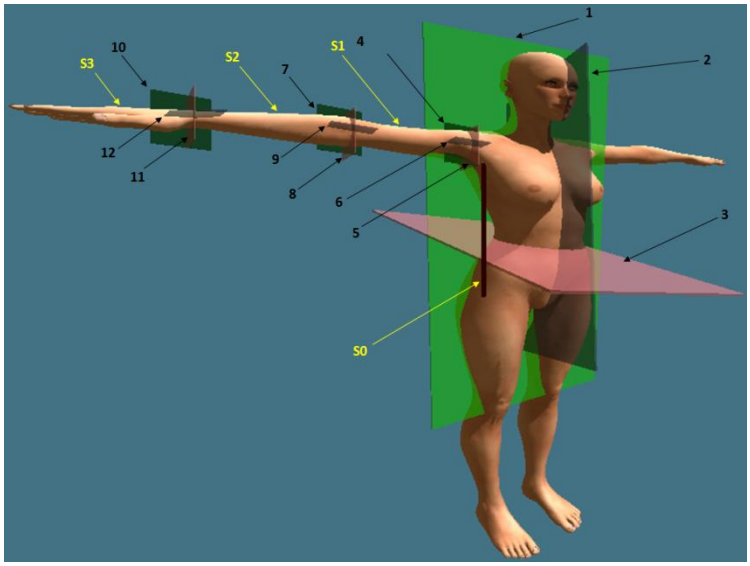


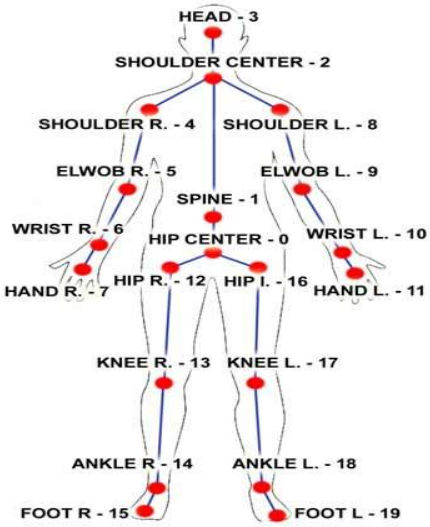
Figure 3.15: The kinect™ for windows

3.6.1.2 The proposed capture system

The purpose of this proposed system is to accurately determine the type of the upper limb movements and the exact thetas that were created during those movements in 3D space. We based on the classification of the upper limb joints defined by Theresa Bissell and Laura Steele [130] to build our new upper limb module which will allow us to determine those different types of upper limb movements in 3D space as can be seen in Fig 3.16.



a) The upper limb module



b) The body index for kinectTM

Figure 3.16: The upper limb description

As can be seen from Fig 3.16, there are the three main body planes coronal, sagittal, and transverse which markers in the figure as 1, 2, and 3 respectively. And for each upper limb joint we create the related three planes based on the fixed reference to that joint. For example, the fixed reference for the shoulder joint planes is the center shoulder-right shoulder vector, the fixed reference for the elbow joint planes is the right shoulder-right elbow vector, and the fixed reference for the wrist joint planes is the right elbow-right wrist vector. And in the same order for the left upper limb.

Theresa Bissell and Laura Steele [130] have classified the shoulder joint under the synovial joint classification, in which the Angular movements increase or decrease the angle between two

bones. Then, flexion movement decreases the angle of the joint and brings the articulating bones closer together see Fig 3.17.a; extension movement increases the angle between the articulating bones see Fig 3.17.b; abduction is the movement of a limb away from the midline body see Fig 3.17.c; and adduction is the movement of a limb toward the midline of the body see Fig 3.17.d. But they have also classified the pivot joints as a type of the synovial joint, these pivot joints consist of a rounded structure that protrudes into a sleeve or ring, and allow uniaxial rotation of a bone around the long axis, which give the shoulder the possibility to move from the flexion movement to the abduction movement in the same or different thetas. From this definition, we need to define the exact shoulder flexion-extension movements, the exact abduction-adduction movements, and most common in-between flexion-abduction movements in 3D space.

We redefine the Flexion-Extension movements in 3D space as the intersection of the transverse plane -6- of the shoulder with the sagittal plane of the body -2-. If there is no intersection then we are in the exact flexion-extension movement. In order to facilitate the intersection determination between these two planes, we calculate the normal vector of each of those two planes, to determine whether they are: a) parallel (no intersection) as in (1), b) perpendicular which means the movement is the exact abduction-adduction movement as in (2), theta of these two movements can be calculated from the created angle between the right shoulder-right elbow vector (S1) and the shafted center shoulder-neck vector (S0) as in (3), c) or they are not parallel and not perpendicular. So, we are in-between flexion-abduction movement and we need to calculate the angle of rotation in the Y axis of the shoulder to find the degree of affiliation of that movement to flexion or abduction movement. In this case we calculate the angle between the planes -4- and -3- as in (4).

$$\frac{x}{a}=\frac{y}{b}=\frac{z}{c}. \text{ Whereas } V_1 =< x,y,z >,\ V_2 =< a,b,c > \tag{1}$$

$$V_1 * V_2 = (x)*(a)+(y)*(b)+(z)*(c)=0 \tag{2}$$

$$\cos(\theta)=\frac{((x)*(a)+(y)*(b)+(z)*(c))}{\sqrt{x^2+y^2+z^2}*\sqrt{a^2+b^2+c^2}} \tag{3}$$

Where V_1 represents the normal vector of plane -6-, and V_2 represents the normal vector of plane -2-

$$\cos(\theta) = \frac{((x)*(a)+(y)*(b)+(z)*(c))}{\sqrt{x^2+y^2+z^2}*\sqrt{a^2+b^2+c^2}} \quad (4)$$

Where V_1 represent the normal vector of plane -4-, and V_2 represent the normal vector of plane -3-

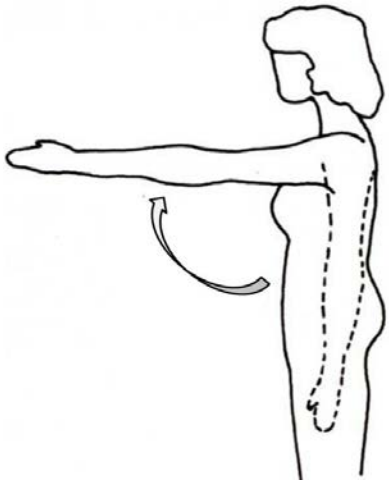
For the elbow joint, they [130] have related the flexion-extension movements to the hinge joint which makes a smooth stable movement. In our system, the elbow angle is calculated in 3D from the angle between the two vectors (S1, S2) as in (3), where V_1 and V_2 represents S1 and S2 respectively. Knowing that the projection of the vector -S1- is always on the plane -9-

For the wrist joint, the wrist flexion-extension angle is created by the projection of the vector -S3- onto the plane -10- which has the normal vector D1, the vector D1 is created by the null product of the vector -S2- as in (5). The wrist abduction-adduction angle is created by the projection of the vector -S3- onto the plane -12- which has the normal vector D2, the vector D2 is created by the null product of the vector -S2- as in (6).

D = null (S3), and then D1 = D (:1) (5)

D = null (S3), and then D2 = D (:2) (6)

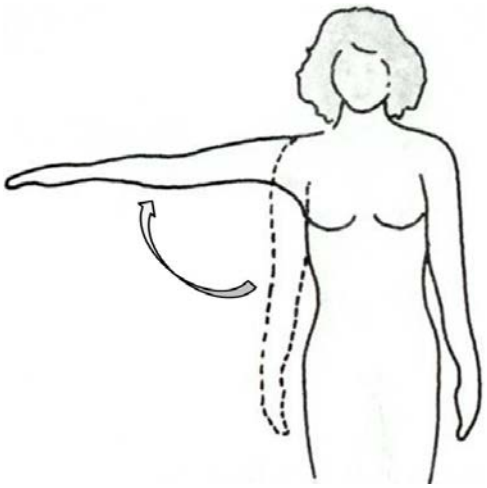
The projection of the vector -S3- onto plane D1 and D2 is called P1 and P2 respectively. The flexion extension angle and the abduction adduction angle can be found by calculating the angle between the vector -S2- and P1 in the flexion-extension, and the angle between the vector -S2- and P2 in the abduction-adduction as in (3).



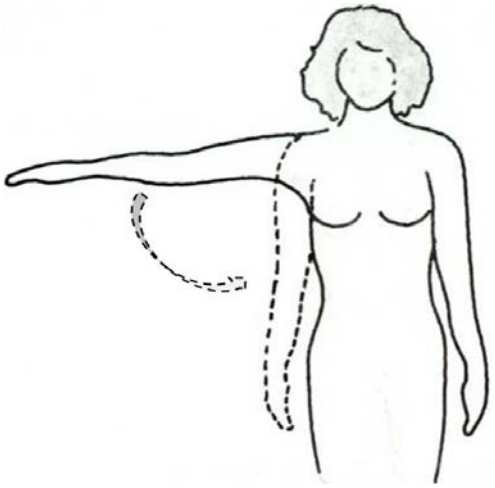
a) The shoulder flexion movement



b) The shoulder extension movement



c) The shoulder abduction movement



d) The shoulder adduction movement

Figure 3.17: The shoulder different movements

3.6.2. A fuzzy logic decision maker for the level of improvements in upper limbs therapy

3.6.2.1 Experimental setup

In this section, we will present the experimental procedure, which contains the participants, the protocol, and the procedure.

1) **Participants**

Two children, 5/7 years old, 114/129 cm, 22/27 kg, boys (S1, S2) respectively, were participated. They were chosen to test the feasibility of the system and its usability for the therapists. Children were chosen based on their ability to practice all proposed joints' recruitments and see if these movements have been correctly transformed to decisions.

2) **Protocol**

Subjects have used the novint falcon haptic device along with VR scenarios for five days, two times a day, and for five minutes each attempt, in order to practice all possible normal joints' recruitments that needed to perform a relative ADLs in future. Each subject has played the two scenarios proposed in each session. In fact, subjects have experienced Shoulder and Elbow Flexion-Extension movements in the first scenario, and Shoulder-Lift Elbow-Extension in the second scenario.

3) **Setup**

Schemas cinematic were developed by using a 3D Virtual Reality (VR) application to control the behavior of the novint falcon haptic device which was used as the therapy hardware. This 3 degree of freedom (DOF) haptic device was used to determine the actual position of the impaired UL in the proposed scenario as well as the time consumed to perform one or more actions as can be seen in Fig. 3.18, the hand of the impaired limb apply an external force on the handle of the falcon to move the blue ball which represents the movement of the device in the VR scenarios, thus the external PC register the position and the time needed to reach that final position or goal position, as well as the number of the connection between the hand and the force feed-back exerted by the falcon to redirect the hand in the proposed trajectory. And then use these

parameters to find out the diverse enhancement of different possible categories (time, position, accuracy...).

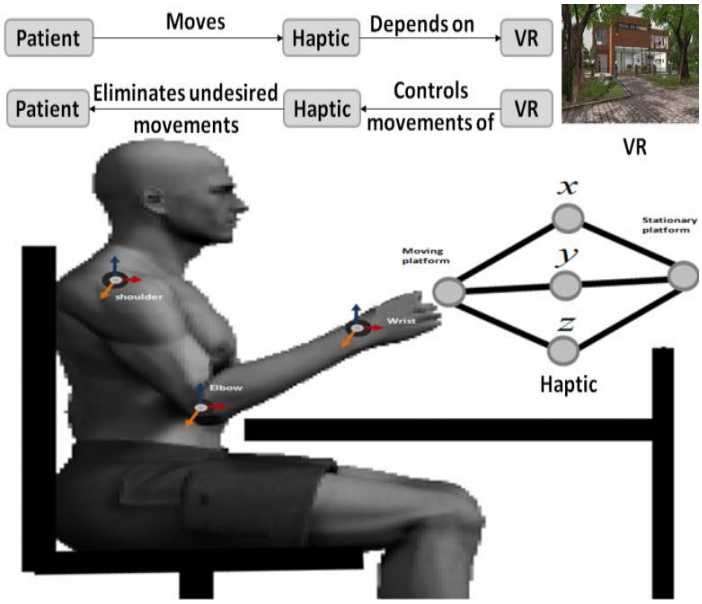


Figure 3.18: Subject with VR scenarios (Fig.3.19, Fig.3.20)

4) **Procedure**

1) Intitial position

- For Shoulder-Elbow Flexion-Extension movements: The subjects were seated comfortably at a height-adjustable table in order to have their shoulder flexion at $\approx 45^0$, elbow flexion at $\approx 135^0$ with the hips and knees flexed 90^0 and both feet flat on the ground. Both elbows were rested on the table so that the shoulder was in the neutral position, the forearm was pronated, and the wrist was also held in neutral with the palms hold the handle of the falcon which was placed at certain height for each child in order to end up with 90^0 of shoulder extension at their maximum reach. They have used a comfortable seat belt to reduce the trunk compensation, knowing that small amount of this type of compensation in this period of age is normal.

- Shoulder-Abduction Elbow-Extension movements: The subjects were also seated at a height-adjustable table in order to have their shoulder abduction at $\approx 45^0$, and elbow flexion at $\approx 90^0$ with the hips and knees flexed 90^0 and both feet flat on the ground. The

haptic device was positioned in the right hand side of the body to enable the children to perform the desired movements. They have also used a comfortable seat belt to reduce the trunk compensation.

2) Flexion-Extension movement

The purpose of multiple goals reach simulation is to improve bilateral shoulder and elbow movements, as well as reaching accuracy. The VR scenario shows a three-dimensional floor, and roads with different spaces. Although Z axis will be fixed at a certain value and remains constant during performing this task, but different values of Z axis can be identified by producing several scenes with different degrees of Zs. However, X axis and Y axis of the novint falcon allow joints to perform shoulder and elbow flexion- extension movements. In addition, virtual obstacles impose the haptic device and then the UL to remain within the proposed trajectory, and make the trajectory towards the goal object more constricted by the time, so joints will be constrained to coordinate in certain normal mechanism in order to reach the goal object and enhance reaching accuracy as can be seen in Fig. 3.19.

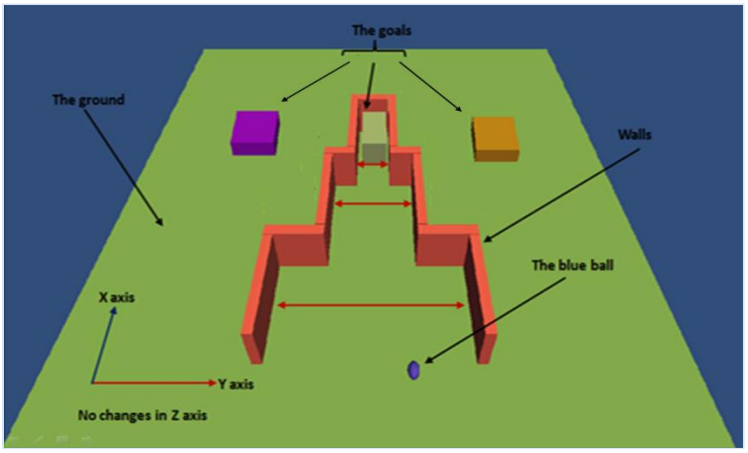


Figure 3.19: Multiple goals reach scenario

3) Abduction-Adduction movement

The main interest of stairs climb simulation is to improve shoulder lift and elbow extension joints' coordinate. As can be seen in Fig 3.20, subjects were practiced shoulder lift and elbow extension by trying to move the blue ball to the goal object. However, all unwanted movements (abnormal joint recruitment) would be prevented by determined certain trajectory to reach the goal. This trajectory allows changes in (X, Y, and Z) axis of UL's joints. Virtual obstacles (stairs, walls, floor, and hidden sky) are developed to enable joints to move certain axis in each level of this scenario. Furthermore, climb a stair requires a successful shoulder/ elbow coordinate to move the blue ball to the next level, this coordinate was required each climb attempt with different Z axis.

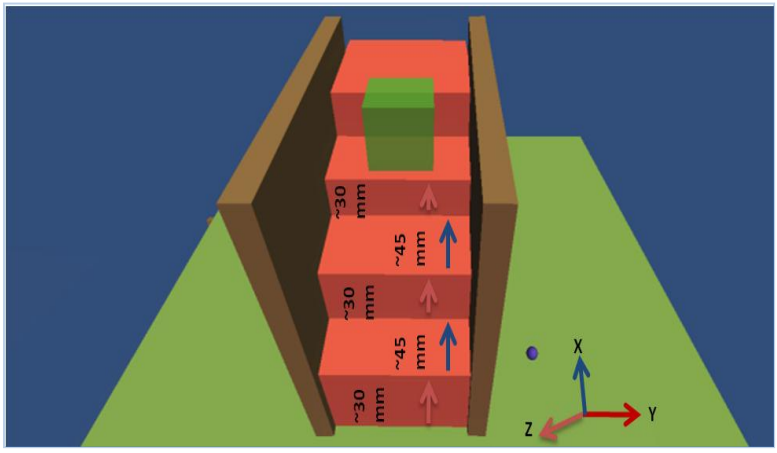


Figure 3.20: stairs climb scenario

3.6.2.2 Data analysis

In both scenarios, the time needed to complete a task represents the speed of the UL during movements. So, as less the needed time as fast the movement of the UL. In fact, if the movement of the UL is fast then it can collect more objects. Thus, we consider this data for the needed time as quantity of the movement.

The collision with virtual obstacles imposes the contact between the UL and the force feed-back of the haptic device to redirect that UL to stay within the proposed trajectory. Thus, the number of collisions with virtual obstacles increases when a child attempts to make other movements or attempts to make a compensation movement to reach the goal point. In other

words, the number of collisions represents the accuracy and smooth of the movement of the UL. So, as less the number of collisions as better the quantity of the movement is.

Each assessment category such as time, and number of collisions, needs to be analyzed, based on the proposed fuzzy approach, in order to determine its affiliation to that category level as following:

1) Patient enhancements: fuzzy approach

Zadeh has defined the fuzzy set as a generalization of crisp set [131]. Each individual in a fuzzy set has a certain degree of membership, which illustrates the level of compatibility of that individual with the concept of that fuzzy set. Each fuzzy set, F, is defined by the set of elements, X, which contains of each element (x) that verify the function F(x), in the closed interval [0, 1]. So, the degree of membership of x in F can be defined as: $\mu_F(x)$: $x \rightarrow [0, 1]$. The fuzzy set F is normal if $sup_x \mu F(x) = 1$, so we distinguish two kinds of membership functions depend on the degree of membership, triangular form, and trapezoidal form to represent our assessment categories as follows:

2) Fuzzification

Inputs for the fuzzification are the time needed to complete a task (T), and the number of contact with the force feed-back or the number of collisions with virtual obstacles (N) which comes from the haptic device. T shows the movement progression in respect of time, for example as much the time is small as much the ability of that UL is increased in terms of the quantity. Whereas N shows the accuracy of that movement, because as much the patient performs the movement without the aid of the haptic device (less number of N) as much the accuracy is. In this section we have used 5 fuzzy sets for each input: very small VS, small S, medium M, big B, and very big VB to include all possibilities for evaluating the movements. We choose triangular form and trapezoidal form to represent the different fuzzy sets as following:

For the triangular fuzzy member:

$$\mu F(x) = \begin{cases} 0 & if\ x < a\ \ or\ \ x > c \\ \frac{x-a}{b-a} & if\ \ a \leq\ x\ \leq\ b \\ \frac{x-c}{b-c} & if\ \ b \leq\ x\ \leq\ c \end{cases} \qquad (1)$$

For example, as can be seen from Fig 3.21. The fuzzy set, S, which represents the small values for the time, contains the following parameters: a=5, b=10, c=15. So the relation would be as follows:

$$\mu F(x) = \begin{cases} 0 & if\ x < 5\ \ or\ \ x > 15 \\ \frac{x-5}{10-5} & if\ \ \ 5 \leq\ x\ \leq\ 10 \\ \frac{x-15}{10-15} & if\ \ 10 \leq\ x\ \leq\ 15 \end{cases} \qquad (2)$$

In our case, if the needed time to complete a task was a number between 5 and 15 seconds, so this particular time is judged as small. Then, we calculate its affiliation to that small area based on the calculation shown in (2).

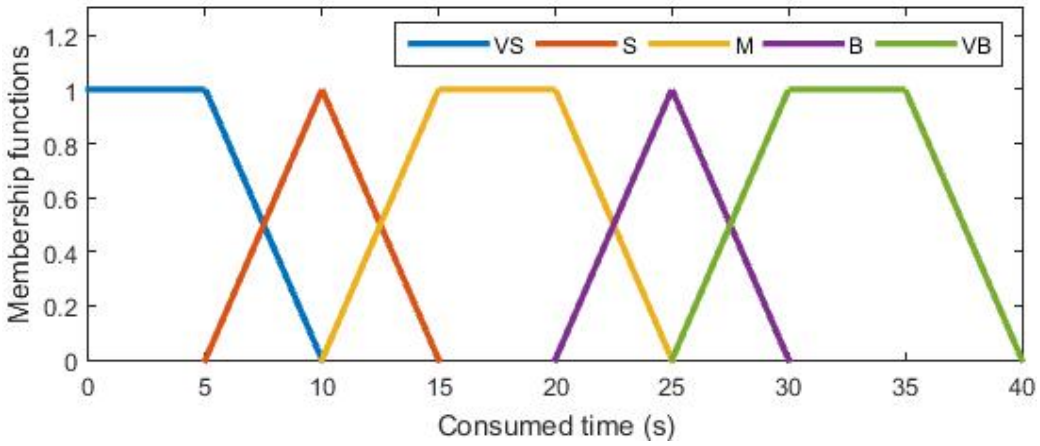


Figure 3.21: Overall expected levels of the proposals calculated when the maximum time is 40

For the trapezoidal fuzzy member:

$$\mu F(x) = \begin{cases} 0 & if\ x < a\ \ or\ \ x > d \\ \frac{x-a}{b-a} & if\ \ a \leq\ x\ \leq\ b \\ 1 & if\ \ b\ \leq\ x\ \leq\ c \\ \frac{x-d}{c-d} & if\ \ c\ \leq\ x\ \leq\ d \end{cases} \qquad (3)$$

For example, as can be also seen from Fig 3.21. The fuzzy set, M, which represents the medium values for the time, contains the following parameters: a=10, b=15, c=20, d=25. So the relation would be as follows:

$$\mu F(x) = \begin{cases} 0 & if\ x < 10\ \ or\ \ x > 25 \\ \frac{x-10}{15-10} & if\ \ 10 \leq\ x\ \leq\ 15 \\ 1 & if\ \ 15\ \leq\ x\ \leq\ 20 \\ \frac{x-25}{20-25} & if\ \ 20\ \leq\ x\ \leq\ 25 \end{cases} \qquad (4)$$

In our case, if the needed time to complete a task was a number between 10 and 25 seconds, so this particular time is judged as medium. Then, we calculate its affiliation to that medium area based on the calculation shown in (4).

The number of collisions levels and the level of enhancement are presented in Fig 3.22 and Fig. 3.23 respectively.

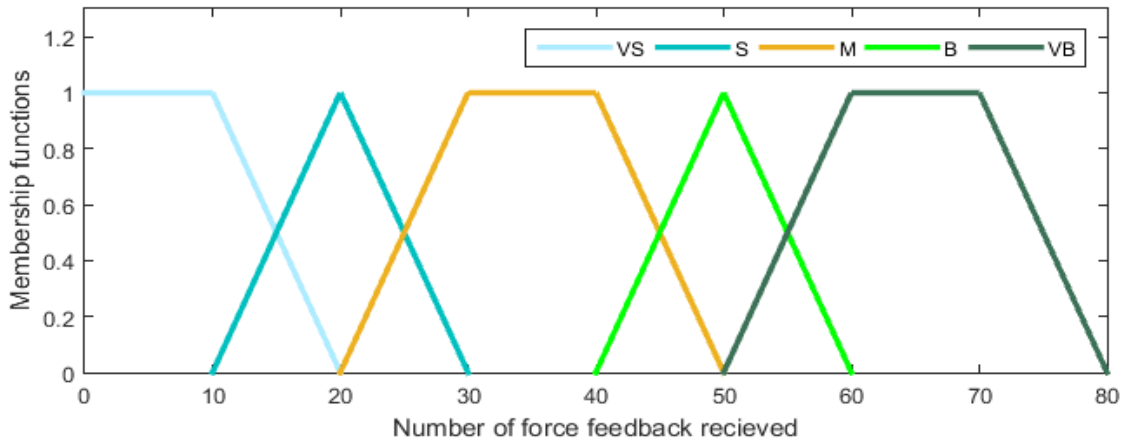


Figure 3.22: Overall expected levels of the proposals calculated when the maximum number of force feedback is 80

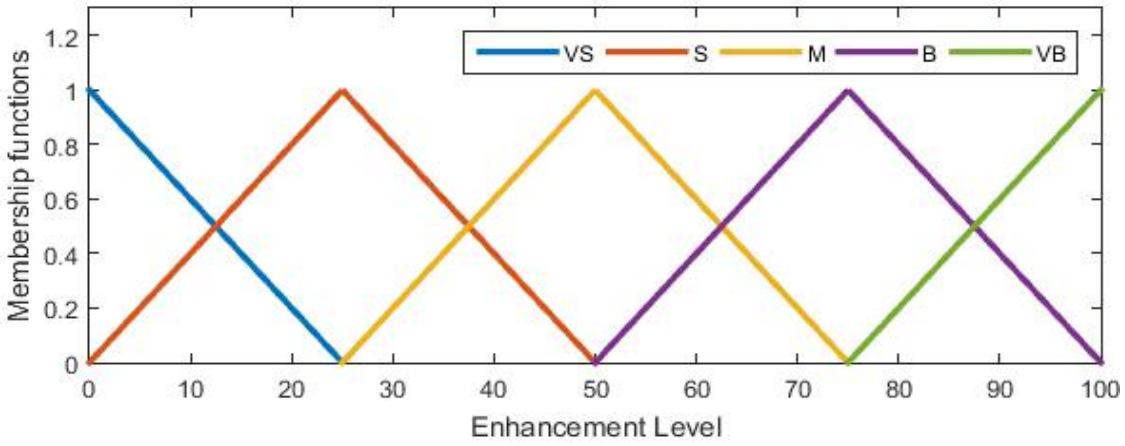


Figure 3.23: Overall expected levels of enhancement

3) Inference

In this section we have used Mamdani method depend on the rules shown in table 3.1. And based on the schema general for fuzzy system which presented in Fig. 3.24.



Figure 3.24: Schema general for fuzzy system

N \ T	VS	S	M	B	VB
VS	VB	VB	M	S	S
S	VB	B	S	S	VS
M	B	M	S	VS	VS
B	M	M	S	VS	VS
VB	M	M	VS	VS	VS

Table 3.1: Fuzzy rule table

From Table 3.1, T is the needed time to complete a task, and N is the number of contact with the force feed-back during that task. This table is created based on the experience of the medical doctors who have the ability of judging movements. For example: If the time (T) is very small (VS) and the number of force feed-back (N) is very small (VS) then the decision (enhancement) is very big (VB), also If the time (T) is very big (VB) and the number of force feedback (N) is

very big (VB) then the decision (enhancement) is very small (VS), and so on. Each field, for example VS, has limits form start point to end point. This period gives the possibility to determine the degree of affiliation of certain movement to that field as can be seen in section 3.6.2.3.

4) Defuzzification

Fuzzy outputs are combined into discrete values needed to drive the decision mechanism. And by applying the centroid method, we can find out the percentage of enhancement, this percentage helps the therapists to make their final decision as following:

$$E^* = \frac{\int \mu(E).EdE}{\int \mu(E).dE} \qquad (5)$$

Whereas E^*, $\mu(E)$ are the enhancement level and the output of the inference rule respectively, for a given consumed time and number of force feed-back received during a movement.

In our case, we combine the two areas of assessment which are T and N. Then we calculate the center of that new area to find the percentage of the level of enhancement of each movement.

3.6.2.3 Experimental results

- ***For the multiple goals reach:***

Both children were performing the suggested multiple goals reach scenario. By the time, the related data, such as the time needed to complete the task and the number of contact with the force feed-back, were collected by the system. Those collected data are used as inputs to the Fuzzification. And then we have applied the proposed fuzzy logic strategy to have the final decision. This decision depends on inputs parameters presented in Fig. 3.25.b. After several attempts of this particular movement a line chart, that illustrates the comparison between the quality and the quantity of this movement in the different attempts, was drawn to help the

therapists to make their choice about the following stage in the therapy process as can be seen in Fig. 3.25.c.

The different positions of the handle of the novint falcon, from the start point to the end point, were collected to draw the trajectory that represents the movement as can be seen in Fig. 3.25.a. An ideal trajectory was drawn for each type of movement. This ideal trajectory represents the correct joint recruitment from the start point to the end point without collisions with the virtual walls or haptic feed-back. The ideal trajectory was drawn by the developers to be compared with other trajectories of children when performing the same scenario.

Achieved trajectories from different attempts by children were compared with the ideal trajectory drawn in green, to see the level of movement accuracy at each attempt. At each trail, the drawn trajectory was compared with the relevant decision, which was come from the fuzzy strategy, to see the harmony between these two methods of assessment.

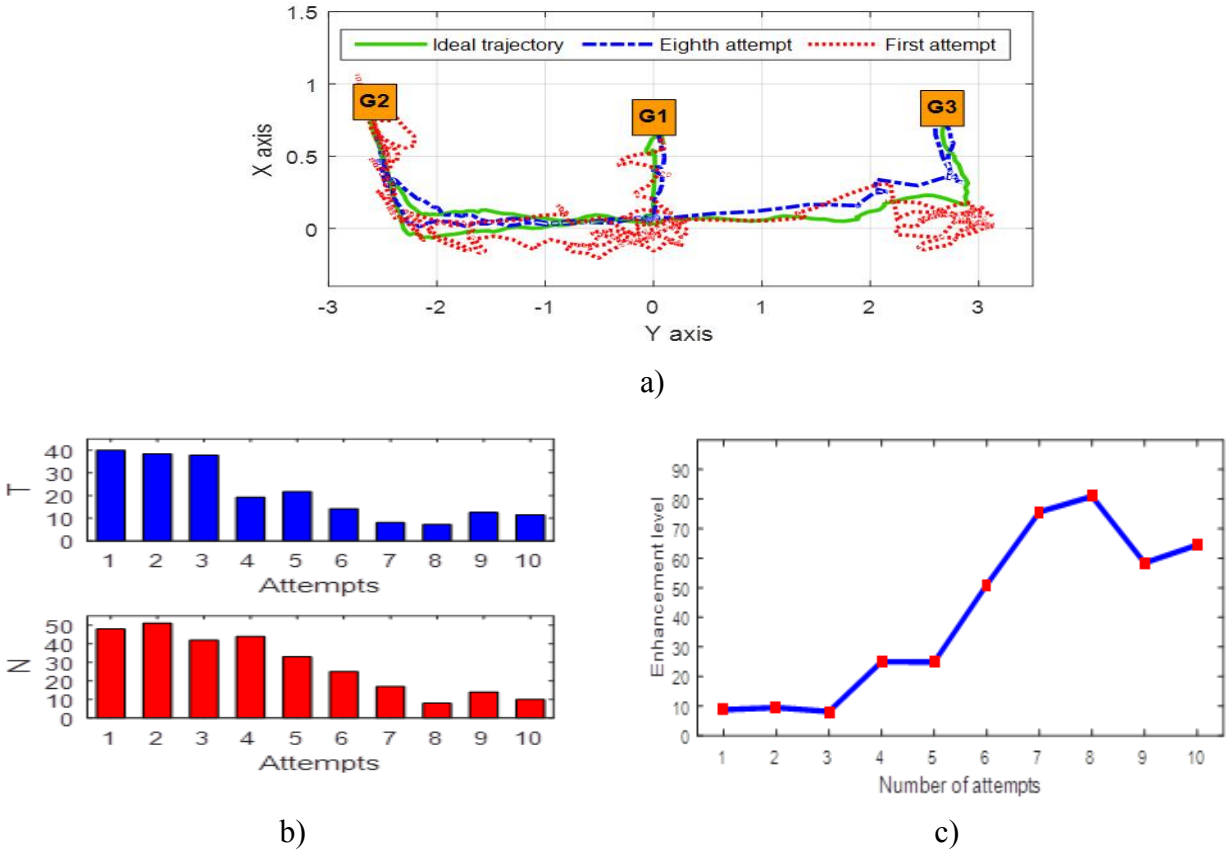
First of all, we are going to apply the fuzzy approach on the attempt number five as an example. As can be seen from Fig. 3.25.b, and c, T=21.7s, and N=33. First of all fuzzification needs to be performed as following: For the given T, and from the Fig. 3.21, we find that this particular time is related to two memberships Medium (M), and Big (B). The next step is to find the degree of affiliation of this time T to each membership as following:

For T: With medium we are going to use trapezoidal fuzzy member because Medium membership is trapezoidal

$$\mu_M(21.7) = \frac{21.7 - 25}{20 - 25} = 0.66$$

And use the triangular fuzzy member for the Big membership because of that the Big membership is triangular

$$\mu_B(21.7) = \frac{21.7 - 20}{25 - 20} = 0.34$$



a)

b)

c)

Figure 3.25: (a) Different trajectories for VR scenario shown in Fig.3.19. (b) Time and number of contacts with the force feedback. (c) The line of enhancement for all attempts

From the concept of our fuzzy approach, we found that the other fuzzy members are equal to zero for this time T.

$$\mu_{VS}(21.7) = \mu_{S}(21.7) = \mu_{VB}(21.7) = 0$$

In other words, this time T is not related to Very small (VS), Small (S), or Very big (VB) memberships.

For N: From the Fig. 3.22. This related just to Medium (M) membership which needs to be counted by using trapezoidal fuzzy member as the Medium membership is trapezoidal

$$\mu_{M}(33) = 1$$

N for the other memberships VS, S, B, and VB is zero. So, this number for collision relates completely to the Medium membership.

Secondly we are going to perform the inference which will give us the exact area of all related memberships to this movement as following:

Rule1: T is medium (M) and N is medium (M) then the enhancement E is small (S). This results (S) has come from Table 1, and depend on the medical doctors' experience.

OR

Rule2: T is big (B) and N is medium (M) then the enhancement E is very small (VS).

By now, we have combined the relations between: 1) The degree of affiliation of T to (M) membership with the degree of affiliation of N to (M) membership. And, 2) The degree of affiliation of T to (B) membership with the degree of affiliation of N to (M) membership.

By applying the results on these rules we found:

Rule1: 0.66 * 1 which has been changed from the general case shown in Fig.3.26, for the Small membership in the enhancement level presented in Fig. 3.23. To the special case related to rule 1 when $\mu_M(21.7) = 0.66$ as shown in Fig.3.27.

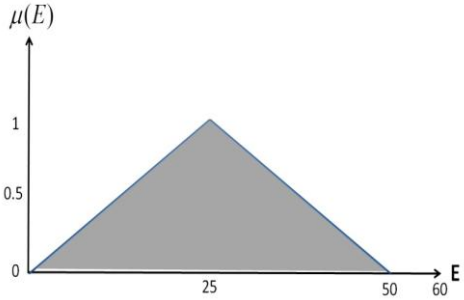


Figure 3.26: The normal member

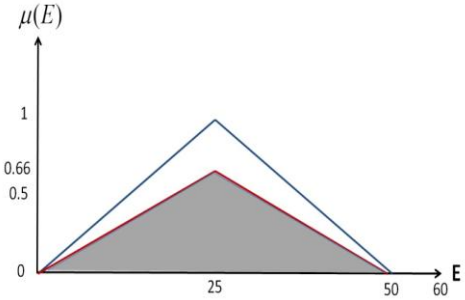


Figure 3.27: The related member

OR

Rule2: 0.34 * 1 which has been changed from the general case shown in Fig.3.28, for the Very small (VS) membership in the enhancement level presented in Fig. 3.23 in the enhancement level. To the special case related to rule 2 when $\mu_B(21.7) = 0.34$ as shown in Fig.3.29.



Figure 3.28: The normal member

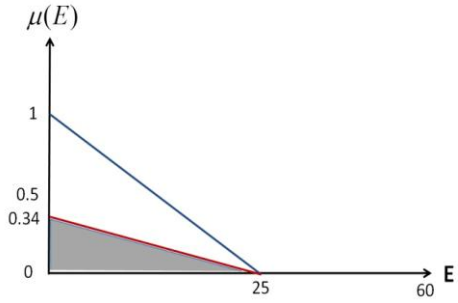


Figure 3.29: The related member

Now, we need to determine the related area to both rules in order to build the final decision about the enhancement level. This final related area ensures that the upcoming final decision is built on all related memberships to this movement. In order to achieve this goal, the max of the results between rule1 and rule2 needs to be calculated as following:

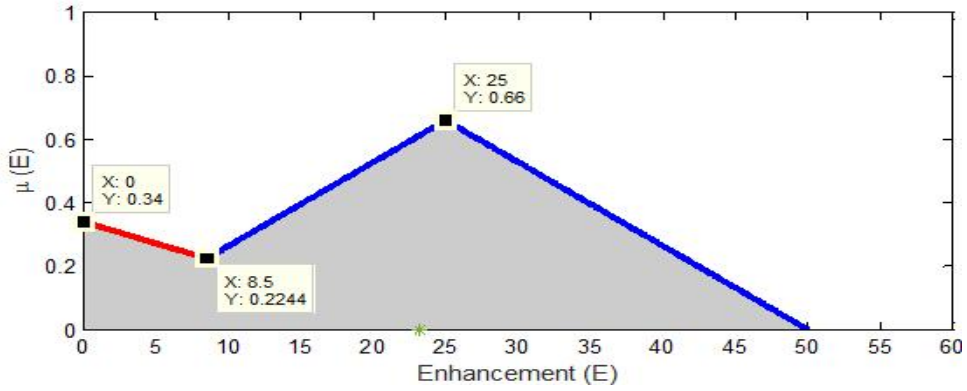


Figure 3.30: The complete related member

Finally, the deffuzzification needs to be applied to obtain the decision of enhancement for this attempt. In our case, the deffuzzification gives us the center point of this final area of memberships.

$$E^* = \frac{\int \mu(E).EdE}{\int \mu(E).dE} = \frac{A}{B}$$

From Fig. 3.30 we will start with A = $\int \mu(E).EdE = 416.5942$

Which was calculated by:

$$\int_0^{8.5}(\frac{-0.34}{25} * E^2 + 0.34 * E)dE + \int_{8.5}^{25}(\frac{0.66}{25} * E^2)dE + \int_{25}^{50}(\frac{-0.66}{25} * E^2 + 1.32 * E)dE$$

And then find the other equation B = $\int \mu(E).dE = 17.945$

Which was calculated by:

$$\int_0^{8.5}(\frac{-0.34}{25} * E + 0.34)dE + \int_{8.5}^{25}(\frac{0.66}{25} * E)dE + \int_{25}^{50}(\frac{-0.66}{25} * E + 1.32)dE$$

This finally gives us the decision about the percentage of the level of enhancement for this attempt as following:

$$E^* = \frac{416.5942}{17.945} = 23.215\%$$

This percentage comes from the application of the fuzzy approach to the obtained data from the system T, and N during performing the fifth attempt of Flexion-Extension movement.

- ***For stairs climb:***

Fig. 3.31 presents the collected data of stairs climb scenario. Those data consist of the needed time to complete the task and number of contact with the force feed-back. The collected data were used to make the final decision about the combined quantity and quality of this movement, based on the inputs to the proposed fuzzy strategy as can be seen in Fig. 3.31.b and c. Also, the drawn trajectories in this type of movement have been collected as can be seen in Fig. 3.31.a.

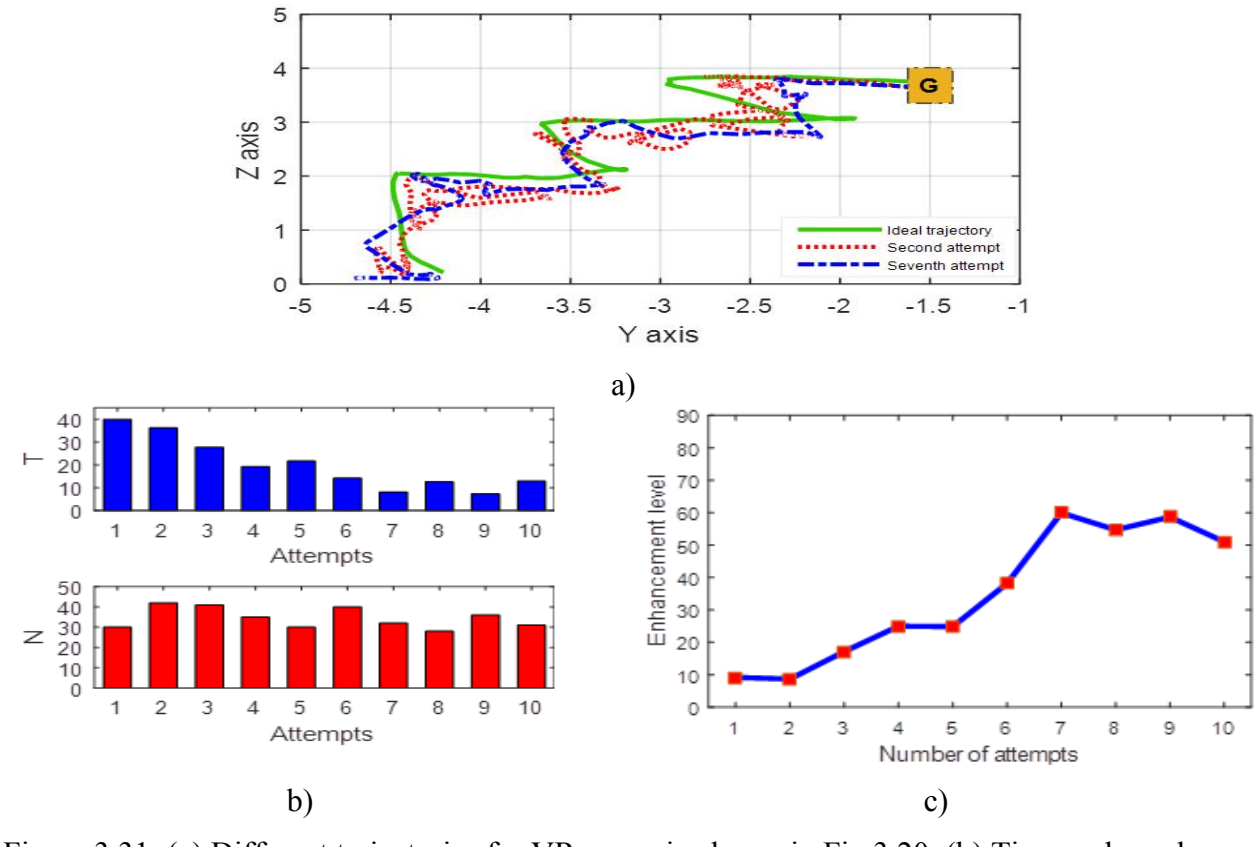


Figure 3.31: (a) Different trajectories for VR scenario shown in Fig.3.20. (b) Time and number of contacts with the force feedback. (c) The line of enhancement for all attempts

3.6.2.4 Discussion

Each subject completed the proposed training activities which concern their ULs. Fig. 3.25 illustrates the flexion extension movement applied by the subject S1. In the first attempt, which was the worst one for that child, the decision showed a little enhancement of this type of movement (8.755%) based on the related inputs of this attempt, which were (T=40.0s, and N=48), also the related trajectory was not compatible with the ideal trajectory of this movement. In other words, in this particular movement the joints of the targeted UL were constrained by the haptic feedback coming from the haptic device to reach the goal. So, the level of enhancement of this flexion extension movement was not good at 8.755%. This percentage has arrived from the degree of affiliation of this movement to the time and the number of contact with the force feedback. Whereas, in the eighth attempt, which was the best attempt, the decision showed a very big enhancement (80.89%) based on the little consumed time (T=7.3s), and the very small number of contact with the force feedback (N=8). In other words, the joints of the affected UL have performed this flexion extension movement with little help from the haptic device, which means that the movement has been performed almost by the UL itself. Similarly, the related trajectory, shown in blue, was the closet one to the ideal trajectory which confirms the decision obtained from the fuzzy strategy. However, Fig. 3.31 shows shoulder lift and elbow extension movement. By applying the same analysis, we can see the harmony between the different decisions and the related trajectories.

As can be seen from Fig. 3.25.c and Fig. 3.31.c, the therapists can observe the overall line of enhancement at each attempt, or the history of the performance of this particular movement, which helps them to make the proper conclusion about the therapy process, because depending on just one session of assessment, like in traditional assessment methods, might be not enough for such decisions.

Although different decisions were build based on the fuzzy rule table, shown in table 3.1, which contains the experience of the therapists, who work in the hospital of rehabilitation, the final decision of the next step of therapy still returns to the therapists . Also, other movements, such as rotation and supination pronation, still need to be considered in order to increase the reliability of this strategy.

3.6.2.5 Conclusion and perspective

The therapists normally based on the results of the measurement method to make the critical decisions about the level of enhancement at any type of movement. Use the traditional clinically measurement, or use measurement devices are the most common methods which help the therapists to make those decisions. This implies that the presence of the therapists and/ or use the measurement device which is difficult in home-based rehabilitation. For these reasons, this work suggests a basic fuzzy logic decision making approach. This approach is based on the time needed to complete a task, and the number of force feed-back needed to keep the UL within the proposed trajectory, in order to provide the therapists with the percentage of improvement in that particular type of movement to help them make their decision about the suitable next step in the rehabilitation process. The gained results from the case study illustrate the percentage of the level of enhancement at each attempt based on the inputs of those attempts. This also provides the therapists with the history of enhancement for each child, which is not possible when they do the traditional assessment from time to time.

In this work, we have used different methods in order to achieve the fuzzification, inference, and defuzzification, which we judge as the most suitable. Investigation of the effect of using the other methods on the accuracy of the final decision needs to apply.

3.7 Home-Based therapy system

Tele-rehabilitation can be defined as that the delivery of rehabilitation service at home. This service can be provided over telecommunication network and the internet. Most types of rehabilitation services fall into two categories: clinical therapy, and clinical assessment. Tele-rehabilitation can deliver therapy to children who cannot go to the hospital or clinic because of various reasons like geographical location, travel time, or children schedule. Tele-rehabilitation also allows for intensive therapy, especially for those which have interactive and motivated environment like virtual reality.

In this work, we have built a secured rehabilitation system to be used in both: clinic, and home. The system presents the VR scenarios to children to allow them play the suggested game. Children play the game using their given username and password to ensure the security of their data, by the time the system collect all related data and send it to therapists and/ or medical doctors via the internet. The system also saves all the data of each therapy session to the local memory of the used computer as can be seen in Fig. 3.32.

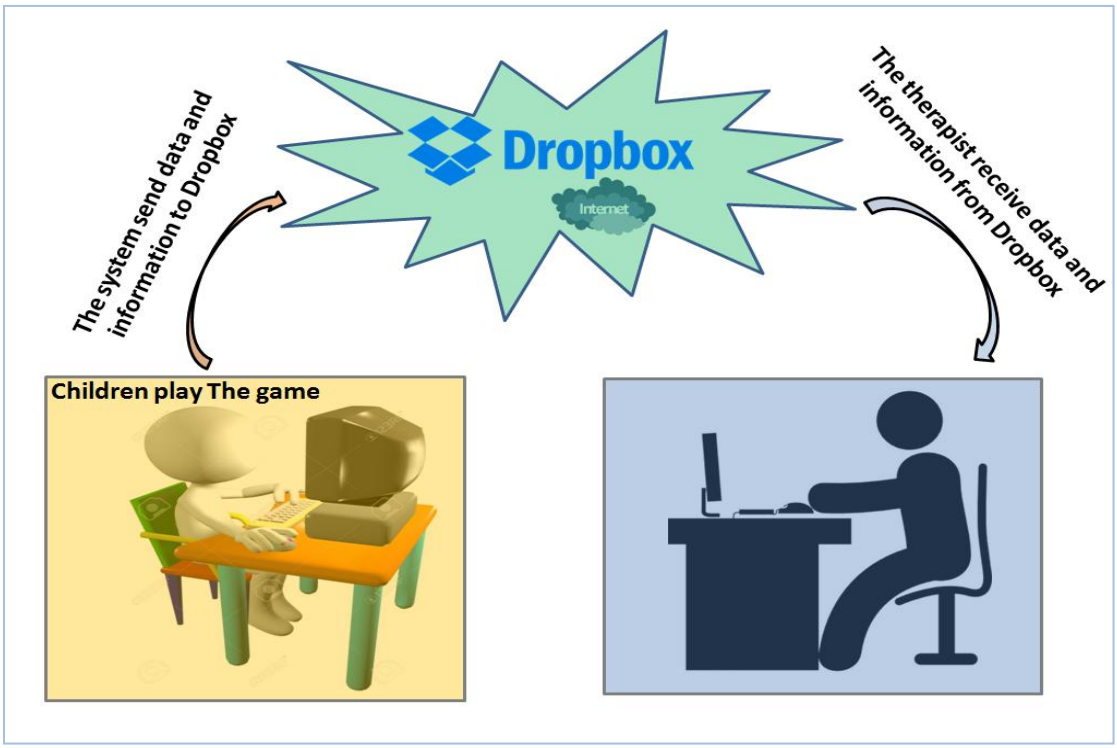


Figure 3.32: The general configuration for the Tele-rehabilitation

As can be seen from Fig. 3.33. The system collects the needed data from each attempt. Those data are: the needed time to complete a task, the number of contact with the force feed-back coming from the haptic device, and the number of collected objects during that particular attempt. Then, the system sends those data to the Matlab executable file. This Matlab file applies the fuzzy system on those data to generate the enhancement decision accordingly. The system creates a folder for that particular child who has performed the session, and put all the information related to that child in his/ her folder. Those information are: the numeric data about each session, and the fuzzy logic decision about the level of enhancement. The numeric data consists of the date and the time of the session, the consumed time during that session, the number of contact with the force feed-back, and the number of collected objects. Finally, the system put those information in the specified folder in the chosen Dropbox. This Dropbox space needs a username and password to access it. The therapists and/ or medical doctors can observe the continuality and the progression of each child during the time. Medical doctors can also specify certain scenarios to children by just put the needed scenarios to the Dropbox space.

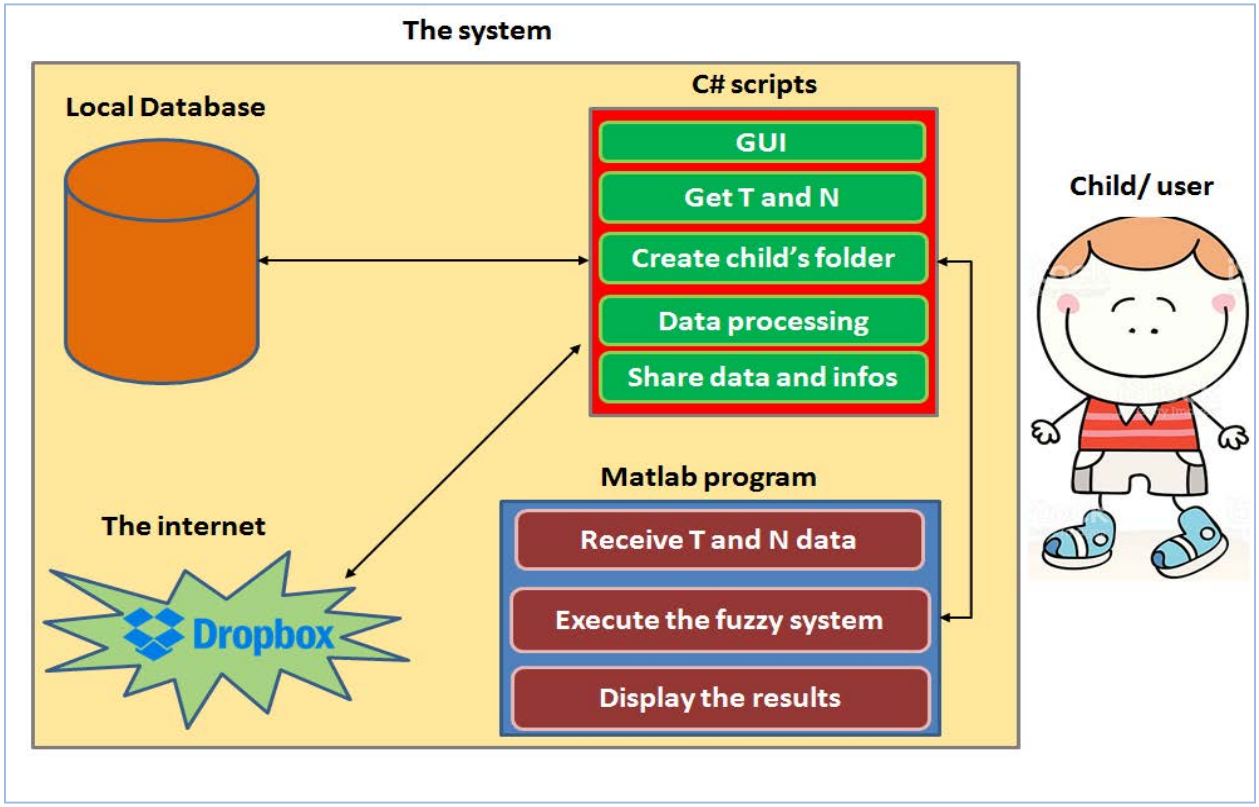


Figure 3.33: Data translation in the Tele-rehabilitation

Chapter 4: The experiments

In this chapter the three different therapy experiments are presented as well as one assessment experiment. Each therapy experiment has been done with different type of children and/ or with different conditions. The first experiment was done with two normal children to validate the integration between the VR and the novint falcon haptic device, and the feasibility of the system and its functionalities. The second therapy experiment was done with two children with hemiplegia in Marc Sautelet rehabilitation center to validate the system, its functionalities, and its effects on brain-motor coordination for children with hemiplegia. The third therapy experiment was done in cadre of tele-rehabilitation to validate its usability in this type of therapy, the repeatability, and its ease of use at homes. Each experiment will be detailed along with its protocol and results. The assessment experiment was done with one subject who was performed all different possible movements for each upper limb joint. This experiment was held on the Vicon system room in the University of Valenciennes.

4.1 The first therapy experiment

Normal children were participated in this case study to study the feasibility of using the tactile sensation along with visual and audio sensation on the joint coordinate system of upper limbs. The proposed movements of this experiment are: Shoulder-Elbow Flexion-Extension, Shoulder-Lift Elbow-Extension, Elbow Pronation-Supination, and all possible Shoulder Circumduction movements. Furthermore, this feasibility consists of the outcome of the system which helps the therapists to make their final decision about the quality and quantity of the proposed movement.

What does study of the feasibility of using visual, audio, and tactile means in our system? One reach to touch movement can be achieved in many joint coordination recruitments, these wide possibilities come from the complex chain setup of the joints of the upper limbs. In our system, each reach to touch movement needs to be performed in a certain joints' recruitment. For example, when the child wants to reach an object that locates right in front of him, he should perform Shoulder-Elbow Flexion-Extension. Other possible compensations to perform this movement, such as trunk pending or shoulder abduction, will be largely eliminated by the system. This system uses these three sensations to guide the children to perform the desired

joints' recruitments. The feasibility here means that whether or not the system guided the children to recruit their joints as needed.

4.1.1 The subjects

Two normal children, five and seven years old 114/129 cm, 22/27 kg, boys (S1, S2) respectively, were participated. They were chosen to test the feasibility of the system and its usability for the therapists. Children were chosen based on their ability to practice all joints' recruitments proposed and see if these movements have been correctly performed and transformed to decisions.

4.1.2 The protocol

Subjects have used the novint falcon haptic device along with VR scenarios for five days, three times a day (sessions), for five minutes each attempt. But the first attempt was neglected for each session. These exercises were done in order to practice some possible normal joints' recruitments that needed to perform relative ADLs in future. Each subject has played the seven proposed scenarios in each attempt. In fact, subjects have experienced Shoulder-Elbow Flexion-Extension movements, Shoulder-Lift Elbow-Extension movements, Elbow-Pronation movement, Elbow-Supination movement, Elbow Pronation-Supination movements, and all Shoulder-Circumduction movements (Internal from inside to outside, Internal from outside to inside, External from inside to outside, and External from outside to inside).

4.1.3 The initial position

- For Shoulder-Elbow Flexion-Extension movements: The subjects were seated comfortably at a height-adjustable table in order to have their shoulder flexion at $\approx 45^0$, elbow flexion at $\approx 135^0$ with the hips and knees flexed 90^0 and both feet flat on the ground. Both elbows were rested on the table so that the shoulder was in the neutral position, the forearm was pronated, and the wrist was also held in neutral with the palms hold the handle of the falcon which was placed at certain height for each child in order to end up with 90^0 of shoulder extension at their maximum reach. They have used a comfortable seat belt to reduce the trunk compensation, knowing that small amount of this type of compensation in this period of age is normal.

- For Shoulder-Abduction Elbow-Extension movements: The subjects were also seated at a height-adjustable table in order to have their shoulder abduction at ≈ 45^0, and elbow flexion at ≈ 90^0 with the hips and knees flexed 90^0 and both feet flat on the ground. The haptic device was positioned in the right hand side of the body to enable the children to perform the desired movements. They have also used a comfortable seat belt to reduce the trunk compensation.

- For Elbow Pronation-Supination movements: The subjects were seated at a height-adjustable table in order to have their shoulder flexion at ≈ 0^0, and elbow flexion at ≈ 90^0 with the hips and knees flexed 90^0 and both feet flat on the ground. The haptic device was positioned in front of the affected side of the body to enable the children to perform the desired movements. They have also used a comfortable seat belt to reduce the trunk compensation.

- For the Shoulder-Circumduction movements: The subjects were seated at a height-adjustable table in order to have their shoulder flexion at ≈ 90^0, and elbow extension at ≈ 180^0 with the hips and knees flexed 90^0 and both feet flat on the ground. The haptic device was positioned in front of the affected side of the body to enable the children to perform the desired movements. They have also used a comfortable seat belt to reduce the trunk compensation.

Splints were used on joints when needed to eliminate these joints movements, in order to enable the targeted joints to perform tasks proposed. These splints allowed us to target one joint each time in some cases which called one joint constraint (OJC). It also allowed us to target two joints in the same time, bilateral joints constraint (BJC). The hand of affected UL would be strapped to the handler of the novint falcon, which would restrict wrist and hand movement by applying force feedback according to virtual reality scenarios (obstacles, walls...). This would work as a simulation of what therapists normally do in the occupational therapy. The 3 DOFs haptic device allows the hand and wrist to be actively positioned in any point within its work-space; it has allowed the subjects to move from point to another point in the virtual scene via a well prepared trajectory to perform the desired angles' motion.

4.1.4 Multiple goals reach scenario

The purpose of multiple goals reach simulation is to improve bilateral shoulder and elbow movements, as well as reaching accuracy. The VR scenario shows a three-dimensional floor, and roads with different spaces. Although Z axis will be fixed at a certain value and remains constant during performing this task, but different values of Z axis can be identified by producing several scenes with different degrees of Zs. However, X axis and Y axis of the novint falcon allow joints to perform shoulder and elbow flexion- extension movements. In addition, virtual obstacles make the trajectory towards the goal object more constricted by the time, so joints will be constrained to co ordinate in certain normal mechanism in order to reach the goal object and enhance reaching accuracy as can be seen in Fig. 4.1.

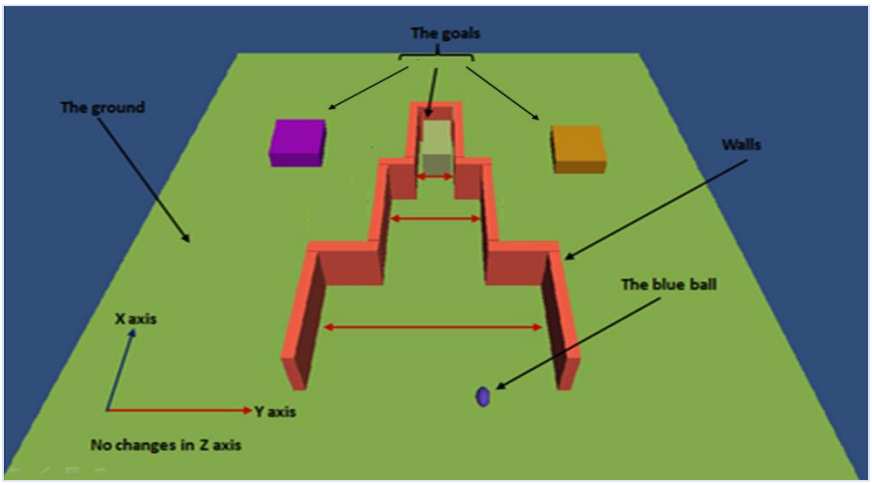


Figure 4.1: Multiple goals reach scenario

4.1.5 Stairs climb scenario

The main interest of stairs climb simulation is to improve shoulder lift and elbow extension joints' coordinate. As can be seen in Fig 4.2, subjects were practiced shoulder lift and elbow extension by trying to move the blue ball to the goal object. However, all unwanted movements (abnormal joint recruitment) would be prevented by determined certain trajectory to reach the goal. This trajectory allows changes in (X, Y, and Z) axis of UL's joints. Virtual obstacles (stairs, walls, floor, and hidden sky) are developed to enable joints to move certain axis in each level of this scenario. Furthermore, climb a stair requires a successful shoulder/ elbow coordinate

to move the blue ball to the next level, this coordinate was required each climb attempt with different Z axis.

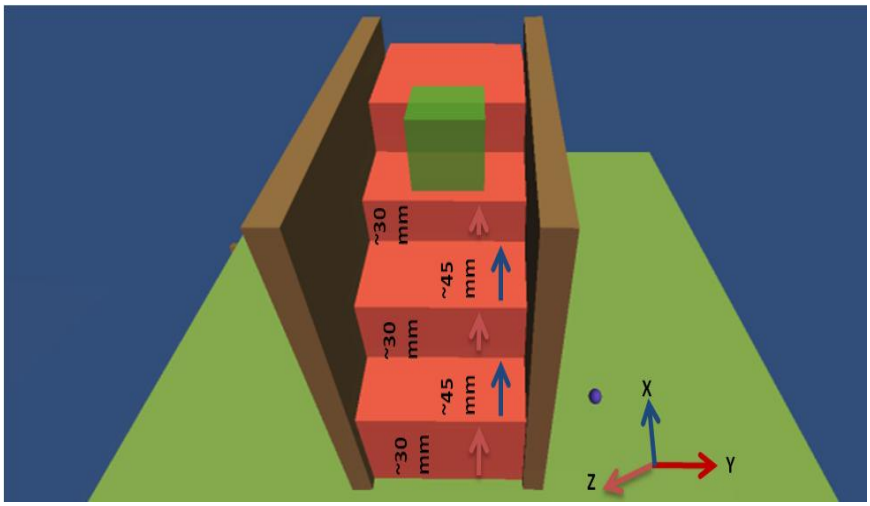


Figure 4.2: stairs climb scenario

4.1.6 Collect moving objects scenario

The main interest of collect moving objects is to improve elbow Pronation-Supination movements. As can be seen in Fig 4.3 a, subjects were practiced elbow pronation, supination, and pronation-supination movements by trying to move the blue ball in order to collect the moving objects which were presented in the VR scenarios. However, all unwanted movements (abnormal joint recruitment) would be prevented by determined certain trajectory to reach the goal. This trajectory allows changes in Y axis of the haptic device. The translate device, which responsible to transmit the rotation movement of the elbow to a straight movement in Y axis of the haptic device, enables the targeted elbow joint to perform Pronation-Supination movements. This scenario was developed to enable rotations with different angles such as 0^0, 45^0, and 90^0 in pronation movement, or 0^0, 45^0, and 90^0 in supination movement.

This movement can be performed by two joints to enable two different types of movements. First, Elbow Pronation-Supination if the elbow flexion is at 90^0. Second, Shoulder Internal-External rotation if the elbow extension is at 180^0.

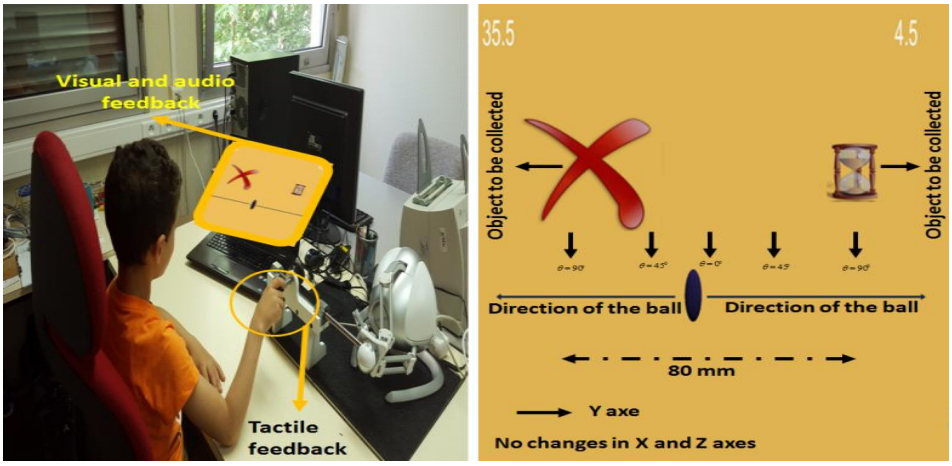
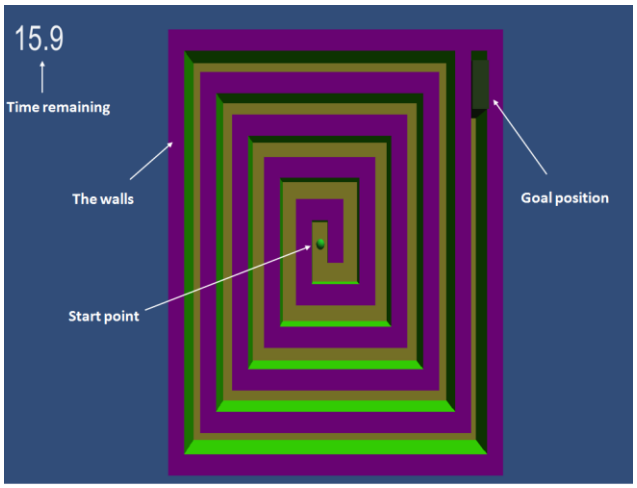


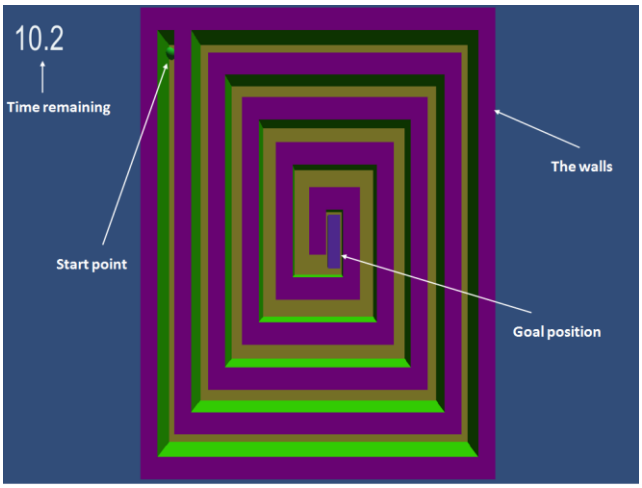
Figure 4.3: The rotation movements

4.1.7 The labyrinth

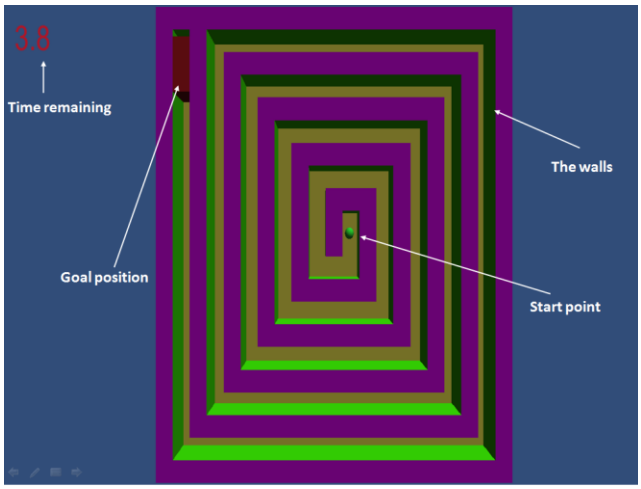
The main interest of the labyrinth scenarios is to improve shoulder different circumduction movements. As can be seen in Fig 4.4 a, subjects were practiced Shoulder Internal-Circumduction from inside to outside, Shoulder Internal-Circumduction from outside to inside as can be seen in Fig. 4.4.b, Shoulder External-Circumduction from inside to outside as can be seen in Fig. 4.4.c, and Shoulder External-Circumduction from outside to inside as can be seen in Fig.4.4.d. The two children have performed these movements by trying to move the blue ball from the initial position presented in the VR scenario to the goal position. However, all unwanted movements (abnormal joint recruitment) would be prevented by determined certain trajectory to reach the goal. This trajectory allows changes in Y, and Z axis of the haptic device and the VR scenario. The walls presented in each scenario control the behavior of the haptic device to constrain the target joint (shoulder) to perform the movement within this defined trajectory. This scenario was developed to enable circumduction movements with different angles.



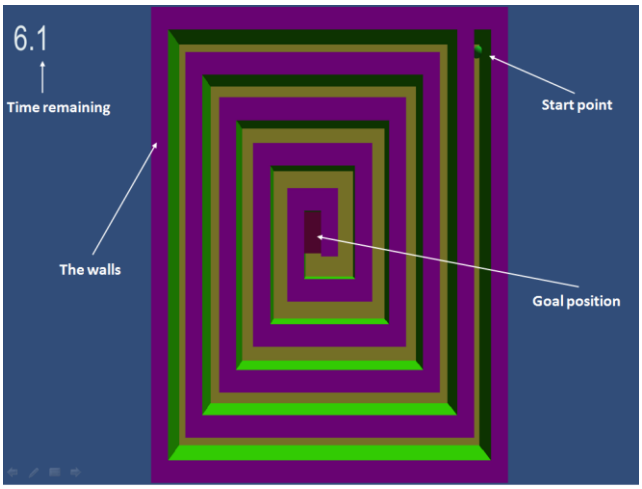
a) Internal Inside-Outside



b) Internal Outside-Inside



c) External Inside-Outside



d) External Outside-Inside

Figure 4.4: The different shoulder circumduction movements

4.1.8 The results and discussion

In this section, all obtained results that related to this first experiment are presented and discussed as following:

4.1.8.1 The results of the multiple goals reach scenario

The related data, such as the time needed to complete the task and the number of contact with the force feedback, were collected to be used as the inputs to the fuzzification. And then we have applied the proposed fuzzy logic strategy to have the final decision, as a percentage, about the

quality and the quantity of the Flexion-Extension movement of involved upper limb. In fact, this decision depends on the inputs parameters presented which have been gained by the system itself. After several attempts of this particular movement, a line chart, that illustrated the comparison between the qualities and the quantity of movement in the different attempts, was drawn to help the therapists to make their choice about the following stage in the therapy process as can be seen in Fig 4.5.

Trajectories that have been drawing from attempt to other attempt have been collected by the system as can be seen in Fig. 4.5. b. Each trajectory shows the created line from the start point to the end point (goal point). A comparison between the different collected trajectories has been done to see which attempt is the most appropriate? This means that if the trajectory is straight from the start point to the end point (without collision with the virtual walls), so the movement has been achieved with high quality as a result of a normal joint(s) recruitment. If the trajectory is winding from the start point to the end point (with some collision with the presented virtual walls), so the movement has been performed with bad quality as a result of abnormal joint recruitment and/ or compensation movements. At each collision with virtual walls, children will have a force feed-back to constrain their upper limb to stay within the defined trajectory.

A comparison between the decision which comes from the fuzzy logic assessment method and the related trajectory at each attempt has been applied to validate the fuzzy decision about the level of the enhancement at those attempts as can be seen in Fig. 4.5. b and d. These comparisons prove the reliability of using the fuzzy logic assessment method to assess the movement performance based on the quality and the quantity of that movement.

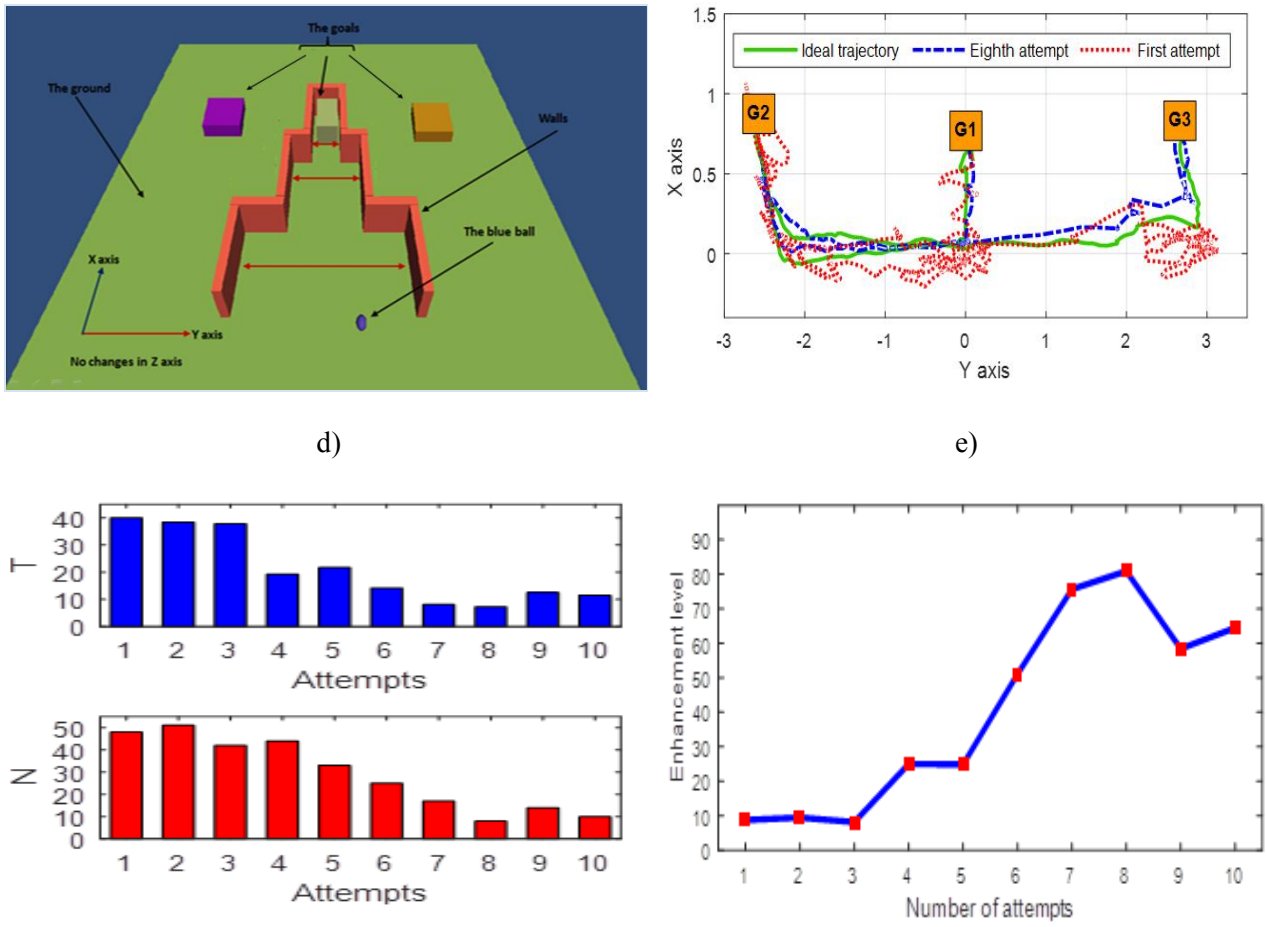


Figure 4.5: (a) Scenario cinematic of the multiple goals reach. (b) The comparison between different trajectories for different attempts. (c) Time and number of contacts with the force feedback. (d) The line of enhancement for all attempts

4.1.8.2 The discussion of the multiple goals reach scenario

Each subject completed the proposed training activities which concern their ULs. Fig 4.5 illustrates the Flexion-Extension movement applied by the first subject. In the first attempt, which was the worst one, the decision showed a little enhancement of this type of movement (8.755%) based on the related inputs of this attempt, which were (T=40.0s, and N=48), also the related trajectory shown in red in Fig. 4.5. b, was not compatible with the ideal trajectory shown in green of this movement. In other words, in this particular movement the joints of the targeted upper limb were constrained by the haptic feed-back coming from the haptic device to reach the goal. So, the level of enhancement of this Flexion-Extension movement was not good at 8.755%.

This percentage has arrived from the degree of affiliation of this movement to the time and the number of contact with the force feedback. Whereas, in the eighth attempt, which was the best attempt, the decision showed a very big enhancement (80.89%) based on the little consumed time (T=7.3s), and the very small number of contact with the force feedback (N=8). In other words, the joints of the affected upper limb have performed this Flexion-Extension movement with little help from the haptic device, which means that the movement has been performed almost by the upper limb itself. Similarly, the related trajectory, shown in blue, was the closet one to the ideal trajectory which confirms the decision obtained from the fuzzy strategy.

As can be seen from Fig 4.5, the therapists can observe the overall line of enhancement at each attempt, or the history of the performance of this particular movement, which helps them to make the proper conclusion about the therapy process, because depending on just one session of assessment, like in traditional assessment methods, might be not enough for such decisions.

Although different decisions were build based on the fuzzy rule table, see chapter 3 section 3.6.2.3.2, which contains the experience of the therapists, who work in the hospital of rehabilitation, the final decision of the next step of therapy still returns to the therapists .

4.1.8.3 The conclusion and perspective of the multiple goals reach scenario

Fig. 4.5.d illustrates the history of the performance of this Flexion-Extension movement. Therapists can easily conclude that the child, who has performed this movement, has been improved in terms of joint recruitment. This improvement has been occurred as a result of the benefits which have been gained from the visual, audio, and tactile feed-back.

Therapists normally based on the results of the measurement method to take the critical decisions about the level of enhancement at any type of movement. Use the traditional clinically measurement, or use measurement devices are the most common methods which help the therapists for making those decisions. This implies that the presence of the therapists and/ or use the measurement device which is difficult especially in home-based rehabilitation. For these reasons, this work suggests a basic fuzzy logic decision making approach. This approach is based on the time needed to complete a task, and the number of force feedback needed to keep the upper limb within the proposed trajectory, in order to provide the therapists with the percentage of improvement in that particular type of movement to help them make their decision about the

suitable next step in the rehabilitation process. The gained results from the case study illustrate the percentage of the level of enhancement at each attempt based on the inputs of these attempts. This also provides the therapists with the history of enhancement for each child, which is not possible when they do the traditional assessment from time to time.

In this work, we have used different methods in order to achieve the fuzzification, inference, and defuzzification, which we judge as the most suitable. Investigation of the effect of using the other methods on the accuracy of the final decision needs to apply.

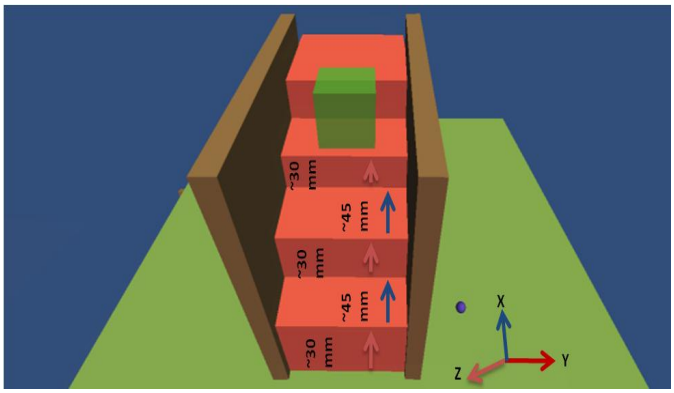
4.1.8.4 The results of the stairs climb scenario

The related data, such as the time needed to complete the task and the number of contact with the force feedback, were collected to be also used as the inputs to the fuzzification. And then we have applied the proposed fuzzy logic strategy to have the final decision, as a percentage, about the quality and the quantity of the Flexion-Extension movement of involved upper limb. In fact, this decision depends on the inputs parameters presented which have been gained by the system itself. After several attempts of this particular movement, a line chart, that illustrated the comparison between the qualities and the quantity of movement in the different attempts, was drawn to help the therapists to make their choice about the following stage in the therapy process as can be seen in Fig 4.6.

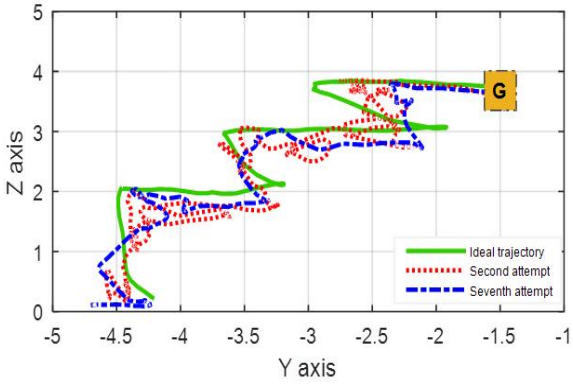
Trajectories that have been drawing from attempt to other attempt have been collected by the system as can be seen in Fig. 4.6. b. Each trajectory shows the created line from the start point to the end point (goal point). A comparison between the different collected trajectories has been done to see which attempt is the most appropriate? This means that if the trajectory follows the defined trajectory in the VR scenario and without collision with the virtual walls, so the movement has been achieved with high quality as a result of a normal joint(s) recruitment. If the trajectory is winding from the start point to the end point with some collision with the presented virtual walls, so the movement has been performed with bad quality as a result of abnormal joint recruitment and/ or compensation movements. At each collision with virtual walls, children will have a force feed-back to constrain their upper limb to stay within the defined trajectory.

A comparison between the decision which comes from the fuzzy logic assessment method and the related trajectory at each attempt has been applied to validate the fuzzy decision about the

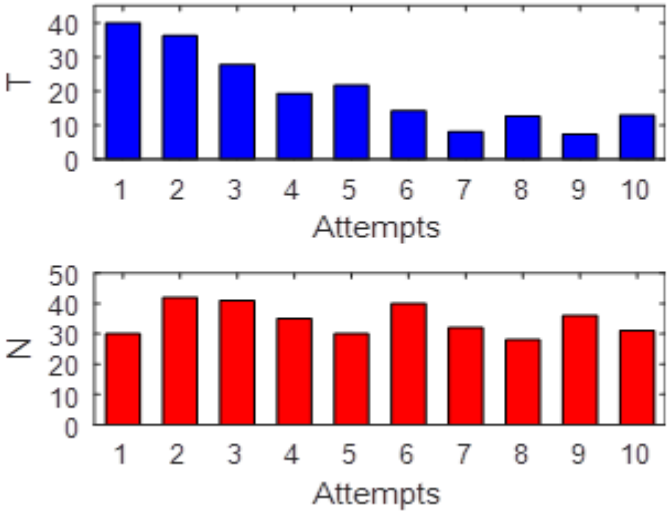
level of the enhancement at those attempts as can be seen in Fig. 4.6. b and d. These comparisons prove the reliability of using the fuzzy logic assessment method to assess the movement performance based on the quality and the quantity of that movement.



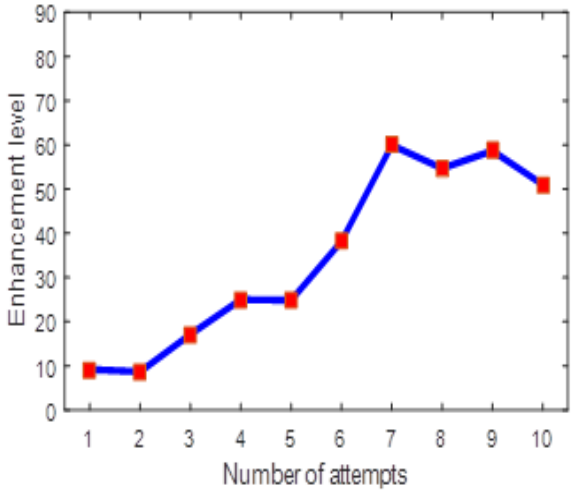
d)



e)



f)



g)

Figure 4.6: (a) Scenario cinematic of the stairs climb. (b) The comparison between different trajectories for different attempts. (c) Time and number of contacts with the force feedback. (d) The line of enhancement for all attempts

4.1.8.5 The discussion of the stairs climb scenario

Each subject completed the proposed training activities which concern their ULs. Fig 4.6 illustrates the Shoulder-Abduction Elbow-Extension movement applied by the second subject. In the second attempt, which was the worst one, the decision showed a little enhancement of this

type of movement (9.35%) based on the related inputs of this attempt, which were (T=38.0s, and N=42), also the related trajectory shown in red in Fig. 4.6. b, was not compatible with the ideal trajectory shown in green of this movement. In other words, in this particular movement the joints of the targeted upper limb were constrained by the haptic feed-back coming from the haptic device to reach the goal. So, the level of enhancement of this Flexion-Extension movement was not good at 9.35%. This percentage has arrived from the degree of affiliation of this movement to the time and the number of contact with the force feedback. Whereas, in the seventh attempt, which was the best attempt, the decision showed a relatively big enhancement (59.93%) based on the little consumed time (T=8.1s), and the very small number of contact with the force feedback (N=32). In other words, the joints of the affected upper limb have performed this movement with little help from the haptic device, which means that the movement has been performed almost by the upper limb itself. Similarly, the related trajectory, shown in blue, was the closet one to the ideal trajectory which confirms the decision obtained from the fuzzy strategy.

As can be seen from Fig 4.6, the therapists can observe the overall line of enhancement at each attempt, or the history of the performance of this particular movement, which helps them to make the proper conclusion about the therapy process, because depending on just one session of assessment, like in traditional assessment methods, might be not enough for such decisions.

4.1.8.6 The conclusion and perspective of the stairs climb scenario

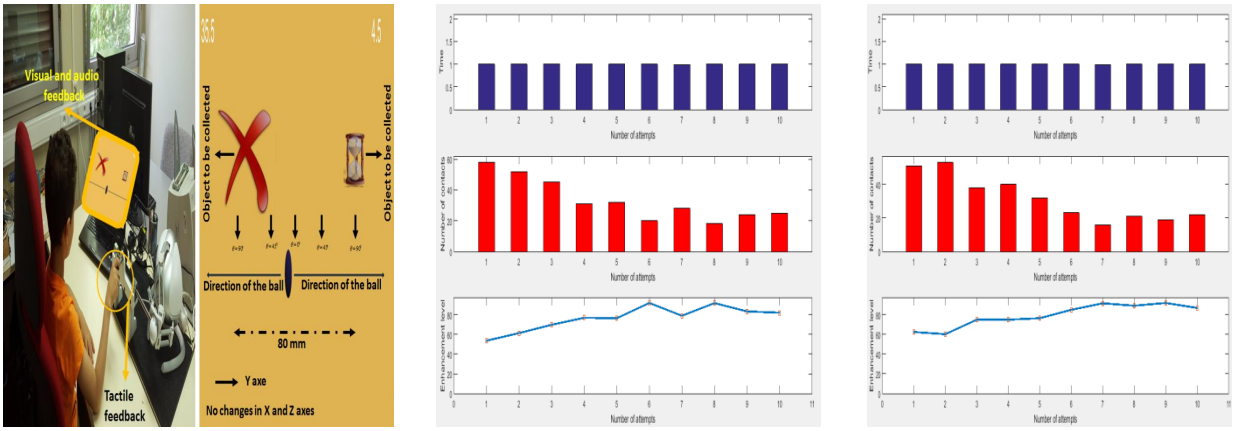
Fig. 4.6.d illustrates the history of the performance of this Shoulder-Abduction Elbow-Extension movement. Therapists can easily conclude that the child, who has performed this movement, has been improved in terms of joint recruitment. This improvement has been occurred as a result of the benefits which have been gained from the visual, audio, and tactile feed-back.

4.1.8.7 The results of the collecting moving objects scenario

For the Elbow Pronation-Supination movements and Shoulder Internal or External movements, the system collects the data about the number of collected objects. These data will be used to judge the performance of the related joints of the upper limb. Fig. 4.7 shows the

performance history of those joints, these lines illustrate the level of the enhancement by the time.

In this scenario, the system calculates the number of collected and uncollected objects as can be seen from the blue bars in Fig. 4.7 b and c, knowing that the system counts the number of uncollected objects from the total objects to be collected in certain time in each attempt. And then, the system uses the fuzzy logic decision maker to find out the quantity of the movement.



a) Pronation-Supination scenario

b) The first child enhancement

c) The second child enhancement

Figure 4.7: Scenario and collected data and the enhancement line for both children

4.1.8.8 The discussion of the collecting moving objects scenario

Each subject completed the proposed training activities which concern their ULs. Fig 4.7 shows the Elbow Pronation-Supination movement applied by both subjects. Fig. 4.7.b illustrates the first child performance data and assessment. In the first attempt, which was the worst one, the decision showed a noticed level of enhancement of this type of movement (53.65%) based on the related inputs of this attempt, which were (T=0.9s, and N=58) knowing that N here represents the number of uncollected objects, in this particular movement the elbow joint of the targeted upper limb was constrained by the translator device, which connected to the haptic device, to reach the goal. This percentage (53.65%) has arrived from the degree of affiliation of this movement to the time and the number of uncollected objects. Whereas, in the eighth attempt, which was the best attempt, the decision showed a significantly big enhancement (91.88%) based on the little consumed time (T=0.9s), and the very small number of uncollected objects (N=18).

In other words, the elbow joint of the affected upper limb have performed this movement with little help from the haptic device, which means that the movement has been performed almost by the upper limb itself. Fig. 4.7.c illustrates the second child performance data and assessment. In the second attempt, which was the worst one, the decision also showed a noticed level of enhancement of this type of movement (60.26%) based on the related inputs of this attempt, which were (T=0.9s, and N=53) knowing that N here represents the number of uncollected objects, in this particular movement the elbow joint of the targeted upper limb was constrained by the translator device, which connected to the haptic device, to reach the goal. This percentage (60.26%) has arrived from the degree of affiliation of this movement to the time and the number of uncollected objects. Whereas, in the ninth attempt, which was the best attempt, the decision showed a significantly big enhancement (92.03%) based on the little consumed time (T=0.9s), and the very small number of uncollected objects (N=16). In other words, the elbow joint of the affected upper limb have performed this movement with little help from the haptic device, which means that the movement has been performed almost by the upper limb itself.

As can be seen from Fig 4.7, the therapists can observe the overall line of enhancement at each child, or the history of the performance of this particular movement, which helps them to make the proper conclusion about the therapy process, because depending on just one session of assessment, like in traditional assessment methods, might be not enough for such decisions.

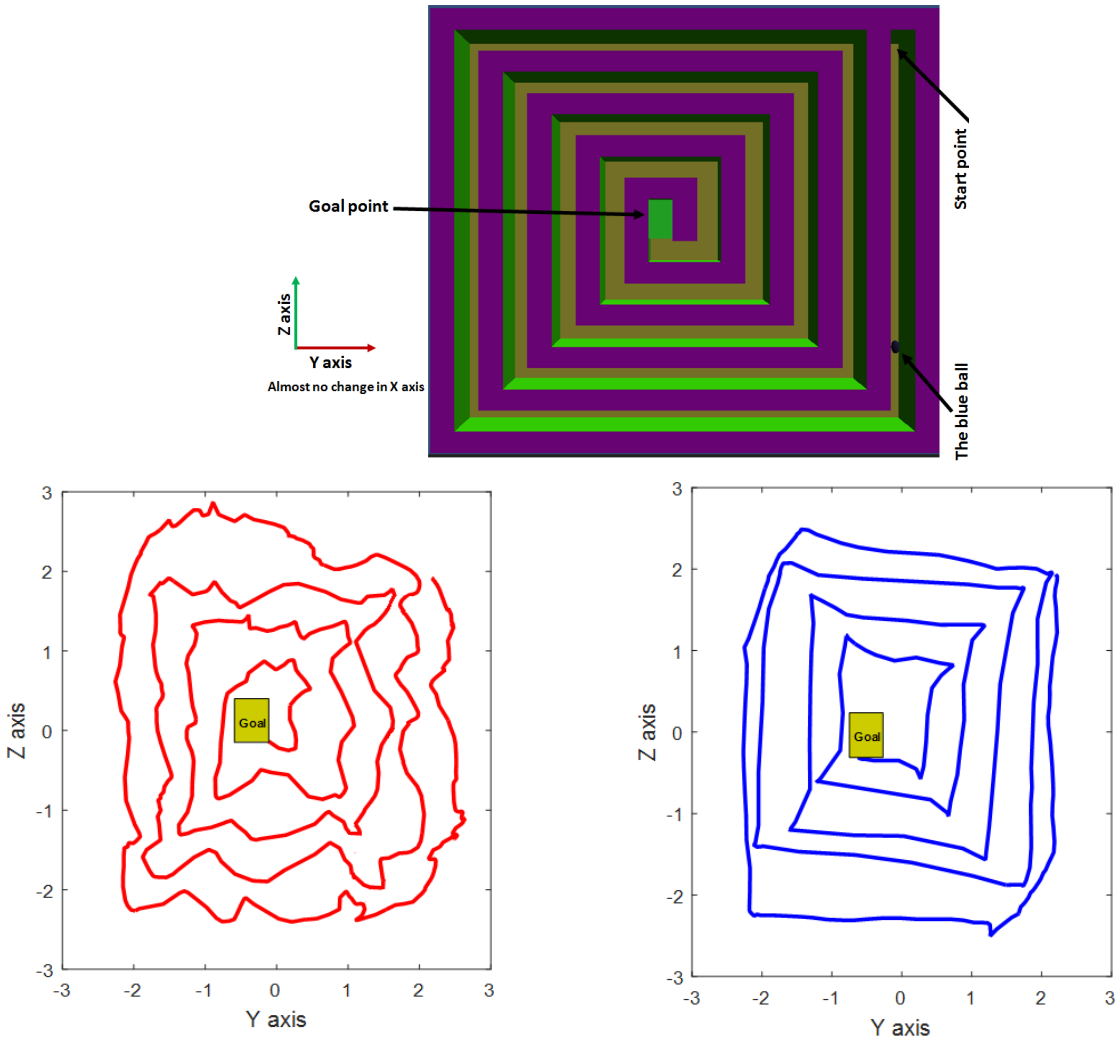
4.1.8.9 The conclusion and perspective of the collecting moving objects scenario

Fig. 4.7 illustrates the history of the elbow performance when doing Pronation-Supination movement. Therapists can easily conclude that the children, who have performed this movement, have started with a good capacity of doing this movement, and they have been improved in terms of joint recruitment and accuracy. This improvement has been occurred as a result of the benefits which have been gained from the visual, audio, and tactile feed-back.

4.1.8.10 The results of the labyrinth scenario

For the Shoulder different circumduction movements, the system collects the data about the number of contact with the force feed-back coming from the haptic device, as well as the consumed time to complete a task. These data will be used to judge the performance of the

related joints of the upper limb. Fig. 4.8 shows the best and worst trajectories which were drawn by the first child.



a) The first trajectory b) The ninth trajectory

Figure 4.8: The different trajectories which were drawn by S1

4.1.8.11 The discussion of the labyrinth scenario

The contact between the upper limb and the force feedback of the haptic device happens when the subjects try to produce abnormal recruitment of joint motion. This normally appears as perturbed (unstable) trajectory, these contacts become as an evident of how many times the abnormal recruitments have been performed. Fig. 4. 8. a, and b illustrate two obtained trajectories for the proposed scenario; the haptic device constrains the upper limb to be within

that trajectory. In Fig. 4. 8 (a) shows that the subject had a lot of attempts to pass the proposed trajectory. But he has been constrained by the haptic device to stay within the trajectory. Whereas in Fig. 4. 8 (b) the subject had less number of contacts with the force feedback, which results in enhancement in this movement. These obtained results show the usability of using visual, audio, and tactile feed-back to constrain joints of the upper limb to avoid abnormal recruitment, which normally happen when trying to produce the required θs.

The wrist angles that are produced in this scenario, are limited comparing with those of shoulder angles, so the scenario needs to be developed taking into account the overload of the wrist joint.

4.1.8.12 The conclusion and perspective of the labyrinth scenario

Upper limb movement control is a regular occupational rehabilitation therapy. The use of benefits that can be gained from the tactile sensation comes from haptic devices as well as visual and audio sensations which offer the possibility of enhancing joints motion of upper limbs. This control for therapy concentrates on constraining joints to apply normal recruitment during movements, by working on each joint separately, and assign scenarios to each joint in order to encourage it to make most of motion that normally done by that joint in ADLs. The results express that this strategy helps the subjects to apply normal joints recruitment as a result of producing the required angles (θ_S) during movements. The reduction of the number of contacts with the force feed-back followed by reduction of consumed time to complete tasks shows the level of enhancement of joints motion.

Future work will evaluate this control strategy for affected upper limbs of children with hemiplegia in the center of rehabilitation Marc Sautelet in Villeneuve d'Ascq.

4.2 The second therapy experiment

The control strategy presented here is based on resistive force feed-back to be applied on the affected upper limb according to predefined trajectories in VR scenarios. The analysis of internal factors such as strength, flexibility, coordination, pain level, motivation, and cognition, are used to establish limitations of movements and its directions, by developing scenarios depending on the length of upper limb and the angle's value that needs to be applied, by asking

patients to use the handle of the haptic device to interact with virtual objects presented in VR scenarios as can be seen in Fig. 4.9.

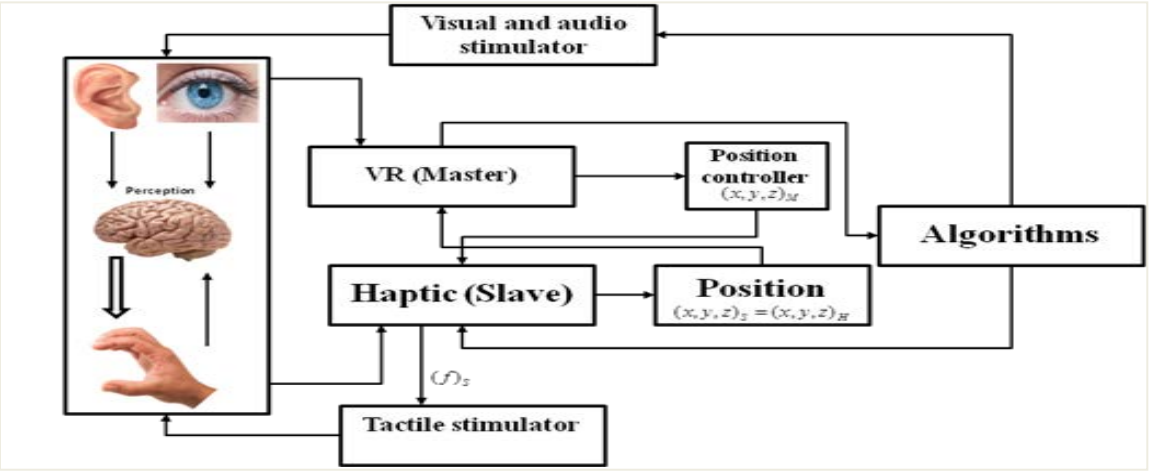


Figure 4.9: Manipulation with sensory substitution

The architecture of the experiment here is based on high level control that uses the low level control of the haptic device to control its behavior according to pre-prepared VR's scenarios. This control involves, the use of the haptic's sensors to work depend on obstacles and conditions in VR, calculating all positions that have been reached by subjects within the trajectories, determine the interaction forces between each joint and the haptic, and apply the suitable force feed-back depend on the positions of input parameters. The developed strategy provides free paths in VR scenes and force feed-back in other directions, in other words "resist-when-needed" model. Haptic device generates force feed-back when subjects attempt to make abnormal joint's recruitment by choosing alternative trajectories to reach the target. Finally, subjects will have a homogeneous visual, audio, and tactile feedback in order to stimulate the affected part of the brain to provide its instructions to incite the targeted upper limb to move correctly.

4.2.1 The subjects

Two children with hemiplegia, C1, and C2, of 7, and 10 years old, girl and boy, respectively, were participated in this study. Both of them were hemiplegic in the right side of the body. The upper limb segment lengths were measured individually. These lengths determine the angles that are going to be performed by using the system depends on the type of the movement. In view of the fact that physical parameters of upper limbs of subjects are different, so an average parameter

has been taken as a based in order to develop an initial scenarios in VR, knowing that our target subjects' ages are in between 5-10 years old.

4.2.2 The protocol

Patients were seated comfortably at a height-adjustable table in order to have their hips and knees flexed 90^0 and both feet flat on the ground. Both elbows were rested on the table, and the wrist was held in neutral with the palms hold the handle of the Novint Falcon® which was placed (height: ~ 12.5 cm, diameter: ~ 2.5 cm), and also at the maximum reach of the participants to avoid the overload range of motion. They were used a comfortable seat belt to reduce the trunk compensation, knowing that small amount of this type of compensation in this period of age is normal. Each child has performed the three suggested scenarios for three sessions in one week period of time. And each scenario was performed three times in every session.

Each subject completed 4.5 hours of training, and about 1 hour of other sensation activities which concern their UL's strength. Children were asked after each attempt to determine the pain level, and the safety of the system by using a traditional pain measurement tool. This study has been done in the center of reeducation Marc Sautelet in Villeneuve d'Ascq France. A therapist who works in the center was presented with each child for all the sessions. The parents of the children have read and signed the accord paper of using the system.

4.2.3 The initial position

- For Shoulder-Elbow Flexion-Extension movements: The subjects were seated comfortably at a height-adjustable table in order to have their shoulder flexion at $\approx 90^0$, elbow flexion at $\approx 180^0$ with the hips and knees flexed 90^0 and both feet flat on the ground. The forearm was pronated, and the wrist was also held in neutral with the palms hold the handle of the falcon which was placed at certain height for each child in order to end up with 90^0 of shoulder extension at their maximum reach. They have used a comfortable seat belt to reduce the trunk compensation, knowing that small amount of this type of compensation in this period of age is normal.

- For Shoulder-Abduction Elbow-Extension movements: The subjects were also seated at a height-adjustable table in order to have their shoulder abduction at $\approx 90^0$, and elbow flexion at $\approx 180^0$ with the hips and knees flexed 90^0 and both feet flat on the ground. The haptic device was positioned in the right hand side of the body to enable the children to perform the desired movements. They have also used a comfortable seat belt to reduce the trunk compensation.

- For Elbow Pronation-Supination movements: The subjects were seated at a height-adjustable table in order to have their shoulder flexion at $\approx 0^0$, and elbow flexion at $\approx 90^0$ with the hips and knees flexed 90^0 and both feet flat on the ground. The haptic device was positioned in front of the affected side of the body to enable the children to perform the desired movements. They have also used a comfortable seat belt to reduce the trunk compensation.

4.2.4 Flexion-Extension scenario

In this scenario, each child had to touch the goal object using the blue ball which represents the movement of the haptic device (Novint Falcon®). This goal object will be destroyed when it has been reached, and other goal object will be appears to encourage the child to move toward that object. By applying this movement, the child will perform the desired shoulder/ elbow flexion-extension. Any other compensation movement will be heavily reduced by the force feedback coming from the falcon, and this force works according to the virtual walls in the VR scenario as can be seen in Fig 4.10.

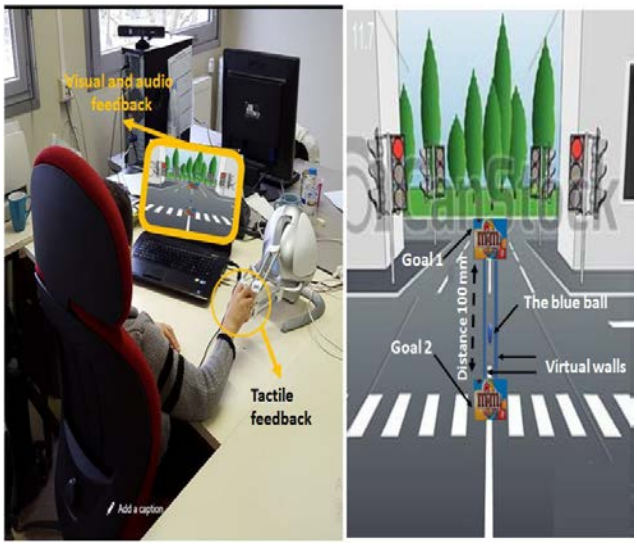


Figure 4.10: Flexion-extension scenario

4.2.5 Abduction-Adduction scenario

In this scenario, each child had to touch the goal object using the blue ball which represents the movement of the haptic device (Novint Falcon®). This goal object will be destroyed when it has been reached, and other goal object will be appears to encourage the child to move toward that object. By applying this movement, the child will perform the desired shoulder/ abduction-adduction. Initial position and the scenario are presented as can be seen in Fig. 4.11. So, shoulder abduction-adduction will be performed. And other compensation movements will be avoided.

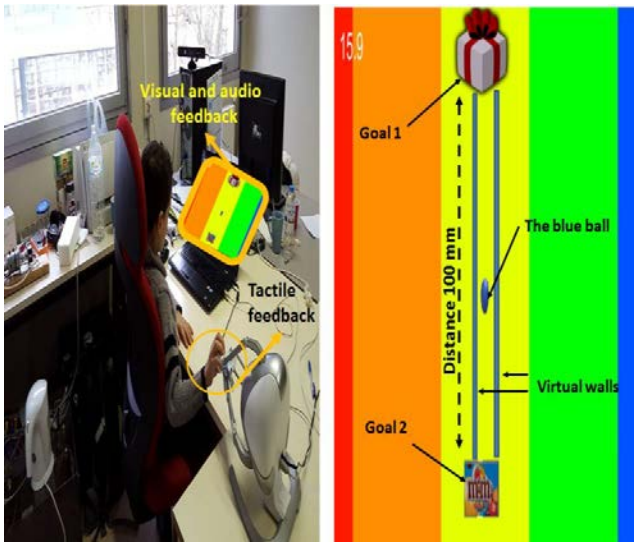


Figure 4.11: Abduction-adduction scenario

4.2.6 Pronation-Supination scenario

In this scenario, each child had to use the other device shown in Fig. 4.12. This device is responsible for converting the circular movement of the hand (elbow pronation-supination) to the straight movement in the Y axis in the VR.

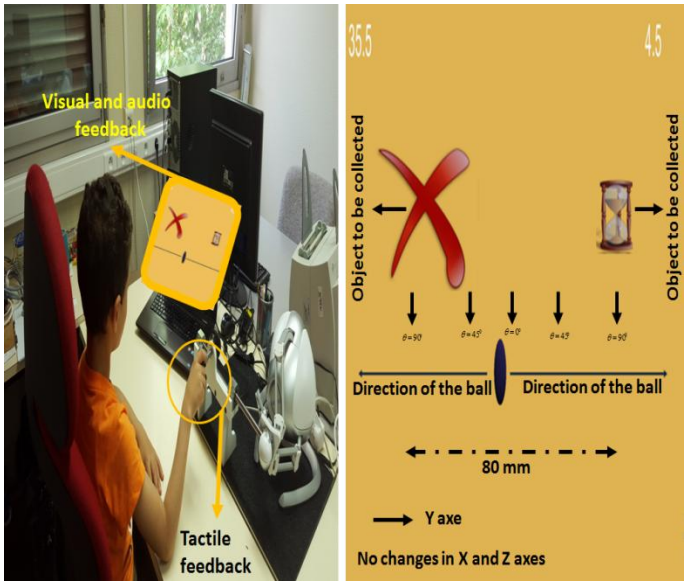


Figure 4.12: Pronation-supination scenario

4.2.7 Results and discussion

Both subjects were attracted to different simulations, and the pain level was almost 0/10 which means there was no pain. However, in the upper limb movement, there are many categories need to be considered to make a decision about the level of enhancement of each movement. In this study, the selective movement (quality), the joints coordinate of the upper limb to make one movement (quality), and the number of collected objects in certain period of time (quantity), were taking into account to make the enhancement decision.

For the quality of the movements, the system calculates the number of interaction with the force feedback coming from the haptic device, to find out the quality of the movement as can be seen in the red bars in Fig. 4.13, 4.14, …, and 4.18 knowing that the force feed-back occurs just when the children attempt to make other trajectories which are not specified in VR scenario, in other words he/ she attempts to make abnormal joint recruitment. For example, in the flexion-extension movements, the child moves the handler of the haptic to reach the next object in the

scenario as can be seen in Fig. 4.10. Then, if the child coordinates their joints to make the correct flexion-extension movement, the blue ball passes through the free trajectory between the two goals in the scenario, and without force feedback. But if he attempts to do an alternative compensation, in order to make these flexion-extension movements, like abduction-adduction movements or shoulder rotation, which results in most cases deviation from the trajectory specified in advance. Then the haptic device provides its force feed-back to impose that upper limb to stay within the pre-defined trajectory. In the meantime, the system calculates the number of the exerted force feed-back as can be seen in the red bars in both Figs. 4.14, and 4.17. As an evidence of how many times that child has attempted to perform other joints coordination or compensation that unwanted to do the desired flexion-extension movement. So, as less the number of interact with the force feed-back as better the quality of the movement is.

For the quantity of the movement, the system also calculates the number of collected and uncollected objects as can be seen from the blue bars in Fig. 4.13, 4.14… and 4.18 knowing that the system counts the number of uncollected objects from the total objects to be collected in certain time in each attempt. For example, in the abduction-adduction movements, the child moves the handler of the haptic to reach the next object in the scenario and from the initial position as can be seen in Fig. 4.11. Then, if the child coordinates their joints to make the correct abduction-adduction movement, the blue ball passes through the free trajectory between the two goals in the scenario, and without force feedback. But if he attempts to do an alternative compensation, in order to make these abduction-adduction movements, like flexion-extension movements or shoulder rotation, which results in most cases deviation from the trajectory specified in advance. Then the haptic device provides its force feed-back to impose that upper limb to stay within the pre-defined trajectory. In the meantime, the system calculates the number of the exerted force feed-back as can be seen in the red bars in both Figs. 4.13, and 4.16. As an evidence of how many times that child has attempted to perform other joints coordination or compensation that unwanted to do the desired abduction-adduction movement. So, as less the number of uncollected objects as better the quantity of the movement is.

From the quality of the movement (red bars), it is hard to decide about the level of enhancement because it is not the only category which responsible for that decision. Also for the quantity of the movement, it is not enough to make a decision for the enhancement level. So, a fuzzy logic decision maker strategy was used to make this decision, by calculate the degree of

affiliation of each type of movement to above described assessment categories (quality, and quantity) as can be seen in blue lines in Fig. 4.13, 4.14… and 4.18.

First child C1 has achieved a remarkable functional improvement especially in joints coordinates during movements, resulted in the reduction of the number of contact with the force feedback coming from the haptic device Fig. 4.13, and 4.14. Whereas child C2 has a reduction in the number of uncollected objects within certain time (quantity) especially in flexion-extension movement as can be seen in Fig. 4.17. In the pronation-supination movements, C1 showed a constantly increasing in the level of performance Fig. 4.15, whereas C2 showed a notice improvement between the first attempt and the last one Fig. 4.18.

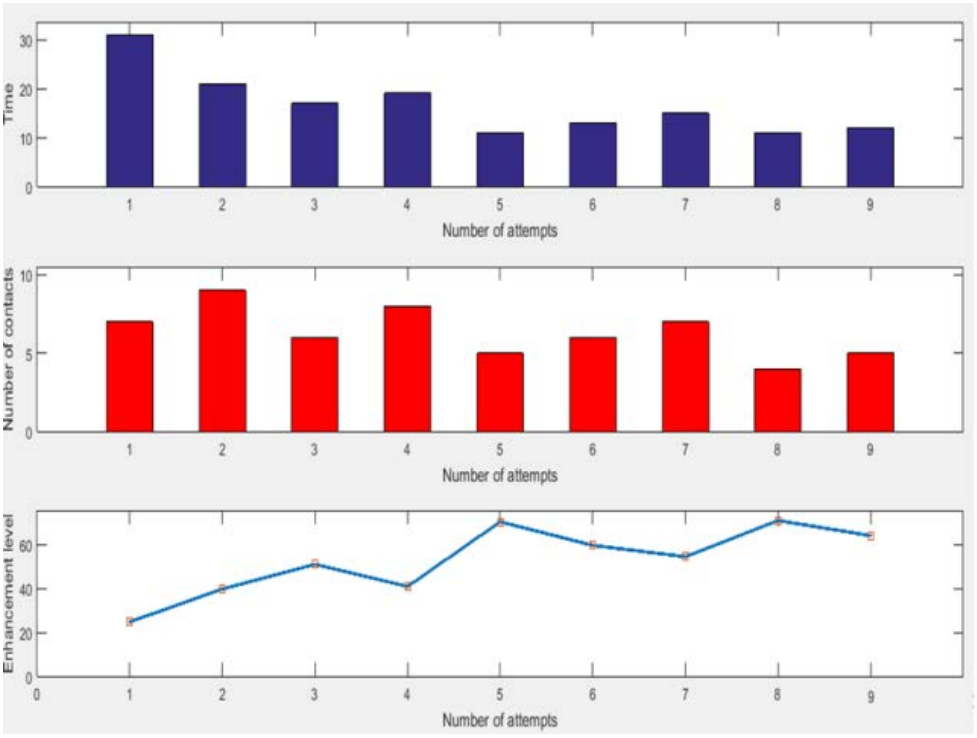


Figure 4.13: Abduction-Adduction performed by the first child C1

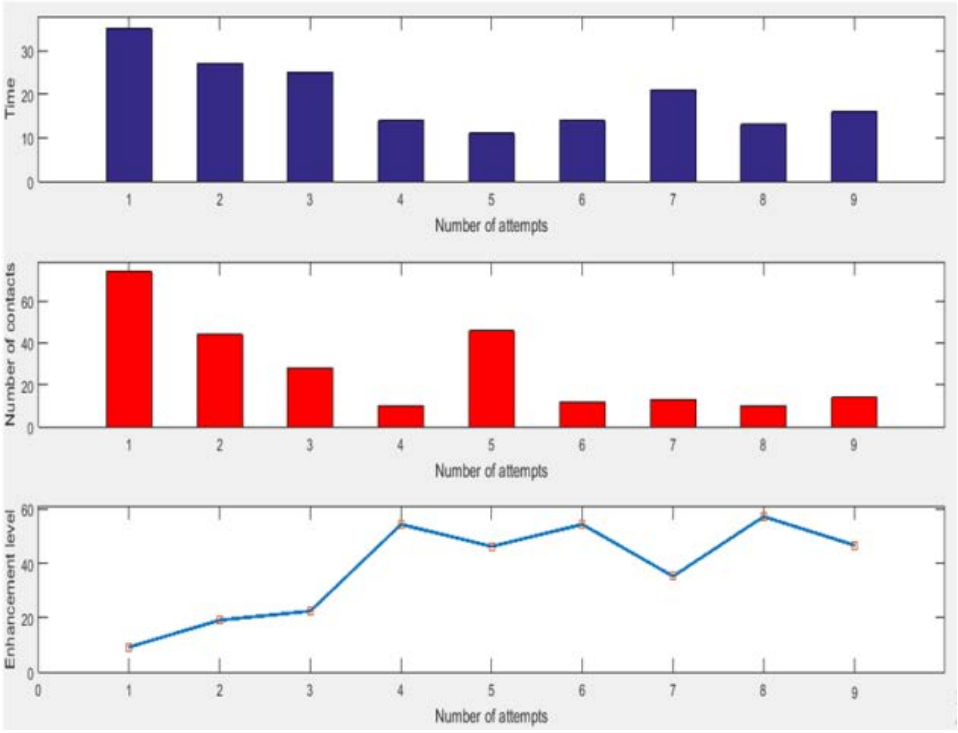


Figure 4.14: Flexion-Extension performed by the first child C1

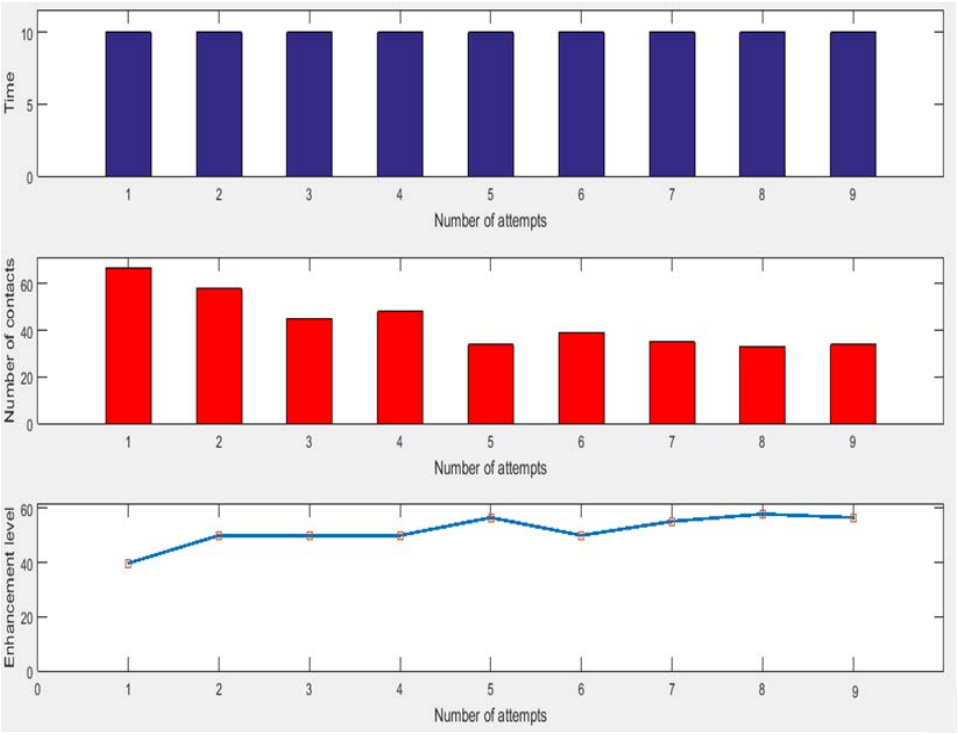


Figure 4.15: Pronation-Supination performed by the first child C1

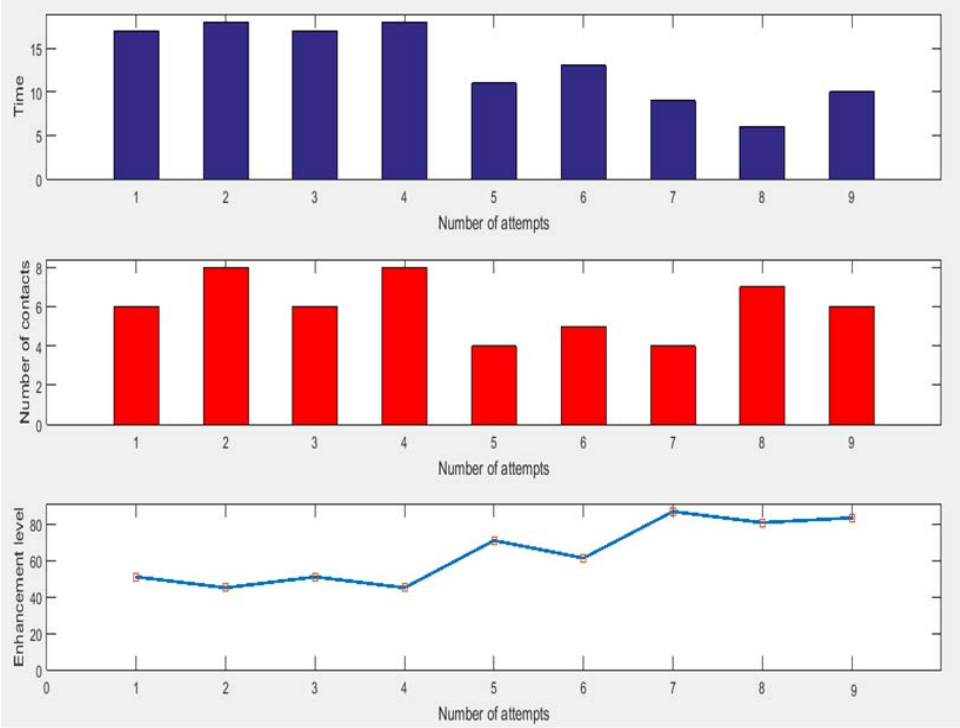


Figure 4.16: Abduction-Adduction performed by the second child C2

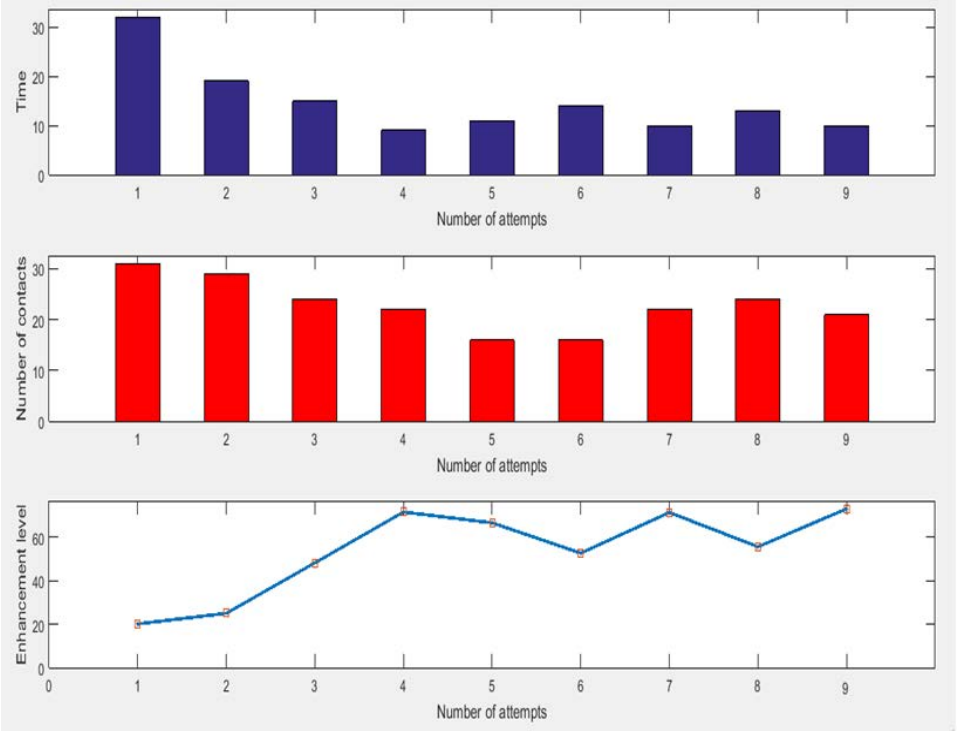


Figure 4.17: Flexion-Extension performed by the second child C2

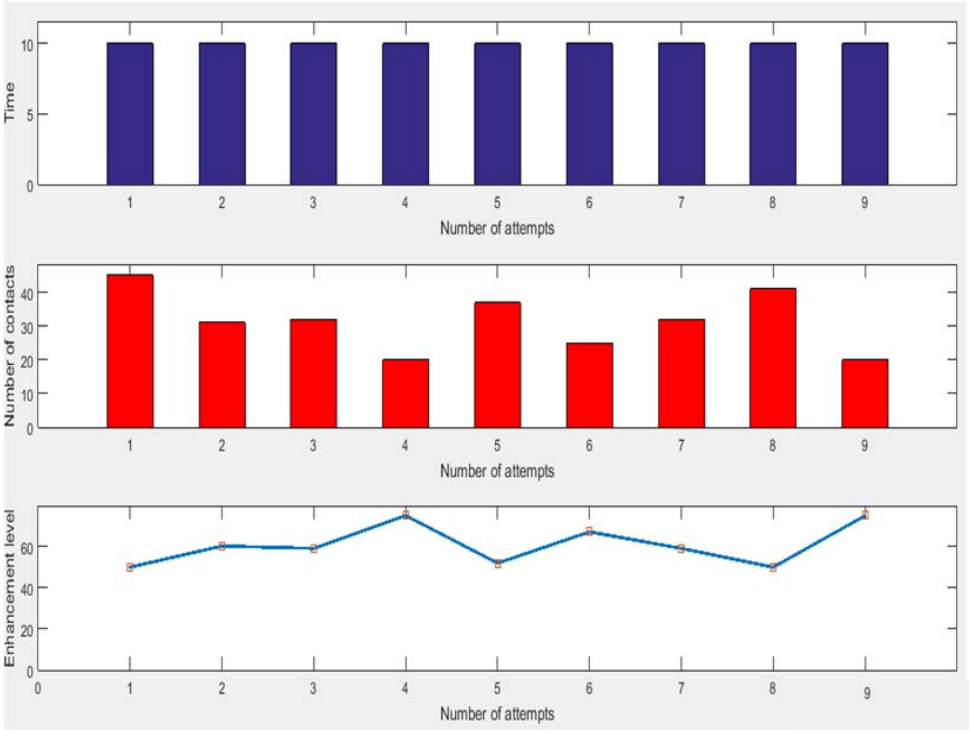


Figure 4.18: Pronation-Supination performed by the second child C2

At the end of the study, the children who participated in this study were asked to perform flexion-extension, abduction-adduction, and pronation-supination movements without using the system to ensure that they can perform ADLs, and they have made those movements by themselves. They had to reposition a cube from initial position to end position as flexion-extension movements, reach a shelf as abduction-adduction movements, and turned a cube from one side to other side as pronation-supination movements.

Both children have gained from the visual, audio, and tactile feedback to stimulate the brain to choose the correct joints coordinate in order to perform movements, and they have collected more objects by the time.

4.2.8 Conclusion and perspectives

Upper limb movement control is a regular occupational rehabilitation therapy. The use of benefits that can be gained from the tactile sensation comes from haptic devices as well as visual and audio sensations come from VR, offers the possibility of enhancing joints motion of upper limbs. This control for therapy concentrates on constraining joints to apply normal recruitment during movements, by working on each joint separately, and assign scenarios to each joint in

order to encourage it to make most of motion that normally done by that joint in ADLs. The results express that this strategy helps the subjects to apply normal joints recruitment as a result of benefits that gained from the different receiving sensations. The reduction of the number of contacts with the force feedback followed by increasing of the numbers of collected goal objects shows the level of enhancement of joints motion.

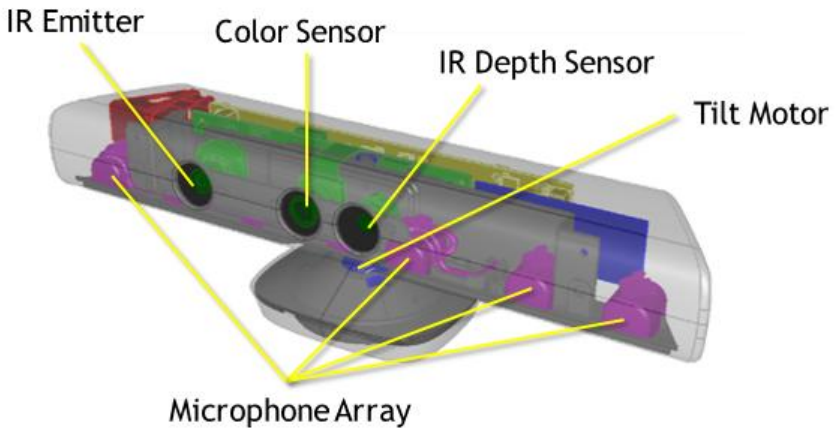
Future work will be that evaluating this control strategy for affected upper limbs of children with hemiplegia in home-based rehabilitation therapy as tele-rehabilitation.

4.3 The third experiment (The first assessment experiment)

Microsoft Kinect™ for windows was used to measure the joints performance. It has been used to ensure that each scenario will constrain the targeted joint(s) of the upper limb to perform the desired movement. For example, when a child executes a scenario for Shoulder Abduction-Adduction movement, the therapists need to know whether this movement has been performed separately or it has been combined with other movement(s) (compensation movements) like Elbow Flexion-Extension.

4.3.1 Equipments

The Kinect consists of three sensors: a projector (an infrared IR emitter), a camera (a RGB color sensor), and an IR camera (an IR depth sensor) as in Picture. 4.1. Body tracking is performed using the depth sensor, so the coordinates (X, Y, Z) of the body joints are correctly aligned with the depth frame only. The Kinect for Windows version 2 SDK 2:0 determines skeleton position information from the provided depth image. The result is Cartesian coordinates of joint positions related in meters with the Kinect depth sensor center as the origin. These skeletons acquire at a rate of about 20 to 26 samples per second.



Picture 4.1: The kinect™ for windows

4.3.2 Case study

Procedure

In order to use kinect™ to find out the type of the movement and to measure the related angles, we confirm its performance with the Vicon measurement device. The subject has performed most of movements which are needed in the upper limb therapy for children with hemiplegia. The subject was instructed to make shoulder flexion-extension, shoulder abduction-adduction, elbow flexion-extension, wrist flexion-extension, and wrist abduction-adduction. Each type of those movements has been repeated 3 times. These movements were measured by using both Vicon and kinect™ devices as in Fig. 4.19.

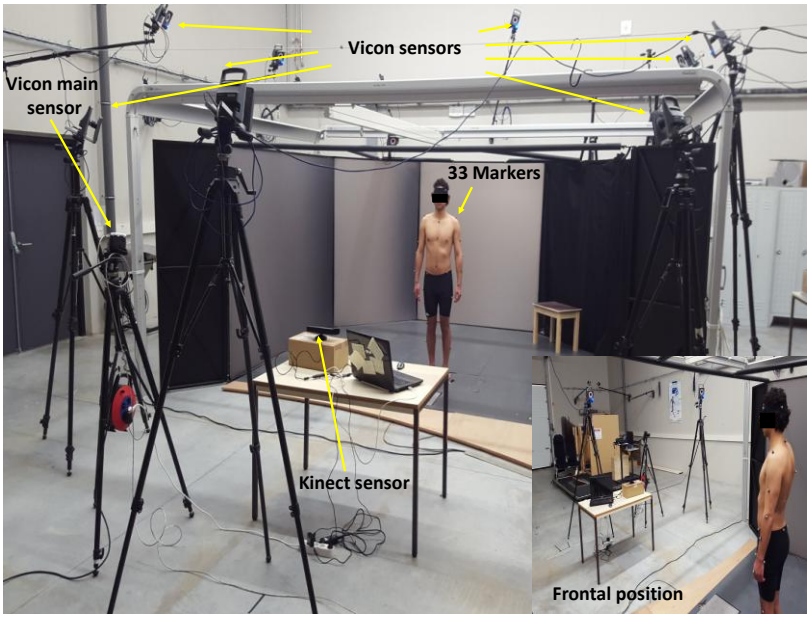


Figure 4.19: The Vicon and Kinect™ systems

4.3.3 Results and discussion

Since the two data sets, the frame rates and time, between the Vicon and Kinect™ are widely different, to make a comparison we based on the values that related to each type of movement and its angles for each peak point as can be seen in Fig. 4.20. In children with hemiplegia therapy processes, the therapists need to know whether or not children can perform a certain movement, for how much amplitude, and can they do it separately or with other compensation

movement. So, the assessment system should provide the therapists with all activities of all joints at all times along with the angles that have been performed by each joint. For example in shoulder joint Flexion-Extension movement, the therapists need to know that: Is the child able to perform shoulder Flexion-Extension? To which angle they can go? Is there any other compensation movement during performing this movement like elbow flexion? To that end, we have developed our assessment system and compare its results with the Vicon results.

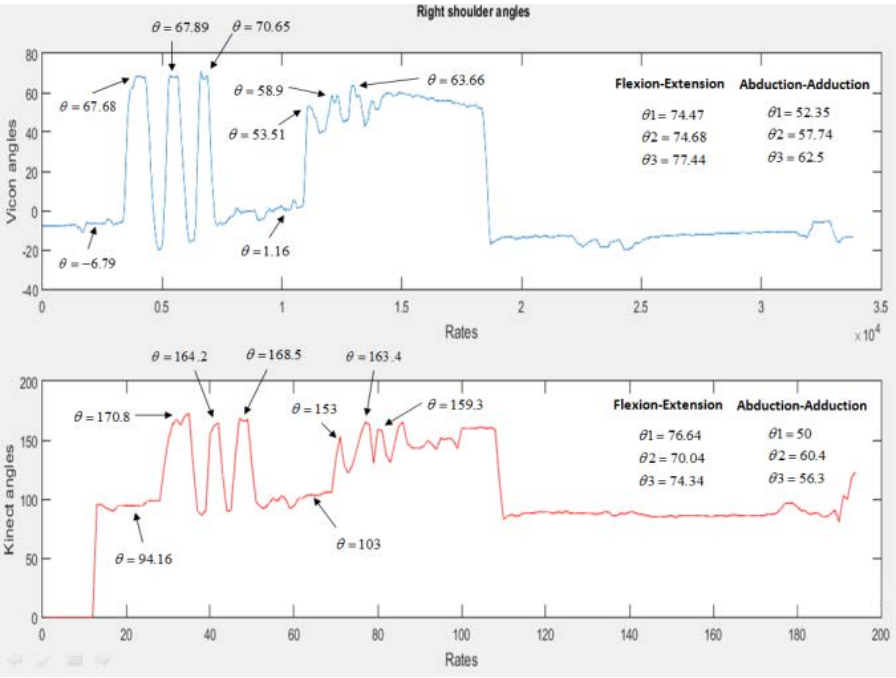


Figure 4.20: a) Right shoulder Flexion-Extension and Abduction-Adduction

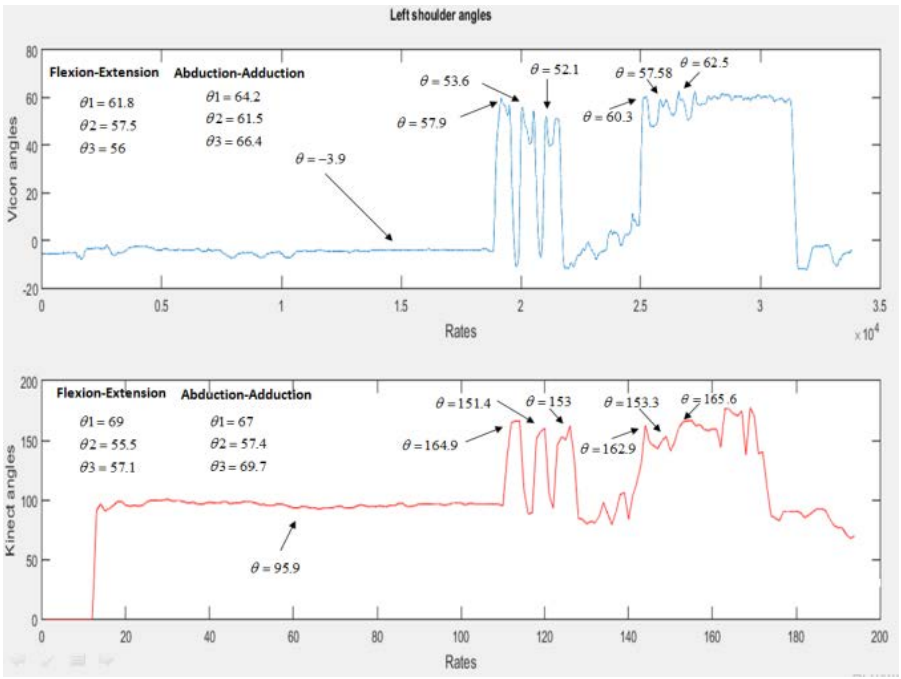


Figure 4.20: b) Left shoulder Flexion-Extension and Abduction-Adduction

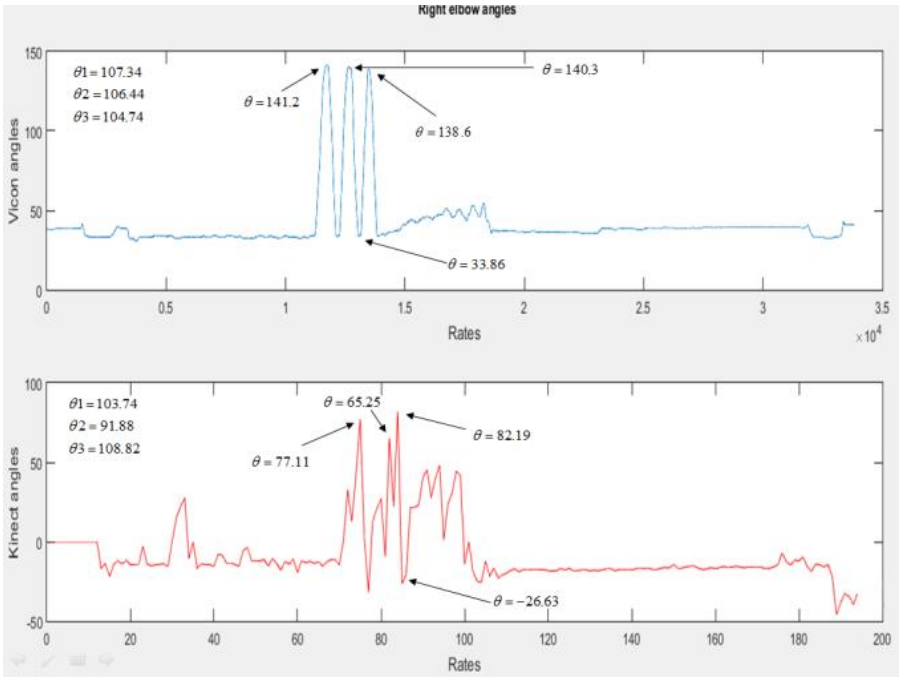


Figure 4.20: c) Right elbow Flexion-Extension

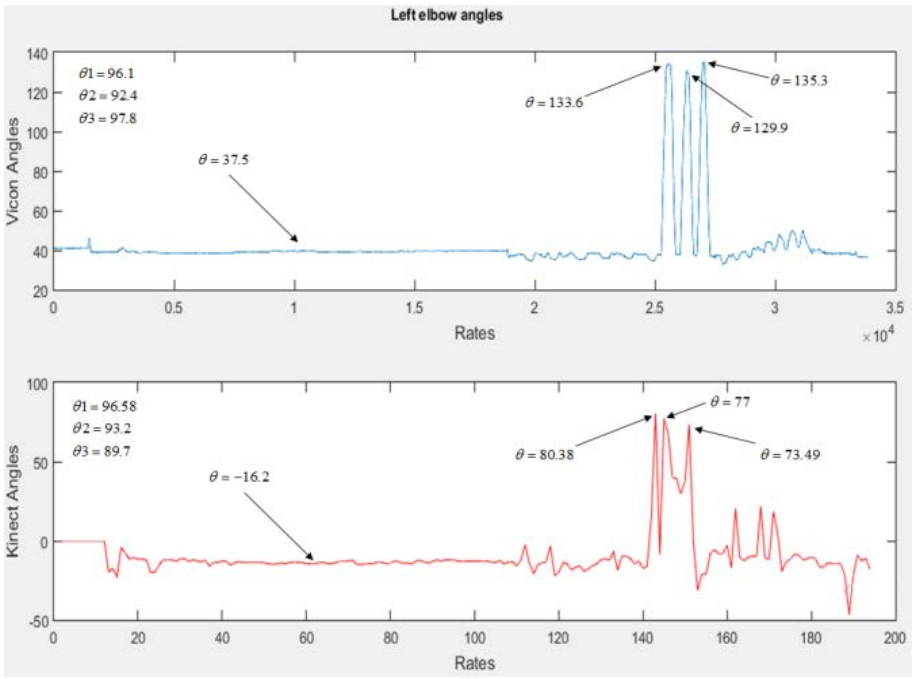


Figure 4.20: d) Left elbow Flexion-Extension

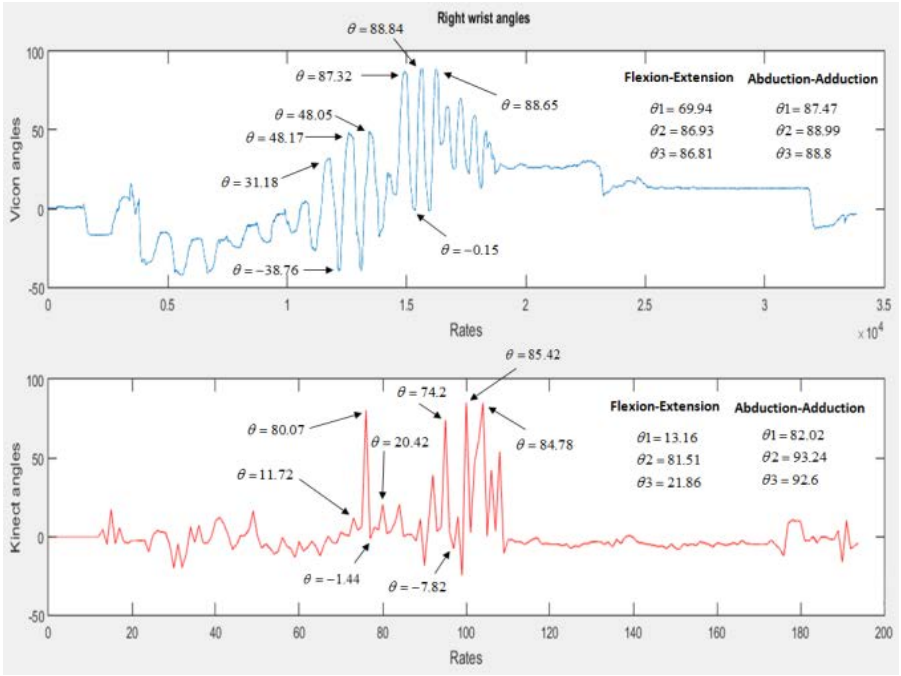


Figure 4.20: e) Right wrist Flexion-Extension and Abduction-Adduction

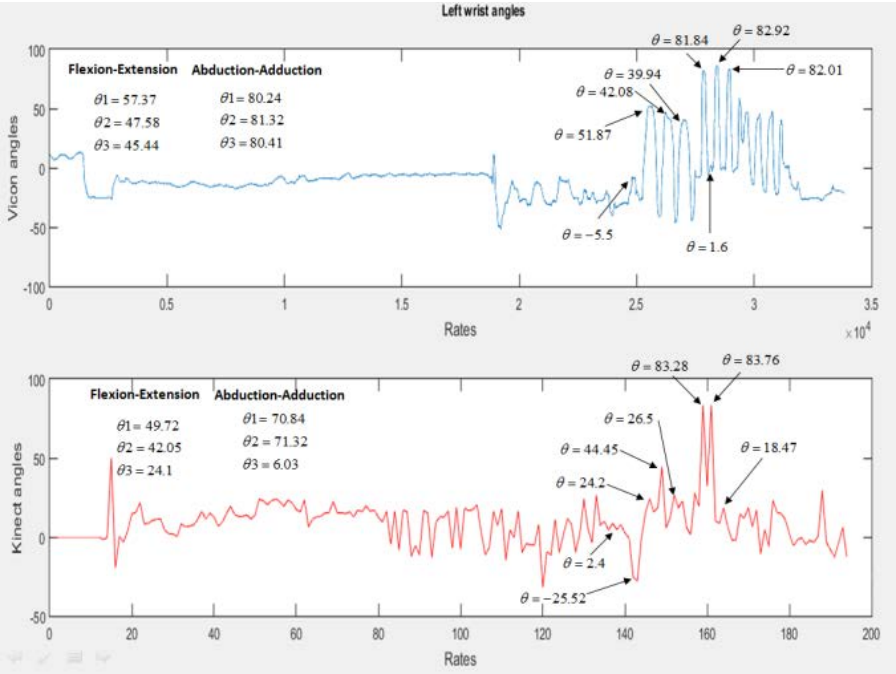


Figure 4.20: f) Left wrist Flexion-Extension and Abduction-Adduction

Fig. 4.20 illustrates the activities that have been performed by each joint at all times. These activities have been measured at the same time by using the Kinect™ and the Vicon. Fig. 4.20.a. shows the right shoulder activities during the time, this joint has performed Flexion-Extension movements for three times and then it has performed Abduction-Adduction movements for three times. This joint stays almost steady for the rest of the time. Fig. 4.20.c. shows the right elbow activities during the time, this joint has performed Flexion-Extension movements for three times and then it remains steady for the rest of the time. Fig. 4.20.e. illustrates the right wrist activities during the time, this joint has performed Flexion-Extension movements for three times, and then it has performed Abduction-Adduction movements for other three times and remains almost steady for the rest of the time. Fig. 4.20.b, d, and f. illustrate the activities that have been performed by the joints of the left upper limb during the time. From this comparison, it can be seen clearly that the kinect shows the type of the movement for all joints of the upper limb along with the other movements that might be performed at the same time.

Now, we need to answer the other question about the angles that have been performed by each joint at each movement type. To this end, we have calculated the errors and its related percentage errors as shown below for each peak point of each type of movement. Knowing that, each type of

movement has been performed three times. We have defined error (E) and its related percentage (PE) as the ratio of the difference of the observed angles of both Kinect™: ROM_K and Vicon: ROM_V

$Error = MeasuredVdue - ActualValue$. So, $E = ROM_K - ROM_V$

$$PercentageError = \frac{|Error|}{ActualValue} * 100. \text{ So, } PE = \frac{|E|}{ROM_V} * 100$$

Table 4.1 illustrates the error percentage at all activities of each joint. We observe that the elbow Flexion-Extension movements for both right and left upper limb have the closest values and less percentage error comparing with the other joints percentage error 6.9 % and 3.1 % in average for right and left elbow Flexion-Extension respectively. Percentage errors of shoulder joint movements show promise results of using kinect™ to measure this joint. Percentage errors of wrist joint movements are less reliable. For example, for right wrist Abduction-Adduction movements the kinect™ has an important precision of about 5.03 % in average percentage error, but for the same joint in Flexion-Extension movements it has less precision for the first and third peaks and an acceptable percentage error in the second peak. For the left wrist, the results of the kinect™ can be used in most cases.

Joint	Side	Type	1ere peak (%)	2eme peak (%)	3eme peak (%)
Shoulder	Right	Flexion-Extension	2.9 %	6.2 %	4.0 %
		Abduction-Adduction	4.4 %	4.6 %	9.9 %
	Left	Flexion-Extension	11.6 %	3.4 %	1.9 %
		Abduction-Adduction	4.3 %	6.6 %	4.9 %
Elbow	Right	Flexion-Extension	3.3 %	13.6 %	3.8 %
	Left	Flexion-Extension	0.4 %	0.8 %	8.2 %
Wrist	Right	Flexion-Extension	81.1 %	6.2 %	74.8 %

		Abduction-Adduction	6.2 %	4.7 %	4.2 %
	Left	Flexion-Extension	13.3 %	11.6 %	46.9 %
		Abduction-Adduction	11.7 %	12.2 %	92.5 %

Table 4.1: the percentage errors of all upper limb joints during performing movements

In this measurement work, arm motion have been classified by the researchers, measured by using Kinect™ device, and validated by comparing the results of the Kinect™ with the Vicon results. Although the frame rate of the Kinect™ (194 angles in the all period of time) is largely smaller than the frame rate of the Vicon (33847 angles in the same period of time), the Kinect™ was able to provide the type of the movement for each joint at each specified time, the history of each joint movements and the combined movements at each time point, and the angles performed by each joint with an acceptable error in most cases.

Nowadays, according to our knowledge, there is a lack of markerless methods for quantitative assessment especially in Home-based therapy. In this work, we have presented results which help the therapists to judge the therapy process for children with hemiplegia based on the presented objective assessment method. These results can be gained by using inexpensive assessment device, markerless, and easy to install which is the best choice for therapy at home.

4.3.4 Conclusions & future work

Most of motions, which related to all upper limb joints, have been performed such as shoulder Flexion-Extension, shoulder Abduction-Adduction, Elbow Flexion-Extension, Wrist Flexion-Extension, and Wrist Abduction-Adduction. We have developed a quantitative assessment method using Microsoft Kinect™ and based on the existing clinical definition of the upper limb motion. Finally a comparison between the results of our system and the results of the Vicon system has been done. This comparison shows a potential use of the Kinect™ in Home-based therapy for children with hemiplegia.

We recognize that the medical specialists would prefer a conclusion of the joint motion along with the results of those motions. So, the future work will concentrate on developing an

algorithm that based on the numeric data, which collected by the Kinect™, to systematically provide therapists with a summary of the joints motions. An exploration of the effects of filtering methods on the kinect's results needs to be done in the future work.

4.3.4 General conclusion and perspectives

In this chapter, the two therapy experiments, which have been done in this PhD study, are described. Each experiment has been clarified with its subjects who have practiced the system, VR scenarios that have been used, results of those experiments, discussion of each scenario, conclusion and perspectives for all proposed scenarios for both therapy experiments. Also, the assessment experiment that has been achieved is presented. This experiment was done to validate the use of Kinect for windows assessment device in the type of movement assessment. And then, results of this experiment and conclusion are illustrated.

Chapter 5: Conclusion and future Perspectives

5.1 Conclusion

This PhD thesis presents the development of a rehabilitation system for the affected upper limbs of children with hemiplegia. This system was developed with main focus on the different difficulties and needs of those children, such as what movements they cannot implement? What are the reasons? How can we make those children perform the desired movement using available technical methods?. This system was developed using user centered design to response to the different requirements of this type of patients. In order to allow the largest number of patients to use and benefit from the system; we have developed it in cadre of Tele-Rehabilitation. This Home-Based therapy imposes us to develop an evaluation system which evaluates the performance of children during executing the system at home, because of that: medical doctors and/ or therapists would not be there to measure their performance. The following conclusion for our proposed rehabilitation system can be drawn:

In this rehabilitation system we have developed a Haptic-Virtual reality game therapy. This system provides different sensation means, visual, audio and tactile feed-back, in conjunction in order to stimulate the affected side of the brain of hemiplegic children to transmit its instruction to the joints of the affected upper limbs to make desired movements. Different VR scenarios have been consulted, developed and validated with medical doctors and therapists in Marc Sautelet rehabilitation center in Villeneuve D'Ascq, France. These scenarios aim to target two main types of movements: Particular movement where the basic movement is targeting like Shoulder Flexion-Extension. Or, functional movements where scenarios focus on the activities of daily living that use certain joint(s) like organizing some objects on a table which require Shoulder-Elbow Flexion-Extension in a functional way to perform this task. A protocol of the therapy was developed for each scenario to enable children, who are going to use the system, to perform the suggested movement in normal joint recruitment.

Each VR scenario has been developed to constrain related joints of the affected upper limb to execute a certain movement, and then repeat this movement until it will be registered in the motor memory of that limb; to be used later on in the activities of daily living when needed. In order to validate the accuracy of the developed VR scenarios; we have developed an assessment

method which will provide us with the type of the movement which has been implemented by the child at each scenario. For example, we have developed a VR scenario which targets Elbow Flexion-Extension movement; so by using this type of movement assessment method we can know whether or not this movement has been performed? Are there any other movements (compensation movements) have been performed?. Assessment systems with markers are used in this type of assessment. But those systems require a huge space, expert people to put its markers in the right places and they are very expensive; so they are not suitable for home-based therapy. Actually, we have used Kinect for windows marker-less and not expensive assessment device in this type of movement assessment. In our knowledge, this device has not been used before in this type of movement assessment; so we had to make new body planes at each joint of the upper limb to make the desired assessment using this Kinect for windows assessment device.

The developed rehabilitation system has been made as Tele-Rehabilitation therapy in order to enable the maximum number of patients to practice the system; especially for those who live far away from the available rehabilitation centers. But in Tele-Rehabilitation systems; medical doctors and/ or therapists would not be there to evaluate the performance of children during the rehabilitation process. So, we had to develop an assessment method to evaluate their performance in the absence of those medical doctors. Fuzzy logic concept has been used in this assessment method to build the evaluation decision based on the quality and the quantity of the movement similar to the therapists' evaluation. This method is based on the needed time to complete a task along with the number of collected objects in that particular time, and the number of contact with the force feed-back coming from the haptic device to keep the affected upper limb within the proposed trajectories. Finally, the system will provide medical doctors and therapists with the history of the performance of children for each type of movements.

Three experiments have been performed in this PhD thesis. Two therapy experiments and one assessment experiment. In the therapy experiments; we have pre-validated the system with two groups of children: normally developed children and children with hemiplegia. Results from these two experiments show the level of the enhancement of the performance of children who have used the system. The assessment experiment has been done to study the feasibility of using Kinect for windows device in the type of movement assessment. Results from this device have been compared with results from Vicon assessment device to find-out the reliability of the

Kinect`s results. The comparison illustrates the feasibility of using Kinect for windows device to assess shoulder and elbow movements; but not for wrist movements.

5.2 Perspectives

In this work, we have developed different VR scenarios; each scenario has its own protocol in order to target the desired movement. As future perspective, an investigation concerns the feasibility of those protocols is needed to determine the best protocol for each movement. This investigation can be done by developing alternative protocols for each scenario and/ or movement in order to judge the efficiency of the developed protocols.

VR scenarios have been developed to motive children with hemiplegia to continue the rehabilitation processes. So, we have developed those scenarios in order to be exciting and most importantly target the desired movement. But there is a conflict between exciting scenarios and the functional objective of each scenario (target the desired movement). For example, we have developed a scenario to target shoulder Flexion-Extension; this scenario has to have a well designed virtual environment to take children' attention. Also, it has to be built with clear objective to avoid dispersion. So, we have to respect the limitation between these two concepts: motivation and dispersion. A future work to describe and determine those limitations is needed to develop the up-coming VR scenarios for rehabilitation.

Home-based therapy is important in terms of allowing as many children with hemiplegia as possible practicing the system. At home, parents will be responsible of all the preparation for the system to let their children start the rehabilitation process. Parental acceptance of the system is critical to continue the Tele-Rehabilitation system. So, a complete study about different aspects concerning this objective is needed. The different aspects might consist of: The available time for parents and their children each week to practice the system, the needed work-space for the system to be installed and the background of parents about the important of using new technologies (in our case Haptic-VR) in rehabilitation field, especially for children.

In this rehabilitation system, we have developed a new method for evaluation. This method is based on the use of fuzzy logic concept in order to evaluate the performance of the affected upper limb of hemiplegic children during the rehabilitation process. In this method, we have used

two entries (T: the needed time to complete a task, and N: the number of contact with the force feed-back) in order to build the evaluation decision. A generalization of this method in order to be usable for open entries, three or four entries which will be defined by medical doctors, might help designers of rehabilitation system to build their Tele-Rehabilitation system in the future.

Children with hemiplegia, who have done the experiment and practice the rehabilitation system, have learned some new movements using their affected upper limbs. Are these movements going to remain in their motor memory? For how long time it will be remained? Will those movements be registered forever?. A regular assessment sessions; for example an assessment each three months, might be a solution for this evaluation manner.

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Appendix A: System preparation

In this appendix, explanations about the used equipments, the definition of the initial position, and the clinical measurement categories are presented as following:

A1. System preparation (Equipments and initial position)

For the position of the haptic device we need to follow the instructions shown in Fig. A.1.



Figure A.1: The haptic device position initial

1- For Flexion Extension movement

The child must seat as explained in chapter 4 section 4.2.3, and the position of the haptic device need to be fixed at the maximum range of motion for this movement. The elbow extension at 180^0, and then we calculate the distance between the end of the table and the haptic. Once this has been done, we must put the haptic at the same position for the upcoming trails to ensure the predictability of the movement. For example, for the child who we will call here as Y1, the haptic device need to be put at 50cm of the table each time he attempts to do the flexion extension movements as can be seen in Fig. A.2.



Figure A.2: Flexion Extension position initial

2- For Abduction Adduction movement

The child must seat as explained in chapter 4 section 4.2.3, and the position of the haptic device need to be fixed at the maximum range of motion for this movement. The elbow extension at 180^0, and then we calculate the distance between the end of the table and the haptic. Once this has been done, we must put the haptic at the same position for the upcoming trails to ensure the predictability of the movement. For example, for Y1, the haptic device need to be put at 43cm of the table each time he attempts to do the abduction adduction movements as shown in Fig. A.3.



Figure A.3: Abduction Adduction position initial

3- For Pronation Supination movement

In this movement, we must ensure that the elbow flexion at 90^0 , and the hand of the patient holds the handle of the translator device for the pronation supination movement as explained in chapter 4 section 4.2.3. The children seat at a chair which enable him to have their elbow flexion at 90^0. For example, for Y1, the translator device need to be put at 25.5 cm of the table each time he attempts to do the pronation supination movements as shown in Fig. A.4.



Figure A.4: Pronation Supination position initial

A2. Clinical measurement categories:

In this section, the different measurement categories, which have been determined by medical doctors and therapists, are presented. Also, table A.1 that contains of all numeric data collected by the system. Those data are to be given to the therapists, and used by the fuzzy system to establish the level of enhancement of each type of the movements.

1- Date of illness diagnostic

2- Patients' age

3- Affected side of the body (right or left)

4- The original side of movement

5- Pain level of each type of movement

6- Proposed time for the movement/ and the number of repetition of that particular movement

Name	Age	six	Affected side	Illness date	Type of movement	Date for the movement	Pain level	Number of repetition	Enhancement level (100%)
Y1	10 years old	Male	Right	5 years ago	Flexion Extension	21-12-2016 10:41:36	2/10	14	23.37%
						21-12-2016 10:44:49	1/10	20	25.00%
						21-12-2016 10:47:42	0/10	37	81.86%
					Abduction Adduction	21-12-2016 10:51:07	0/10	36	81.7%
						21-12-2016 10:53:39	0/10	28	62.06%
						21-12-2016 10:56:27	0/10	29	69.87%
					Pronation	21-12-2016 11:01:42	0/10	27	50.00%
						21-12-2016 11:05:47	1/10	42	50.00%
						21-12-2016 11:07:57	1/10	42	50.00%
					Supination	21-12-2016 11:09:21	0/10	44	53.65%
						21-12-2016 11:11:46	0/10	35	50.00%

						/	/	/	/
					Pronation Supination	21-12-2016 11:22:20	0/10	35	50.00%
						21-12-2016 11:25:26	0/10	49	60.26%
						21-12-2016 11:27:47	0/10	48	59.09%
					Flexion Extension	22-12-2016 10:37:23	2/10	25	50.11%
						22-12-2016 10:40:07	2/10	25	48.36%
						22-12-2016 10:44:55	0/10	26	51.86%
					Abduction Adduction	22-12-2016 10:50:06	0/10	29	70.4%
						22-12-2016 10:53:02	0/10	31	86.89%
						22-12-2016 10:57:05	0/10	38	86.72%
					Pronation	22-12-2016 11:17:51	0/10	59	73.06%
						22-12-2016 11:21:51	2/10	65	76.05%
						22-12-2016 11:25:44	2/10	77	89.18%
					Supination	22-12-2016 11:28:13	0/10	71	79.88%
						22-12-2016 11:30:41	0/10	62	75.21%
						/	/	/	/
					Pronation Supination	22-12-2016 11:42:37	0/10	60	75.00%
						22-12-2016 11:45:25	0/10	43	51.94%
						22-12-2016 11:48:06	0/10	55	67.13%
					Flexion Extension	23-12-2016 10:20:36	1/10	23	40.04
						23-12-2016 10:25:07	0/10	23	31.94%
						23-12-2016 10:27:36	0/10	24	49.93%
					Abduction Adduction	23-12-2016 10:31:46	0/10	30	86.89%
						23-12-2016 10:36:04	0/10	26	58.95%

						23-12-2016 10:42:09	0/10	34	83.25%
					Pronation	23-12-2016 11:00:16	0/10	47	57.87%
						23-12-2016 11:03:45	0/10	55	67.13%
						23-12-2016 11:06:34	0/10	57	69.82%
					Supination	23-12-2016 11:09:38	0/10	67	76.98%
						23-12-2016 11:12:42	0/10	60	75.00%
						23-12-2016 11:14:53	0/10	73	82.05%
					Pronation Supination	23-12-2016 11:17:20	0/10	48	59.09%
						23-12-2016 11:20:05	0/10	39	50.00%
						23-12-2016 11:22:26	0/10	60	75.00%

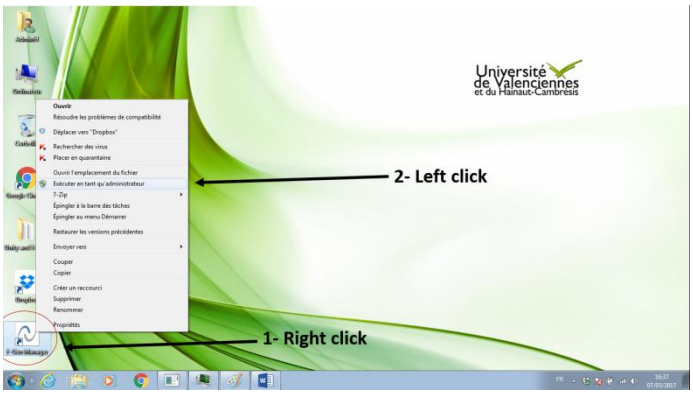
Table A.1: The collected numeric data

Appendix B: The rest of the scenarios

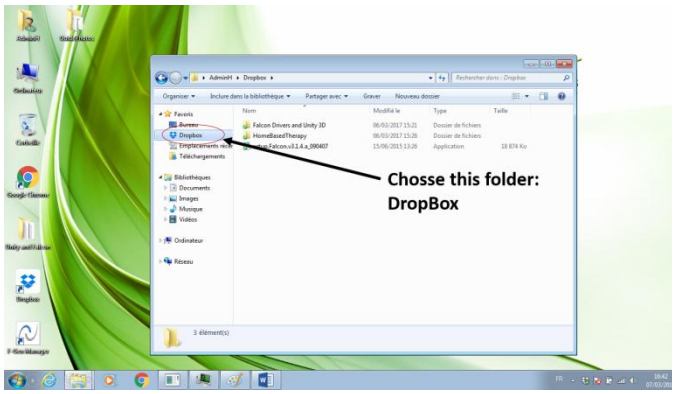
In this appendix, explanations about the rest of developed scenarios are presented as following:

B.1. Pronation scenario

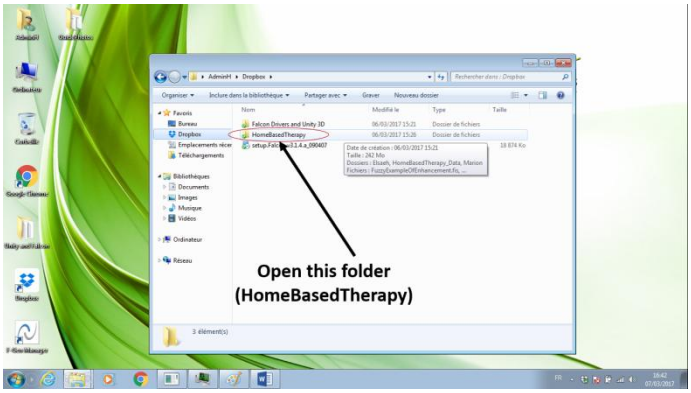
Therapists/ parent follow the instruction presented in Fig. B.1. a, b, c, d, e, f, g, and h respectively.



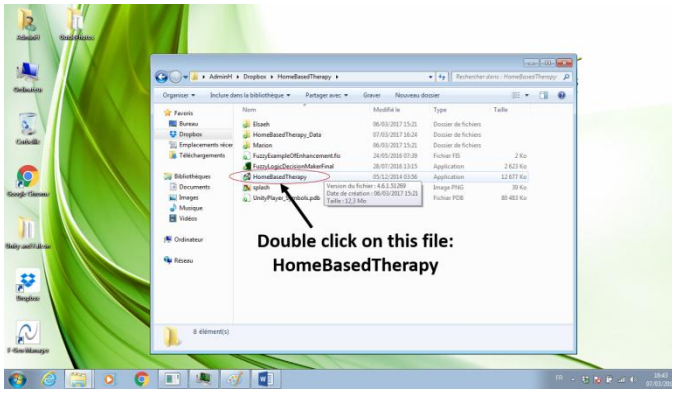
a) Start the haptic device



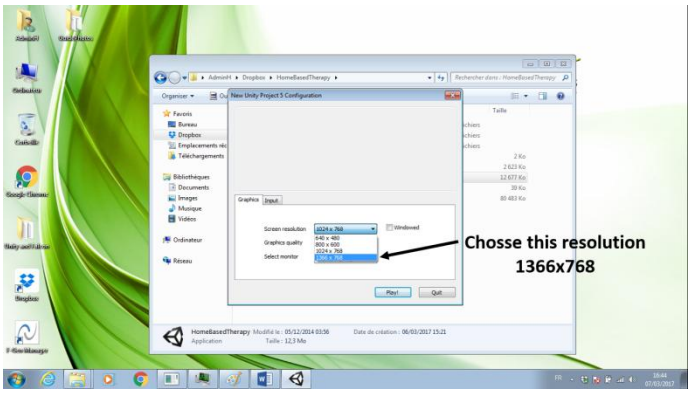
b) Open Dropbox



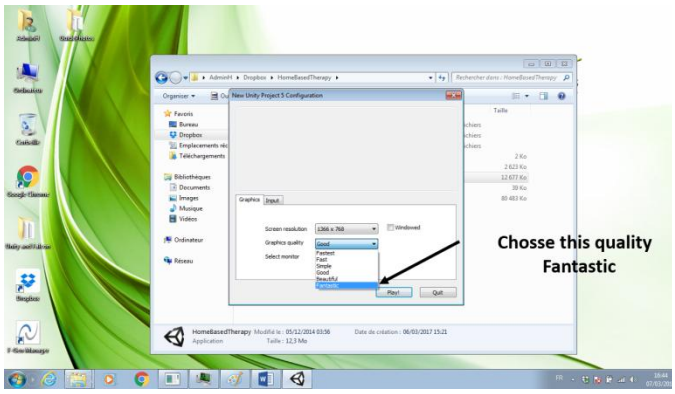
c) Open HomeBasedTherapy folder



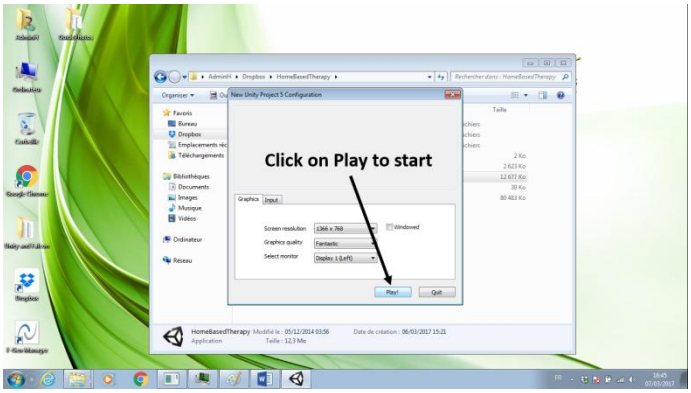
d) Execute the therapy file



e) Choose the right resolution



f) Choose the best display quality



g) Start the game

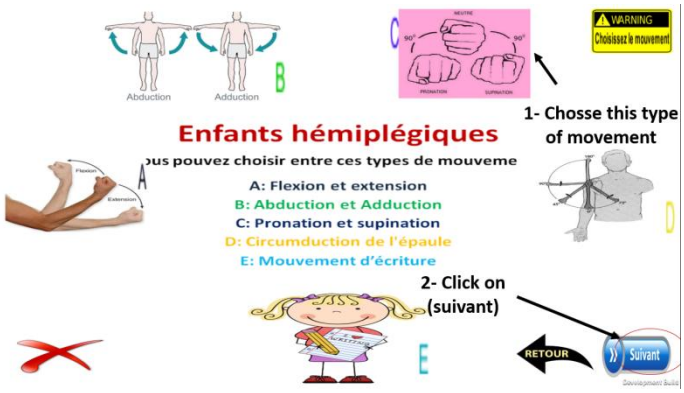


h) Write the child's name and play

Figure B.1: the steps to start the system

Then they must choose the type of movement from the list of movements shown in Fig. B.2. a, and then click (suivant). A screen which explains the initial position of this movement will appear as shown in Fig. B.2. b, the parent must read, understand and apply this position to his or her child, after which he must click on the (suivant). A time screen will appear as in Fig B.2. c, and he must choose the time for this movement and click on the (suivant). A screen that explains the protocol for this movement will be shown by the system Fig. B.2. d. Therapists/ parent should explain the scenario to her child and run the system when her child is ready to make the desired movement. Now they have to choose the pronation movement as in Fig. B.2. e, and click (suivant). The scenario which enables the child to practice pronation movement will be appeared

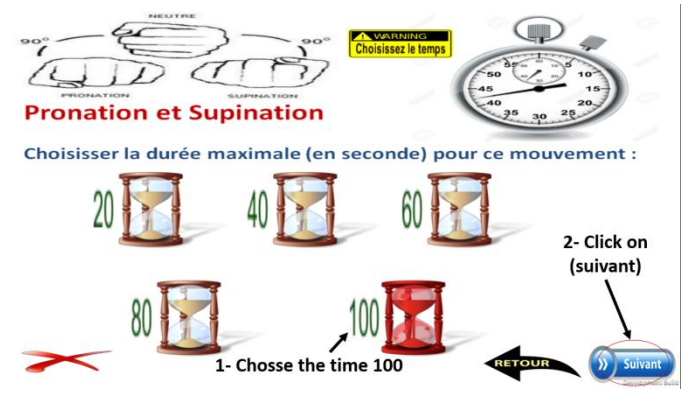
as in Fig. B.2. f. This scenario has a virtual wall which will constrain children to move within a certain space (the left hand side part). This space is responsible for the pronation movement.



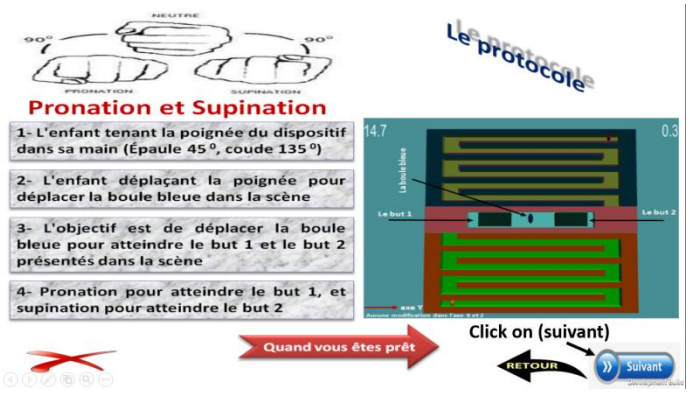
a)



b)



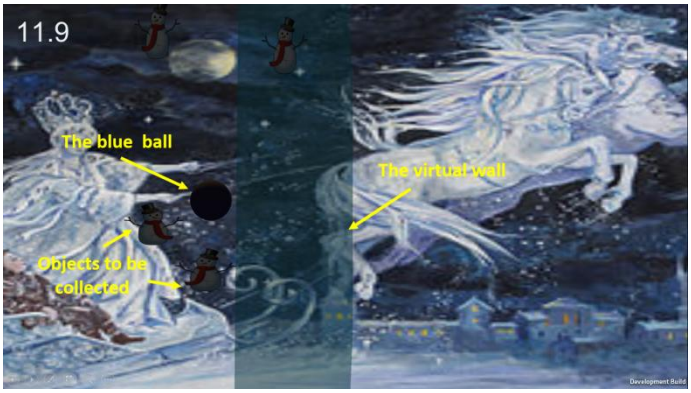
c)



d)



e)

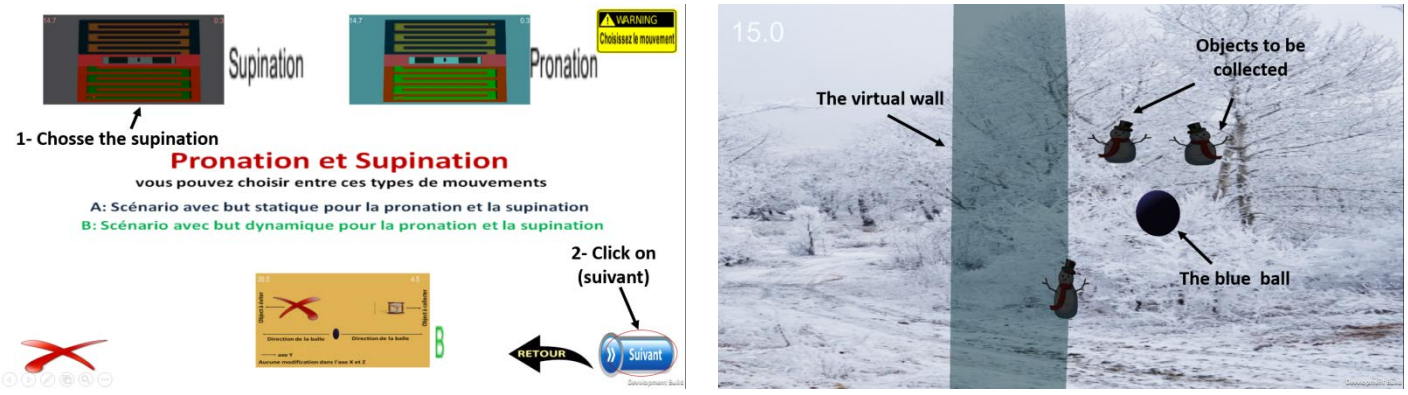


f)

Figure B.2: the steps for the pronation movement

B.2. Supination scenario

Therapists/ parent have to follow the same steps presented in the above section B.2. a, b, c, and d. Then, they have to choose the supination movement as shown in Fig. B.3. a. The scenario which enables the child to practice supination movement will be appeared as in Fig. B.3. b. This scenario has a virtual wall which will constrain children to move within a certain space (the right hand side part). This space is responsible for the supination movement.

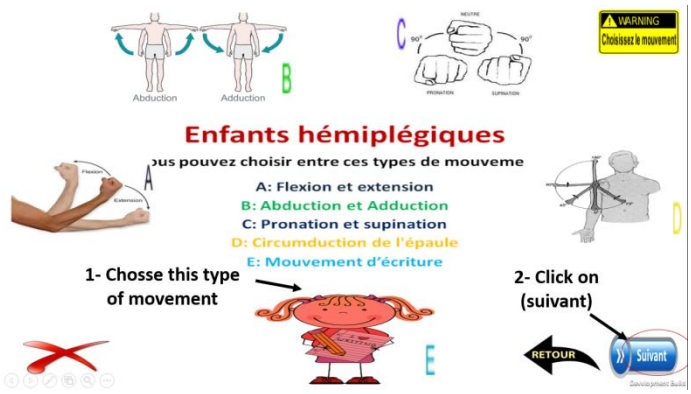


a) b)

Figure B.3: The steps for the supination movement

B.3. Writing movement scenario

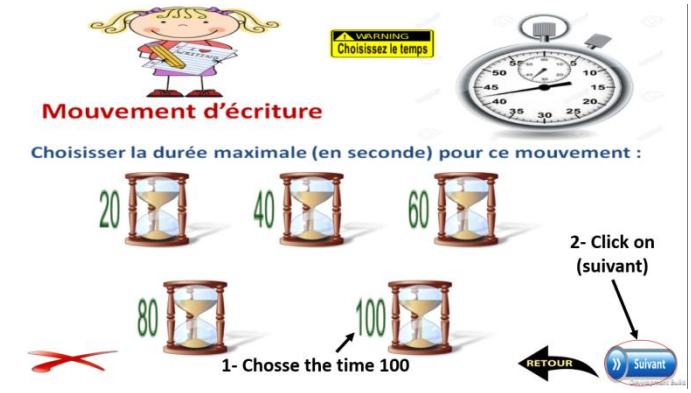
Therapists/ parent must choose the type of movement from the list of movements shown in Fig. B.4. a, and then click (suivant). A screen which explains the initial position of this movement will appear as shown in Fig. B.4. b, the parent must read, understand and apply this position to his or her child, after which he must click on the (suivant). A time screen will appear as in Fig B.4. c, and he must choose the time for this movement and click on the (suivant). A screen that explains the protocol for this movement will be shown by the system Fig. B.4. d. Therapists/ parent should explain the scenario to her child and run the system when her child is ready to make the desired movement. The scenario which enables the child to practice the writing movement will be appeared as in Fig. B.4. e. This scenario has a virtual wall which will constrain children to move only on the Y axis. This configuration allows children to coordinate the joints of the upper limb to make the movement which is similar to the writing movement. Finally, they have to end the system as in Fig. B.4. f.



a)



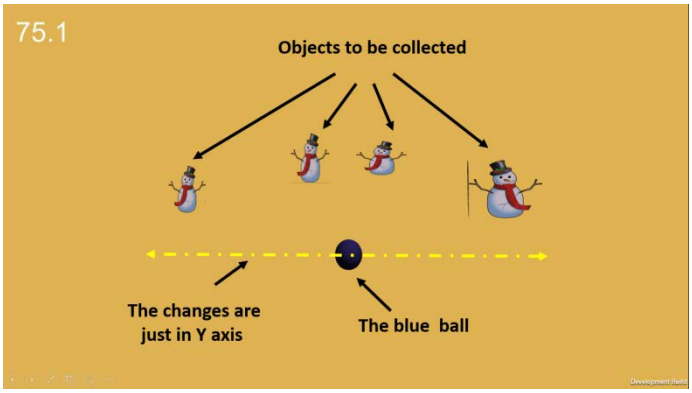
b)



c)



d)



e)



f)

Figure B.4: The steps for the writing movement