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A REAL-TIME SKELETON-BASED PHYSICAL REHABILITATION PLATFORM

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"…exercise may be one of the most powerful tools to fight some symptoms and to slow the Parkinson's disease degenerative nature."

Online article on the website of the National Young Onset Center of the American Parkinson Disease Association (APDA) [1].

Abstract

The present thesis develops a virtual real-time physical rehabilitation platform tailored to Parkinson's Disease (PD) patients. Proper exercises for PD patients are drawn from references, including also the corresponding instruction video, in order to be executed in a daily routine exercises set. The Microsoft Kinect v1 sensor and OpenNI v2 framework with Nite middleware are employed to implement body-tracking techniques detecting the skeleton model of an individual patient. The patient stands in front of a Kinect device, and by the time he is recognized as a platform user, the instruction video demonstrates the correct performance of corresponding exercise offering real-time guidance. While the patient performs an exercise through a virtual environment created with Unity3D game engine, accurate 3D skeletal joint data are extracted in space measurements and stored frame-by-frame, so that the doctor would be able to supervise the patient's progress in a long-time manner. Movement repetitions, either in a cyclic or straight movement pattern, of each exercise are recognized in real-time and counted on both the right and left side of the patient's body. When the required repetitions of an exercise are executed, the exercise is considered as successfully performed and a grade estimation of patient's mobility is calculated in order to estimate each performance. Then the patient is encouraged to continue to the next exercise until all the daily set of exercises is completed. We envision assisting PD diagnosis by offering medically useful measurements and functionalities with this accurate computer vision platform, capable to be easily installed either in clinic or at home.

Περίληψη

Η παρούσα διπλωματική εργασία αναπτύσσει μια πλατφόρμα πραγματικού χρόνου ως λογισμικό ικανό να υποστηρίξει ασκήσεις για φυσική αποκατάσταση προσαρμοσμένη σε ασθενείς που πάσχουν από την νόσο Πάρκινσον. Ασκήσεις γυμναστικής κατάλληλες για ασθενείς Πάρκινσον αντλήθηκαν από την βιβλιογραφία, συμπεριλαμβανομένου και του αντίστοιχου βίντεο οδηγιών, με σκοπό να εκτελούνται σε ημερήσια βάση. Ο αισθητήρας (sensor) Microsoft Kinect v1 και το OpenNI v2 πλαίσιο λογισμικού (framework) με ενδιάμεσο λογισμικό (middleware) το Nite χρησιμοποιήθηκαν για να εφαρμόσουν τεχνικές ανίχνευσης ανθρώπινου σώματος εξάγοντας το σκελετικό μοντέλο του ασθενούς. Ο ασθενής στέκεται μπροστά στη συσκευή Kinect, και μόλις αναγνωριστεί από το σύστημα ως χρήστης της πλατφόρμας, το βίντεο οδηγιών επιδεικνύει την ορθή εκτέλεση της κάθε άσκησης, προσφέροντας έτσι καθοδήγηση πραγματικού χρόνου. Κατά τη διάρκεια της εκτέλεσης μιας άσκησης, μέσω εικονικού περιβάλλοντος που δημιουργήθηκε με το πρόγραμμα Unity3D, εμφανίζονται ακριβή ανθρωπομετρικά δεδομένα που προσδιορίζουν την θέση του σκελετικού μοντέλου του ασθενούς στον τρισδιάστατο χώρο τα οποία και αποθηκεύονται καρέ-καρέ (frame-by-frame), έτσι ώστε ο γιατρός να είναι σε θέση να επιβλέψει μακροπρόθεσμα την πρόοδο του ασθενούς. Επαναληπτικές κινήσεις, είτε σε κυκλική είτε σε ευθεία τροχιά, της κάθε άσκησης ανιχνεύονται σε πραγματικό χρόνο και καταγράφονται τόσο στην δεξιά όσο και στην αριστερή πλευρά του σώματος. Όταν εκτελεστούν οι ζητούμενες επαναλήψεις, η άσκηση θεωρείται επιτυχώς ολοκληρωμένη και υπολογίζεται ένας βαθμός εκτέλεσης για να εκτιμήσει την κινησιολογία του ασθενούς στην εκτέλεση κάθε άσκησης. Τότε ο ασθενής ενθαρρύνεται να συνεχίσει στην επόμενη άσκηση, μέχρις ότου να ολοκληρωθεί όλο το ημερήσιο σετ ασκήσεων. Οραματιζόμαστε να προσφέρουμε ένα βοηθητικό εργαλείο στην διάγνωση του Πάρκινσον παρέχοντας χρήσιμες μετρήσεις και λειτουργίες στην ιατρική με αυτήν την πλατφόρμα τεχνητής όρασης, η οποία μπορεί εύκολα να εγκατασταθεί είτε σε κλινικές εγκαταστάσεις είτε στο σπίτι του ασθενούς.

1. Project Vision

Since the first studies on the benefits of physical activities appeared in references, a new insight came out into how the human body can be manipulated and modified for different purposes. A recent review appears in [2]. Nowadays, technological advances allow the development of new intervention strategies that could benefit individuals with motor dysfunctions. As more studies appeared, it became clear that individuals with neurological disorders could benefit a lot from physical activities by improving mobility, functional independence, muscular strength, flexibility and balance with subsequent functional improvement for individuals with Parkinson's Disease (PD).

However, PD patients require specific physical activities, such as exercises focusing on strength training, balance and aerobic conditioning, as well as the use of external cues during gait, which can result in overall improvement in motor performance. Moreover, it is possible that intensive and daily persistent exercise contributes to brain repair, delaying the progress of PD's degenerative nature. Therefore, efforts should be implemented in clinical and investigative research to collect information related to properly structured programs of physical activities, regarding type of activity, frequency and program duration.

The present thesis presents a virtual rehabilitation platform tailored to patients with neurological disorders or motion impairment. The platform is sufficiently generic and modular to accommodate conditions such as PD, stroke recovery, athlete recuperation etc. Virtual Reality technology is currently widely applied in physical rehabilitation therapy and the availability of simple prototyping platforms with innovative interfaces opened many discussions on designing original rehabilitation applications as mentioned in [3]. The ability to track skeletal joint positions using Microsoft Kinect is very useful to rehabilitation, either in a clinical setting or at home. Motor impairment has been shown to be the most important barrier for this category of people. Unfortunately, according to the National Parkinson Foundation [4], most doctors still use only their experience to identify and grade PD. More objective criteria would be medically valuable to a lot of these situations. The platform presented in the present work offers physiotherapy measurements useful for long-term assessment of PD patients by recording the quality of execution of the selected physiotherapy exercises.

More specifically, the work involved firstly led to a collection of exercises aimed at PD patients: appropriate exercises were drawn from the references, including also the corresponding instruction video. Each exercise was performed by a trainer and the session was recorded to demonstrate the correct performance of each exercise by the patient offering real-time guidance. Patient that stands in front of Kinect device should try to execute the physiotherapy exercise shown. According to specific patient's movement disabilities, exercises are prescribed by the doctor.

While the patient performs an exercise, computer vision techniques (through Nite middleware) are employed to implement body tracking and extract the patient's skeleton in real-time. When the patient has completed the exercise, the platform computes a grade for that particular session based on the patient's performance. After a set of exercises has been executed, the 3D joint coordinates are stored for each execution so that the quantity of performance can be assessed and the exercise is assigned a grade. A proper historical record of exercise performance could be used to assess patient progress.

We envision offering a powerful software tool to assist PD diagnosis by offering medically useful measurements and functionalities with this accurate computer vision platform. Using OpenNI v2 framework and Nite middleware, we achieve great robustness on real-time body-tracking measurements, even in seated position exercises, which still is a great barrier for skeleton-based applications. Also, a solution to patients' contact with their doctor, physiotherapist and trainer is achieved with this platform, which is easily installed either in clinic or at home.

2. Related Background

2.1 Neurological Physiotherapy

Neurological physiotherapists often specialize in different hospital departments to provide the best possible patient care, but essentially facilitate the treatment of a host of neurological conditions, many of which have adverse effects on range of motion or co-ordination. The aim of neurological physical treatment is to restore mobility as much as possible by using a host of different exercises and routines to improve muscular strength, core stability, balance, posture, and through these, self sufficiency. Neurological disorders often result in muscular atrophy or the loss of coordination, and a physiotherapist will attempt to restore these using strengthening and stretching routines, hydrotherapy, and electrotherapy. A physiotherapist will be constantly monitoring the patient's progress and making adjustments according to how the individual is coping. Muscular training is only part of restoring functionality however, and he will probably incorporate relevant coordination exercises and skills to restore movement by means of practicing daily actions, e.g. walking, changes of posture, stretching exercises etc.

From a neurological physiotherapy point of view, PD involves a deficiency of a particular neurotransmitter called Dopamine that leads to the gradual degeneration of a part of the brain called the Substantia Nigra, which usually results in a tremor that worsens as the disease progresses. Neurological physiotherapy can help correct any postural or positional difficulties, aiming to facilitate day to day living the best way they can, restore normal motor function, improve coordination and muscle strength, as well as the range of movement available. Other aspects of neurological conditions that can benefit from physiotherapy, as mentioned at UK Health Centre [5], are Brain injury or damage, Stroke, Cerebral Palsy, Chronic pain, Dementia and Spinal Cord Injury.

Neurological physiotherapy as a specialist practice is based on a number of principles that reflect the goals of each performer, like the Bobath concept that was originally developed for conditions affecting the central nervous system. According to International Bobath Instructors Training Association [6], the Bobath concept is a problem-solving approach to the assessment and treatment of individuals with disturbances of function, movement and postural control due to a lesion of the central nervous system. Essentially this approach focuses on exercising the nervous and muscular systems to improve motor function and the goal is to restore fine movement control. The Carr and Sheppard concept aims to make physical therapy task oriented, where functional ability is restored and the patient is actively involved.

While these tasks are being performed, the muscles and neural pathways are simultaneously trained because they focus on relearning and practice basic and essential functions, as mentioned at [7]. Physiotherapists conduct their own assessments to establish the best way to conduct rehabilitation, based on their findings, experience and active scientific research.

2.1.1 Parkinson's Disease

When people think of the various movement disorders like PD, they usually envision an elderly man or woman. PD mainly develops in people over the age of 50, It becomes more common with increasing age, about 5 in 1000 people in their 60's and about 40 in 1000 people in their 80's, but young people between 20 and 30 years old can also get diagnosed with PD, having a slower disease progression because their generally healthier state as mentioned at Theracycle Blog [8]. Genetic (hereditary) factors may be important in the small number of people who develop PD before the age of 50, it affects both men and women and usually it is not inherited, according to UK Medical Resources [9].

Doctors define PD as a chronic persistent disorder of part of the brain. It is named after the doctor who first described it. It mainly affects the way the brain co-ordinates the movements of the muscles in various parts of the body. The main symptoms of PD are usually stiffness, tremor, and slowness of movement. Other symptoms may also develop and typically become gradually worse over time and physical treatment often provides good relief of symptoms for several years. However, the speed in which these symptoms become worse varies from person to person and it may take several years before they become bad enough to have much effect on patient's life.

A small part of the brain called the substantia nigra is mainly affected. This area of the brain sends messages down nerves in the spinal cord to help control the muscles of the body. Messages are passed between brain cells, nerves and muscles by chemicals called neurotransmitters. Dopamine is the main neurotransmitter that is made by the brain cells in the substantia nigra. To PD patients, a number of cells in in this part of the brain become damaged and the exact cause of this is unknown. Over time, more and more cells die and dopamine production is reduced, and their combination causes slowed and abnormal nerve messages to the muscles.

Three common PD symptoms that gradually develop are:

- Slowness of movement (bradykinesia). It may become more of an effort to walk or to get up out of a chair, but the diagnosis of PD may not become apparent unless other symptoms occur. In time, a typical walking pattern often develops, which is a 'shuffling' walk with some difficulty in starting, stopping, and turning easily.

- Stiffness of muscles (rigidity). Muscles may feel tenser and arms do not tend to swing as much when walking. In the early stage of the disease, one side of patient's body may be more affected than the other.

- Tremor (Shaking). It is very common, but does not always occur and it affects the fingers, thumbs, hands, arms, or other parts of the body. It is most noticeable at resting and may become worse at anxious or emotional conditions; while it tends to become less doing a focused movement, such as picking up a glass.

There is no diagnosis test that can prove PD, the diagnosis is based on these typical symptoms and when symptoms are mild it is really obscured. Guidelines for treating PD are released by the Scottish Intercollegiate Guidelines Network [10]. An initial treatment using a dopamine agonist, levodopa with a dopa-decarboxylase inhibitor or a monoamine-oxidase inhibitor is suggested:

- Levodopa increases the levels of dopamine in the human body and registers an improvement to the majority of PD patients. However, while a low initial dose suffices, chronic users commonly develop incapacitating problems such as 'on-off' effects (abrupt switches between being able to move and becoming immobile) or muscle problems leading to uncontrollable sudden movements or dyskinesia too.

- Dopamine agonists are medicines that act on the same receptors in the brain as dopamine, acting like a substitute. The difference with levodopa is that they do not need to be converted in the patience body to be active. Some commonly used types are Ropinirole, Pramipexole and Rotigotine. Sometimes a dopamine agonist, like Apomorphine, is used in combination with levodopa in people who have PD in its later stages who have severe episodes where they become immobile.

- Monoamine oxidase-B inhibitors are another alternative to levodopa for early PD, including selegiline and rasagiline. These medicines work by blocking the effect of a chemical in the brain called monoamine-oxidase-B (MAO-B), which is involved in the breakdown of levodopa and dopamine. If the action of MAO-

B is inhibited then the effect of any dopamine lasts longer and it may delay the need for levodopa for months or years. Sometimes these medicines are also used in combination with levodopa in later stages of PD.

- Catechol-O-methyltransferase inhibitors (COMT) are relatively new medicines, including tolcapone and entacapone. These are used to help stopping the breakdown of levodopa by patient's body, so more of each dose of levodopa can get into the brain in order to operate. A COMT inhibitor is sometimes advised in addition to levodopa when symptoms are not well controlled by levodopa.
- Other medicines are sometimes used to help relieve symptoms having various effects which try to correct the chemical imbalance in the patient's brain, including beta-blockers, amantadine and anticholinergic medicines. One of these may be tried when symptoms are mild, but levodopa or a dopamine agonist maybe likely needed at some point of the treatment.

The treatment schemes and doses can vary greatly from person to person and the dose of the medicine with usually needs to be increased over time to help keeping side-effects to minimum. As the disease progresses combinations of medicines may be required for best control of symptoms, as they may not be so well controlled. One main aim of PD scientific researches is to find medicines that prevent the damage to the affected cells, rather than just treating the symptoms, which is the main value of treatment at present. Further research on these chemicals continues. Research into PD is also active using stem cell therapy to help treat PD.

The other main part of PD treatment is of course in the hands of a physiotherapist that can advise on posture, walking and exercises. PD patients are advised to exercise regularly as much as they can. This may not be possible when the condition is more advanced, but it is something to consider when symptoms are not too bad. They may walk more slowly than before, but a daily walk and some simple stretching physiotherapy exercises, is the best exercise and may help to loosen up stiff muscles.

For our platform, physical rehabilitation exercises will be properly drawn from references in consultation with cooperating doctors, in a manner to be suitable for PD patients neurological recovering, as shown at [11]. These rehabilitation exercises are supposed to be performed every day with decent accuracy and adjustable workload by doctor for each one individual. We envision offering a diagnostic tool to offer assessment to prior knowledge of individual's performance with the corresponding medicine, so that medical diagnosis could be achieved in a shorter and more accurate term.

2.2 Related Technologies

Virtual Reality (VR) technology is currently widely applied in physical rehabilitation therapy in many forms of virtual environment applications as shown at [12]. It is an artificial environment created by special software, such as Unity3D game engine, with the patient operating through his representative element or character. VR interfaces require physical activities to interact naturally with computer interfaces by simply gesturing or speaking. A. Mauro [13] mentions among others that VR is an immersive, interactive, 3D computer-simulated environment occurring in real-time and has the ability to represent real-life tasks by offering multiple benefits as tracking specificity, adaptability to each patient, instance or daily repeatability, attractiveness to concentration, remote data access, telerehabilitation and in-home safety. While physiotherapy sessions often cannot fulfill the required frequency of practice, at-home exercises can achieve this goal. According to [14] effective rehabilitation programs form an essential component of the physiotherapeutic continuum assisting patients with motor disabilities improves their physical and psychological condition while providing an at-home exercises solution.

VR environments can provide realistic rehabilitation training in different scenarios and phases of patient's therapy, offering specificity to real-time motion measurements and precise adaptability to each patient's body. Computer-based rehabilitation programs could be developed using readily available, inexpensive, well known and current hardware sensors through virtual reality platforms as:

- Sony EyeToy (http://us.playstation.com/ps2/accessories/eyetoy-usb-camera-ps2.html)
- Nintendo Wii (http://www.nintendo.com/wiiu/what-is-wiiu)
- Microsoft Kinect (http://www.microsoft.com/en-us/kinectforwindows/)

H. Bateni [15] concludes mentioning "physical therapy training on its own or in addition to Wii Fit training appears to improve balance to a greater extent than Wii Fit training alone". Several interacting functionalities are available for an optimal user experience through Microsoft Kinect for Windows sensor instead of other sensors, which supports full body tracking, gesturing and voice commands. These functionalities provide controller-free interaction as well as keyboard-free, mouse-free or remote-free interaction. Full body tracking is available simply by standing in front of the sensor; gesturing functionality is activated by simply waving your hand, and voice commands respond to the sound of your voice when key-words are triggered. Accurate body tracking availability is the main reason that Kinect device was chosen for the implementation of our platform.

The Kinect is a powerful peripheral device which provides depth, image, and audio sensors to interact with a VR environment. It was a clear choice to attempt to use this incredible technology to provide a low cost and effective toolkit for biomedical engineers. The ability to track joint positions for Microsoft Kinect is useful for rehabilitation both in a clinical setting and at home. The overarching goal of this research is to determine whether the Kinect and the data supplied are conducive to be used by medical scientists. Patients shall be following a set of exercises shown on a TV screen, while the collected data would be fed back to the doctors supervising the patient, thereby decreasing the number of his visits to the hospital, making this a convenient affair for both the patient and the doctor. The potentials and the limitations of e- rehabilitation are various and it could be used to help promote physical rehabilitation at home by reducing the frequency of hospital visits or hospital length of stay, resulting in the reduction of healthcare cost. The Kinect can surely be a useful tool for at-home therapy while being readily available, easily installed and used flexibly in any home space. Moreover, it has compact size and does not require any clothing sensors that could limit patients' movements and lead to data distortion. Computer-based rehabilitation exercises using the Kinect, according to [16], are mentioned to be safe and feasible for people with PD, although intervention trials are needed to test their safety, feasibility and efficacy at home.

Kinect's potential for use in physical therapy is widely identified. A. Rizzo et al [17] studied how video games that require player movement could motivate persons at risk for obesity to engage in physical activities. For the demonstration of that concept, a Kinect-based computer game that could be controlled with gestures instead of mouse and keyboard commands was successfully developed. Referring to similar aims, Extreme TuxRacer is an open source project for experiments offering high-quality graphics, sound and game-play to attract game developers. In addition to keyboard controller, it can be controlled by full body motion supported by Kinect virtual keyboard. The purpose of the experiment aims to change keyboard-based interfaces into full body motion control or control through gestures. Also, Yao-Jen Chang et al [18] developed a Kinect-based rehabilitation system to assist therapists at their work with students who had motor disabilities. This program used the motion tracking data provided by the Kinect device to determine whether the patient's movements reached the rehabilitation standards, providing also a tele-rehabilitation utility with the therapist able to view the user's progress.

Falls are the leading cause of accidental injury-related deaths in the elderly; a fall can lead to a loss of independence, or even to fear of falling. Rehabilitation programs involving physical exercise have proved that the most successful way to reduce the risk of falls is the in-door performance. Having consulted users and health experts, S.Uzor and L. Baillie [19] concluded that games and visualizations for falls they developed were able to overcome the major limitations of standard care, and that they were usable and acceptable to the users, performing effective rehabilitation both in their laboratory and at home.

Moreover, H. Kayama et al [20] developed a new game concept, called Dual-Task Tai Chi. It was demonstrated with the Kinect device that it can quantitatively evaluate various functions that are known risk factors for falling in elderly adults, as dual-Task training that has been attracting attention to improve balance. A total of 41 elderly individuals participated and their cognitive functions were assessed before and after training, concluding that Dual-Task Tai Chi training is effective for improving executive cognitive functions.

Many clinical studies have shown that the arm movement of patients with neurological injury is often slow. M. Elgendi et al [21] evaluated the speed of arm movements in healthy subjects in order to validate the efficacy of using a Kinect device for automated analysis. The consideration of arm movement appears trivial at first glance, but in reality it is a very complex neural and biomechanical process that can potentially be used for detecting neurological disorders. The developed algorithm was able to classify the three arbitrary speed classes with an overall error of 5.43% for interclass speed classification and 0.49% for intra-class classification, which concluded to be the first step toward laying the foundation for future studies that investigate abnormality in arm movement via use of a Kinect. Furthermore, O. Geman [22] proposed a system for screening and motor rehabilitation of Parkinson's patients for tremor symptom correction. Many publications deal with arm speed and tremor especially in stroke patients such as [23] and [24].

O. Assad et al [25] demonstrated the development process of a collection of five motion-based games for Parkinson’s disease patients, aimed at supporting their exercises routines in various playful environments. The game design challenges for PD patients and solutions used in the games are described and the results of a conducted field test are showing a very positive motivational effect on the overwhelming majority of the patients.

W. Yu et al [26] describes a new real-time multimedia environment for the rehabilitation of PD patients integrating two well known physiotherapy techniques, multimodal sensory cueing and BIG protocol, with visual and auditory feedback for creating an engaging mediated environment designed to cover therapist and patient needs. The Lee Silverman Voice Treatment (LSVT) programs for individuals with PD have been developed and researched over the past 20 years beginning with a focus on the speech motor system known as LSVT LOUD and more recently have been extended to address limb motor systems known as LSVT BIG. The unique aspects of the LSVT programs include the combination of an exclusive target on increasing loudness in the speech motor system and making bigger movements in the limb motor system. Also focus is made on sensory recalibration to help patients recognize if these movements with increased amplitude are within normal limits, even if they feel “too loud” or “too big”, to train self-cueing and attention to performance to facilitate long-term maintenance.

Freezing of gait (FoG) is a disabling symptom commonly occurring in the latter stages of PD. It is characterized by brief episodes of inability to step, or by extremely short steps that typically occur on gait initiation or on turning while walking. FoG heightens the risk of falls, which leads to loss of independence. Aggravated mobility and difficulties in activities of daily living have a direct effect on the quality of life of patients, demanding attention from a carrier or causing affected people to move into specialized institutions. In the absence of any completely effective pharmacological treatment for FoG, technology-based solutions to alleviate the symptom and prolong patient's ability to live independently are eagerly being sought. Boris Takac et al [27] presented a model which runs independently for each camera in a distributed system, both for scene setup and people tracking. Data on the appearance of people being tracked is maintained in one central processing node and shared to every camera on request. For re-identification between cameras, an appearance model based on the person's color histogram and height along with the known average movement times between cameras is used. This indoor position tracking system is just the first step toward the final goal of FoG detection based on context. For daily use it is important that the system can automatically recognize the patient and record behavioral data for context modeling at home.

A methodology for mapping in-door gait speed, measured unobtrusively and continuously in the homes of older adults is presented by E. Stone and M. Skubic [28]. A Kinect-based gait system was used to collect in-home gait data on 15 older adults over time periods of up to 16 months, which concluded that accurate mapping of in-door sensor data to well studied domains facilitates clinical interpretation.

C. Chang et al [29] demonstrated the initial analysis and comparison of the motion tracking technology between the low-cost Kinect and a high-cost multi-camera lab-based OptiTrack system. This comparison is an important aspect of the development of low-cost game-based VR rehabilitation tools. Based on experiments made, results concluded to prefer Kinect as a promising VR neurological rehabilitation tool for use in clinic and at home.

M. Holden [30] describes the various VR systems that have been developed for use with patients with areas covered including stroke rehabilitation, acquired brain injury, PD, orthopedic rehabilitation, balance training, wheelchair mobility and functional activities of daily living training, and the newly developing field of tele-rehabilitation. The paper concludes with major findings that people with disabilities appear capable of motor learning within virtual environments and movements learned in VR transfer to real world equivalent motor tasks in most cases. Motor learning in real world versus virtual environments is compared and some advantage for VR training has been found in all cases, moreover no occurrences of cyber sickness in impaired populations have been reported to date in experiments where VR has been used to train motor abilities.

Although the Kinect gaming practice is a promising tool, J. Paavola's more recent study [31] questions the usefulness VR interfaces for brain injury patients and argues that conclusions cannot be generalized to the entire traumatic brain population. He also points out a technology gap for some patients with brain injury. In addition, navigating the Kinect interface menu may be challenging and playing virtual games may cause cyber-sickness in patients with brain injury. Another serious limitation of this study is the lack of information on the transfer of motor skills learned during the game performance to real-world behavior and changes in performance of activities of daily living were not assessed in their patients. Whereas these arguments do not appear to be valid for the PD population in our study, we have incorporated a feedback mechanism that informs the patient about the quality of performance.

The 3D space modeling presents a very important tool for analysis of the movement both in medicine and engineering. Video sequences acquired by a complex camera system can now be replaced by much simpler devices to analyze video frames with sufficient accuracy to enable a very precise data analysis. The use of Kinect device allows a simple 3D modeling using image and depth sensors for data acquisition with the precision of 4-40 mm depending upon the distance from the sensor. A.Prochazka et al [32] presents the use of Kinect for data acquisition, as well as data processing in the MATLAB environment and application of the 3D skeleton model in biomedicine.

We took advantage of Kinect's depth maps following patients' movements through body-tracking techniques where their skeletal joints are identified and tracked. Body tracking technology helps motivate people with motor disabilities to increase the number of exercises and improve the motor proficiency, while providing medically useful information in measuring precision in patient's performance. Space measurement data as X-Y-Z positions of these joints are obtained from the 3D sensor in real-time. Kinect is also used to perform multiple and complex tasks, enhancing more sensory feedback and motivating different modes of exercise, which can be impossible to achieve in a daily routine with standard physiotherapy procedures for PD patients. Hence, development of an application to rehabilitate dynamic postural control for PD patients through full-body multi-directional stretching tasks is attempted, allowing more frequent repetition of exercises in order to stimulate neural reactivation in regions of the brain where movement control operates. K. LaBelle [33] determines that the Kinect has much potential for use in stroke rehabilitation as a tool for both physical therapists and stroke survivors.

"Kinect for Windows helps motivate patients to do physical therapy and the data set we gather when they use the RMT is becoming valuable to demonstrate what form of therapy is most effective, what types of patients react better to what type of therapy, and how to best deliver that therapy. Those questions have vexed people for a long time," says Dr. R. Komatireddy [34], co-founder at Reflection Health. Because Parkinson's tremor or gait are still unknown issues we argue that nonlinear dynamic parameters have certain peculiarities and can be used in knowledge discovery. Reflection Health is on a medical mission to make physical therapy more effective for patients and more measurable for clinicians. It paired Kinect for Windows sensor technology and software development kit (SDK) with its proprietary software to deliver an interactive solution that could help patients and physicians improve physiotherapy results. The technology, which went into clinical trials in October 2012, makes physical therapy come alive by using the Kinect for Windows sensor and SDK to delivery customized therapy plans to patients. Our project is built with OpenNI, which provides greater accuracy on feet joints, even in seated stances, but hasn't been tested in clinical environments.

B. Lange et al [35] presents three potential applications of the new depth sensing camera technology from Primesense middleware and Kinect sensor exploring the integration of virtual environments, gesture controlled games and game development to target specific movements for rehabilitation. The benefits of implementing this technology in these three areas demonstrate the potential to address certain aspects of sensory or motor loss experienced by an individual and record targeted responses permitting assessment of functional performance. Furthermore, it is mentioned that the integration of motor rehabilitation with similar sensing systems for tracking human movement is believed to revolutionize therapeutic exercise activities at home.

T. Lu et al [36] presented a motion-sensing based management system for smart context-awareness rehabilitation healthcare including various balance exercise, built by the integration of the physiological sensing and feedback coaching. The home-end system can not only provide the exercise coaching instruction, the balance stability analysis, and the motion similarity analysis in real-time, but also simultaneously transmit the user image, exercise skeleton streaming, center of pressure, center of gravity and physiological information to the telecare-end center. According to the combination of the home-end and the telecare-end as well as the real-time care management of one-to-multiple personal balance exercise monitor, this system can provide user various personalized balance exercise prescription and cardiac rehabilitation coaching in an effectiveness rehabilitation exercise environment. Therefore, via this telesystem, the spinocerebellar ataxia patients in balance rehabilitation stage can monitor the execution status of the rehabilitation exercise prescription, as well as the long-term monitored and evaluated the predicted goal of the rehabilitation exercise balance stability in order to improve patient's compliance.

B. Andika [37] aimed to create an interactive and intelligent rehabilitation exercises system called RehabMe by exploiting Kinect and openspace3D game engine. RehabMe sustains patients' interest in performing exercises through immersive and interactive game-plays while carrying out an embedded assessment of rehabilitation progress. The embedded assessment features enable physiotherapists to remotely monitor the progress made by patients using quantifiable parameters such as repetition, response time, accuracy and number of correct moves. Therefore, it facilitates the growing needs of home-based rehabilitation by enabling an enjoyable interactive experience for patients and fulfilling clinical requirements of therapists at the same time. Our project can provide more skeletal data in more robust and less resource-hungry techniques, but has no immersive game-approach and no remote connection is provided.

Also, another similar project, which is a physical rehabilitation program called InfoStrat ReMotion360 [38]. ReMotion360 uses Kinect to measure and provide on screen feedback for 2D range of simple motion exercises and their movement target either in a clinic or at home. Moreover, our thesis is taking advantage of Kinect's depth sensor and develops an application with 3D graphics, for more accurate recording of individual's skeletal information in more representational way. This also gives information about patient's position on ground level while executing the exercise, which can be very useful for a more comprehensive view, providing more 3D dimensional information and measuring individual's stability. A fuller comparison of Remolution360 with our platform project appears in Chapter 5 (Discussion and Future Work).

Clinically feasible methods of assessing postural control such as timed standing balance and functional reach tests provide important information; however, they cannot accurately quantify specific postural control mechanisms. R. Clark et al [39] assessed the concurrent validity of Microsoft Kinect against a benchmark reference, a multiple-camera 3D motion analysis system, in 20 healthy subjects during different postural control tests. Kinect and 3D motion analysis systems had comparable inter-trial reliability and excellent concurrent validity; however, ordinary least products analyses demonstrated proportional biases for some outcome measures associated with the pelvis and sternum. These findings suggest that Kinect can validly assess kinematic strategies of postural control; therefore it can be used as a useful tool for assessing postural control in medical use.

M. Saputra et al [40] developed an application that tracks and locates human's presence and position in indoor environment using multiple depth-cameras with extremely low accuracy error. An alternative method is presented by X. Wei et al [41] for capturing full-body motion data using a single monocular depth camera achieving great accuracy in comparison against Kinect. Depth data, silhouette information, full-body geometry, temporal pose priors, and occlusion reasoning into a unified Maximum A Posteriori (MAP) estimation framework are integrated. 3D tracking process requires manual initialization and recovery from failures, but this challenge is addressed by combining 3D tracking with 3D pose detection. This combination automates the process with significant improvement in robustness and accuracy of the system. This algorithm, although being processor-heavy, is highly parallel and is therefore easily implemented on a GPU device capturing a wide range of human movements in real- time.

Finally, S.Nejati [42] have designed and implemented an open-source multi-layered application that will act as an exercise portal for patients and therapists, allowing therapists to create their own custom gestures and deliver the therapy session to user and also monitor user progress and updates. This project consists of several components and utilized many new technologies implementing a powerful real-time gesture recognizer mechanism. The result of this project is a robust and extendable application that can provide solutions for personalized physicotherapy with Kinect.

3. Platform Implementation

3.1 Platform Components and Implementation Methodology

Microsoft released Kinect in November 2010, as an extension to their gaming console Xbox 360. The new devices enabled users to control and interact with the system without using the conventional user inputs and controllers. Kinect is also able to gather and respond to audio commands by users and act accordingly, but the most ground breaking technology is Kinect motion capturing features. It can detect the presence of users in front of it; and it can also provide the location of skeleton model joints in 3D space in real-time.

Microsoft Kinect device is composed by a Microphone Array, a Color Sensor (RGB camera) and an IR Depth Sensor with an IR Emitter on the same band. The Color Sensor has a resolution of 640×480 pixels, while the IR Depth Sensor uses a matrix of 320×240 pixels or 640x480 pixels. Two sensors make up the depth component of the Kinect: the IR Emitter, which is an infrared projector, and the IR Depth Sensor, which is a monochrome CMOS sensor. These are the basis for gesture recognition and skeleton tracking technologies. The IR Emitter shines a grid of infrared light on the field of view, and a depth map is created based on the rays that the IR Depth Sensor receives from reflections of the light off of objects in the scene. All the sensors are housed in a horizontal bar attached to a base with a motorized tilt pivot that allows it to adjust the sensors' direction up or down. Using audio, image, and depth sensors, it can achieve detection of objects, human speech recognition, body tracking interaction interfaces etc. Unlike previous attempts at gesture or movement-based controls, it does not require kind of accessory from the user to wear to track the users' movements. All these parts together make up the Microsoft Kinect device (see Figure 1).

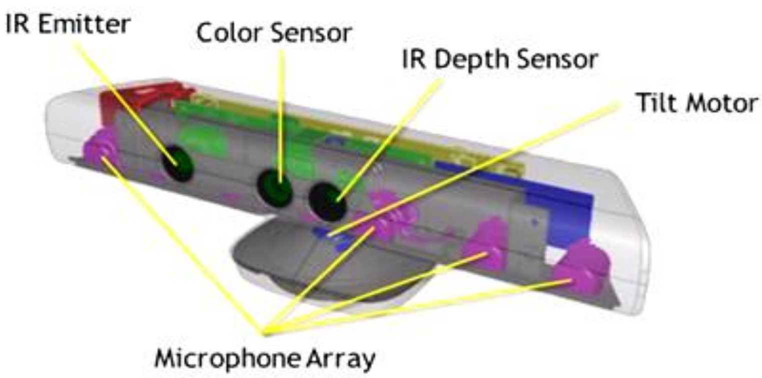

Figure 1 – Microsoft Kinect Device

While this technology was praised by industry, Microsoft Kinect SDK was not released until June 2011. The first version of the SDK allowed developers to gather the joint locations of detected skeleton in real-time and incorporate the data into their applications under .NET environment. The developers immediately took advantage of this new technology and whole new types of application showed that Kinect could be used in various and innovative ways. These applications ranged from games by various companies, retail and window shopping applications, music applications, medical applications etc. Microsoft did not initially release any drivers or SDKs to enable the Kinect to be used with a personal computer, and in fact at first the company discouraged efforts by the computing community to enable this. Later Microsoft modified its statement and intentionally discloses the USB port to be used for connecting the device to the Xbox. It attracts many developers to initiate open source projects to develop drivers, SDKs, and APIs to be used with personal computers. The explosion of these efforts was doubtless when the first open source Kinect driver was available.

Currently, two kinds of frameworks have been developed, OpenNI developed by Primesense and Official Microsoft Kinect SDK. One of the biggest advantages of the SDKs is joint-tracking without calibration and working with audio. It enables the tracking of 15 skeletal joints by default, in which X-Y-Z coordinates are given for each joint position in a frame-by-frame manner. The main purpose for present thesis is to demonstrate that it would be possible to develop medically useful skeleton tracking with the Kinect. Skeleton tracking is the processing of depth image data to establish the positions of various skeleton joints on a human form. Joint tracking algorithm identifies joint positions by processing a depth image. This algorithm first comes up with a joint guess for each pixel in a depth image, along with a confidence level for each pixel, which is really useful to conceder especially when we are dealing with medical applications.

Microsoft promotes a concept expressing that users are the input devices. With skeleton data, applications can do the same things a mouse or touch device can. The difference is that the depth component allows the user and the application to interact as a way that has never been done before. It can create custom gesture and detect them using skeleton data frames. For example, to detect whether you are walking or not, the algorithm checks five joint points, including right and left knees, right and left feet, and hip center. Using two boolean values, namely right-rise and left-rise, for checking which leg is above the other and comparing the z axis with knee and hip center. Most of movement calculations are based on two or more joint locations, distances and joint angles to calculate the distance between two points for 2- and 3-dimensional points, respectively.

This platform will employ as hardware the Microsoft Kinect device and supporting SDKs implementing computer vision body-tracking techniques to measure the accuracy of the patient's performance. The dominant development platforms supporting the Kinect sensor and on which applications may be built are:

- Microsoft SDK (http://www.microsoft.com/en-us/kinectforwindows/develop/new.aspx)
- OpenNI Framework (http://www.openni.org/openni-sdk/)

After evaluating these platforms, we choose to work with OpenNI Framework because it is open source and portable to multiple operating systems (MAC, Linux, Windows). The reason of its multiplatform nature is that it is built in C++ programming language. On the other hand Microsoft SDK, which is built in C#, is targeting at windows systems & Xbox game console, which are licensed. OpenNI framework is an open source SDK used for development of 3D sensing middleware libraries and applications. Moreover, the same OpenNI API can function with different motion sensors, like Kinect, Primesense and Asus Xtion, and there is a great academic online community with a lot of contributions.

Meaningful to our SDKs evaluation was also the fact that OpenNI recently updated and improved their skeleton model in OpenNI version 2. Despite the fact that Microsoft also released a new SDK at the first half of 2014, the skeleton model remained unimproved providing the same functionality as the one in previous SDK versions. Running examples of skeleton implementations from internet sources, OpenNI with Nite skeleton model provides much better results, with greater accuracy especially at torso joints when user turns around, and feet joints even at seated positions.

At the core of our system lies a real-time registration process that accurately constructs 3D depth map with body-tracking techniques, even in the case of significant occlusions. Nite is a middleware supported by OpenNI Primesense, used for computer vision applications such as tracking hands' location, scene analysis for separating users from background, various gesture recognitions and of course accurate user skeleton joint tracking. The greatest advantage of Nite middleware is that it boasts a thin host and minimal CPU load, suitable for real-time natural interfaces. In the meanwhile, Primesense recently discontinued while Apple Inc. declared their interest in claiming the company's titles, but our research continued, mostly for comparison reasons with the newest Microsoft SDK and having no knowledge about how is Apple going to use Primesense software.

In order to develop decent visual parts of our project we used Unity3D game engine which is one of the most powerful 3D game engines available. Unity3D is not open source, but it is free for developing an engineering project, obtaining good results without using the professional edition. Meaningful to our game engine selection is the fact that it can collaborate with OpenNI & Nite middleware, and ZigFu is a good example of a famous project that can control a 3D avatar in Unity3D using the OpenNI framework. OpenNI v2 cannot collaborate with Unity3D by default, because OpenNI framework is written in C++ and Unity3D supports scripts written in C#, JavaScript and Boo. Some can create a C++ code, then compile it to Dynamic-Link Library (DLL) and use it as plug-in, but this requires Unity3D professional edition. To overcome this barrier we needed a wrapper that can port the SDK of OpenNI and NiTE from C++ to C#. ZigFu project does that, but it is not open source and it provides a very abstract API, so that a developer cannot make severe changes needed for our platform.

Recently, S. Falahati [43] released a wrapper from C++ to C# for OpenNI and NiTE, but it was released based on Microsoft .NET framework version 4 in order to be used for specific windows namespaces and not especially to be used for Unity3D development. However, Unity3D is a cross-platform application and for that reason it uses MonoDevelop environment. MonoDevelop supports .NET framework until version 2, so we had to adapt Falahati's wrapper code, making many various modifications to Falahati's wrapper code in order to get it collaborate with Unity3D. Falahati's methodology was the chosen implementation method to translate OpenNI C++ code to Unity3D C# code. A lot bibliography was studied and various applications were tested through [44]-[52], in order to conclude to best suitable implementation method for our system. Overall, this platform is using Microsoft Kinect Sensor, employing OpenNI v2 framework and Nite middleware, and, through a C++ to C# wrapper, developed in Unity3D game engine (see Figure 2).

Using OpenNI v2 framework and Nite middleware, we have the ambition to achieve great robustness on our body-tracking measurements, even in seated position exercises, which still is a great barrier for skeleton-based applications. We expect the results to be really accurate and medically useful in order to improve PD medical diagnosis, to sustain a remote database with patients' progress and provide a powerful diagnostic tool, offering also a solution to patients' communication with their doctor, physiotherapist and trainer at home.

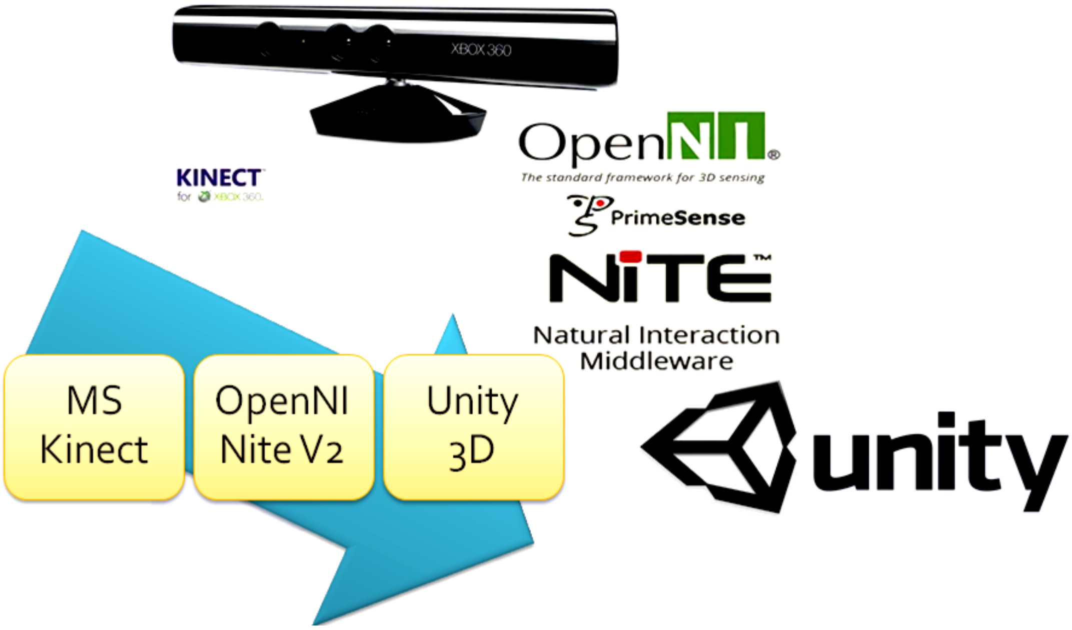

Figure 2 – Platform Components

3.2 Strategy of Implementation Approach

To start with, appropriate exercises for PD patients are drawn from references in the form of pictures with drown arrows for guidance. These exercises are considered to be single patient entities and fully prescribed as a function of time in a frame-by-frame manner.

As already explained at previous chapter (3.1), we had to select our platform components and get them to communicate with each other. After the evaluation of the SDKs supporting the Kinect Sensor, we had to port OpenNI v2 framework and Nite middleware to Unity3D game engine. Many alternative solutions were studied and Falahati's wrapper code with various modifications was the chosen implementation method to translate OpenNI C++ code to Unity3D C# code.

Our skeleton model was designed using the supported body-tracking model of Nite middleware. Unique key names were given for all joints and all bones, and hierarchy of these skeleton objects was built. They were implemented as subclasses of class skeleton, in order to have the same properties inherited for each joint and bone as 3D skeleton objects. The skeleton objects are 31, consisted of 16 joints and 15 bones (see Figure 3).

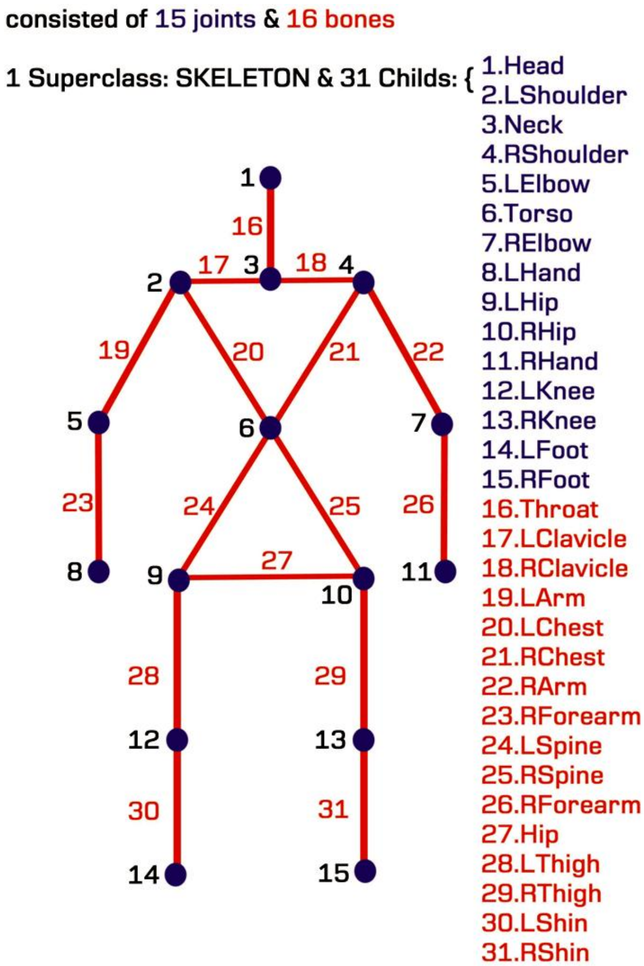

Figure 3 – Skeleton Model

Our first simple applications were created in Unity3D environment to familiarize ourselves with the development of our project. We displayed the Color Sensor, the IR Depth Sensor Output and build a depth map with normalized results through histogram equalization methodology. Then, through Nite middleware we achieved users' detection and we displayed the users detected with a color layer over depth image. Moreover, 3D real-time skeleton joints of the users' skeleton were detected and displayed in the 2D depth image (see Figure 4). We also achieved real-time synchronization of the streams exported from the Color Sensor and the IR Depth Sensor, which successfully includes the detected skeleton joints exported from Depth Map. One image through both sensors is depictured, and this is the main 2D image we want the user to visualize while performing the physiotherapy exercises, which is designed to be real-time colorful display of himself with overlaid his skeleton joints (see Figure 5).

Figure 4 – 1st row: RGB Color Sensor & IR Depth Sensor Output, 2nd row: Non-normalized Depth Map & Depth Image with Histogram Normalization, 3rd row: User Detection & Skeleton Joints on Depth Image.

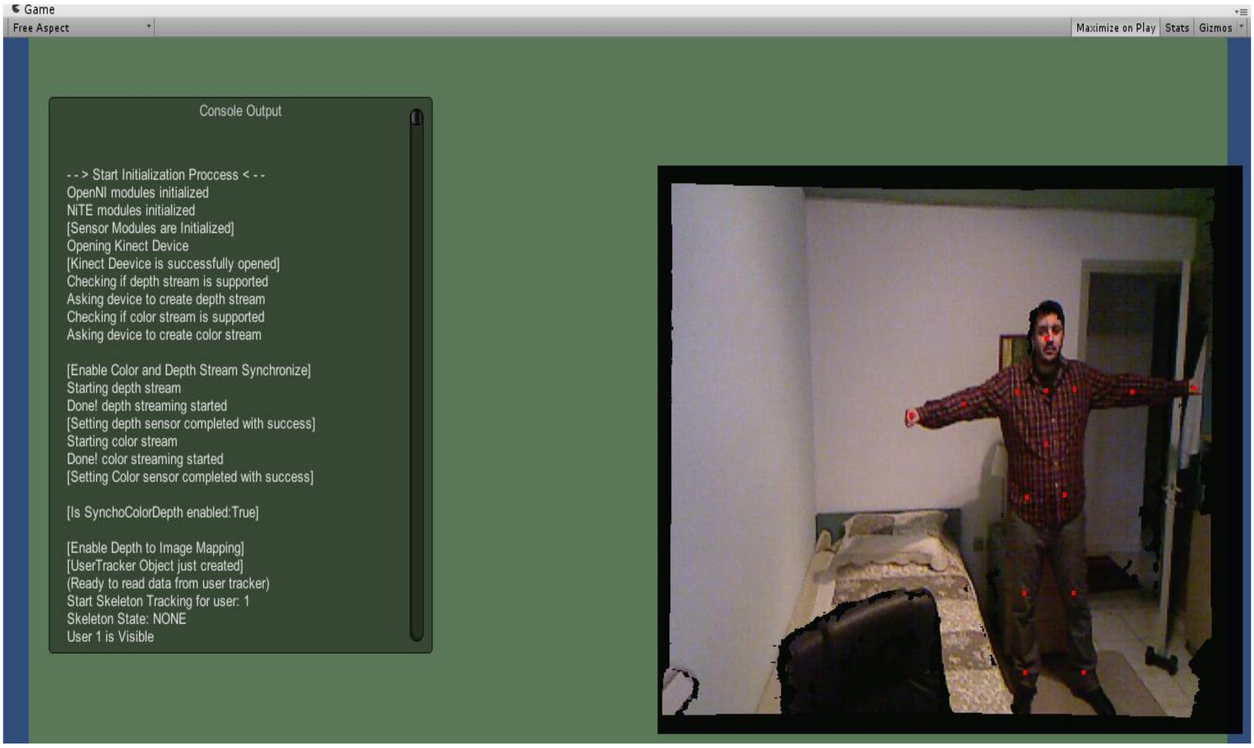

Figure 5 – Synchronized RGB Color and Depth Streams

At this point it is important to highlight that although 2D image is displayed, the positions of the joints are calculated in a 3D space manner, giving us information for the exact localization of each joint in 3D space. Through x, y, z dimensions each one of the detected skeleton joints is represented by a vector3 structure that contains its position in space. So, data regarding 3D joints' positions are stored in a text file in a frame by frame manner. A text file used for data storage is automatically exported by the completion of each exercise, which contains the x, y, z position of each one of 15 skeleton joints detected, at any corresponding frame. Worthy to mention is that RGB data whose resolution is 1280 x 960 produce 12 fps frame rate, and RGB data whose resolution is 640 x 480 produce 30 fps frame rate. Dealing with medical application, chosen resolution is 640 x 480 with frame rate at 30 frames per second in terms of more detailed storage of frame-by-frame joints storage. Except the text with positions of joints, a colored video is also exported with the patient performing the exercise. This file is exported in ONI file format (its extension is ".oni") and it can be useful for a doctor to detect more details for the performance of the specific exercise, such as facial expressions, performing difficulties, unstable movements etc.

After user skeleton is successfully tracked we can obtain, every X-Y-Z space dimensions of every skeletal joint in each frame. In Figure 6 you can see a sample of these data stored in a text file, demonstrating per 3 frames (102, 103, 104), the 15 tracked joints in 3 dimensions (X-Y-Z accordingly).

102	126.7892	383.9624	3628.135	150.3819	81.87766
	3695.215	-40.97108	83.0031	3728.236	341.735
	80.7522	3662.194	-170.5745	-147.4033	3829.593
	479.4843	-170.3543	3706.357	-267.8388	-273.2516
	3611.206	580.3613	-262.7835	3456.083	151.4966
	-180.7144	3710.624	45.48592	-442.6764	3744.52
	259.7366	-443.9365	3707.547	39.47641	-939.1428
	3794.491	271.9026	-936.7272	3723.362	82.70972
	-1370.118	3902.041	294.4612	-1393.217	3826.75
103	128.0579	383.8735	3627.805	148.691	84.28442
	3695.923	-42.05637	81.20817	3725.014	339.4383
	87.36069	3666.831	-176.2647	-148.1204	3809.558
	456.5385	-157.0473	3714.357	-266.0169	-258.0205
	3615.826	590.306	-244.9278	3459.089	155.5479
	-176.9043	3713.263	45.23675	-439.9827	3748.473
	279.5727	-436.2035	3712.733	39.00234	-932.7664
	3798.083	266.6391	-921.8263	3713.467	83.71178
	-1372.964	3906.717	281.4078	-1359.878	3817.919
104	128.8623	384.7004	3628.039	150.2059	82.26654
	3695.526	-40.53954	79.58477	3724.852	340.9513
	84.94832	3666.199	-168.9767	-150.2373	3807.794
	456.1389	-149.6327	3716.496	-265.3907	-177.0968
	3615.605	605.626	-228.5305	3447.677	156.6586
	-180.3083	3713.484	45.15122	-444.5417	3749.578
	281.0712	-441.2248	3713.306	40.23293	-939.0767

Figure 6 – Stored Skeletal Joint Space Positions per Frame

Furthermore, we are going to explain in detail, tracking capabilities during exercise session performance, and what tracking techniques this platform concluded to use. User tracking, joint orientation and distance calculations are some of the functions we took advantage. Through Nite Middleware we could track as many users as your processor power allows it to (see Figure 7). Meaningful to mention at this point is that the random error of any of these depth measurements increases quadratically with increasing distance from the sensor and reaches 4 cm at the maximum range of 5 meters. As a single-user interface we only track one user to extract his skeleton model, although other users are tracked in background. First user detected is automatically selected and other users detected are ignored. If the first user is lost from sensor, he is considered as not visible for a couple of seconds and he is not instantly untracked, due to noisy environment considerations. At Figure 8 you can see a console output for a demonstration of that function with a second user passing between Kinect sensor and the first user, showing that interruption from other persons passing through is considered and the first user is persistently tracked as not to be lost from sensor.

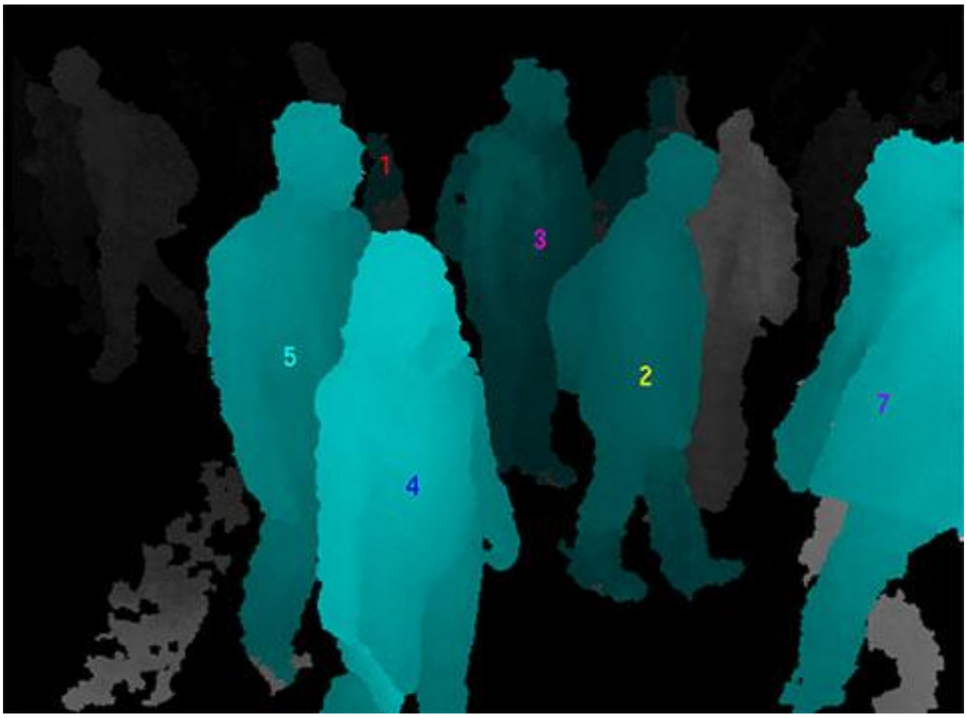

Figure 7 – User Tracking through Nite Middleware

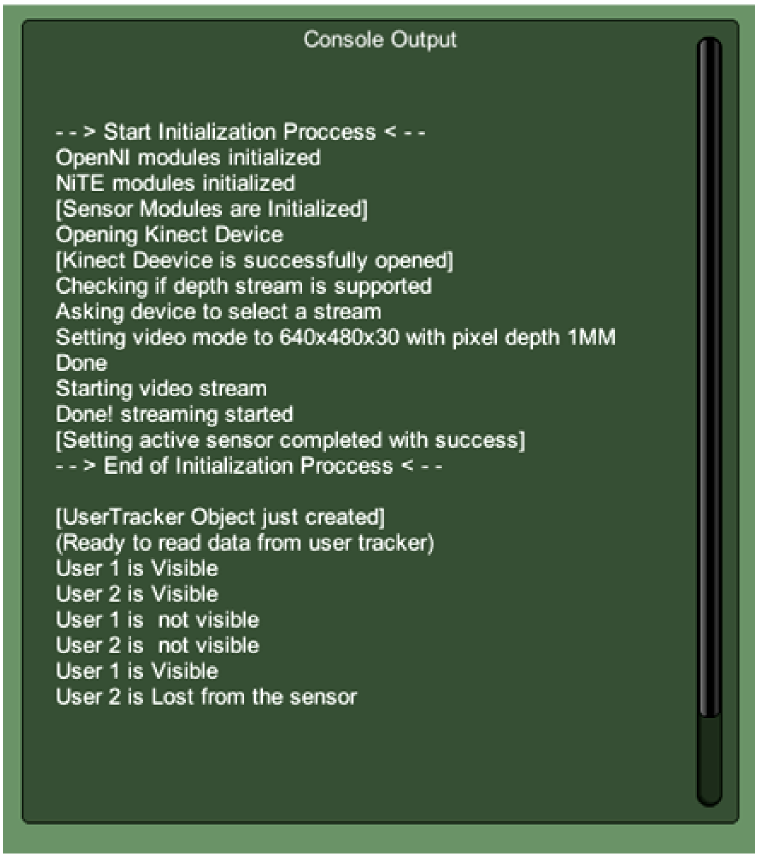

Figure 8 – Demonstration of First User Persistent Tracking

3.3 Major Project Components

Patients with neurological disorders are known to benefit from physical practice, which improves mobility and functional independence through increased muscular strength, flexibility and balance control. The present thesis aims to contribute to the development of a virtual rehabilitation platform tailored to PD patients which will consist of the following fundamental entities.

A curriculum of PD-specific upper and lower body exercise drawn from references is built. These exercises are considered to be single user entities and are fully prescribed as a function of time in a frame-by-frame manner. Each such exercise is performed by the trainer and recorded by an RGB camera to generate a video to be shown to the patient as real-time exercise instructions.

Several interacting functionalities are available for an optimal user experience through Microsoft Kinect for Windows sensor, which supports controller-free interaction and accurate full body tracking, simply by standing in front of the sensor; which is the main reason that Kinect device was chosen for the implementation of our platform. Moreover, Kinect is a promising VR neurological rehabilitation tool for use in the clinic and home environment with spatial adaptability, low-cost and easy installation.

This platform employs OpenNI v2 framework with Nite middleware, and through a C++ to C# wrapper, is developed in Unity3D game engine. OpenNI Framework was chosen because it is open source, portable to multiple operating systems and suitable for development of 3D sensing middleware libraries and applications. Moreover, the same OpenNI API can function with different motion sensors like Kinect, Primesense and Asus Xtion. Nite is a middleware supported by OpenNI Primesense, used for computer vision applications such as separating users from background, and user skeleton joint tracking. The greatest advantage of Nite middleware is that it boasts a thin host and minimal CPU load, suitable for real-time natural interfaces. In order to develop decent visual parts of our project we used Unity3D game engine which is one of the most powerful 3D game engines available. Unity3D can collaborate decently with OpenNI & Nite middleware through a C++ to C# wrapper, and there are great online communities with a lot of contributions on all of these technologies.

People with disabilities appear capable of motor learning within virtual environments and movements learned in VR transfer to real world equivalent motor tasks. In our virtual rehabilitation platform the patient can stand in front of a monitor to view the recorded video of the exercise and a Kinect sensor to obtain his/her skeleton in real-time. Following a proper instruction, the patient will be directed to replicate an exercise as precisely as possible. The patient's skeleton will be drawn and overlaid on patient's real-time video as the exercise progresses.

Deviations of patient's skeleton are calculated so that the accuracy and a percentage grade of patient's performance are assessed. The patient's skeleton data stream will be stored for each exercise performed at the end of an exercise session. To aid the attending physician assess the progress of a patient's condition between sessions, appropriate cumulative measurement metrics per exercise will be created and stored to be displayed to the doctor. As an added value, doctors will be able to assess the short- and long-term effectiveness of prescribed drugs and modify medical prescription on a timely basis.

Using OpenNI v2 framework and Nite middleware, we achieved great robustness on our body tracking measurements, even in seated position exercises, which still is a great barrier for skeleton-based applications. We expect the results to be really accurate and medically useful in order to improve PD medical diagnosis, to sustain a remote database with patients' progress and provide a powerful diagnostic tool, offering also a solution to patients' communication with their doctor, physiotherapist and trainer at home. Motor learning in virtual environments versus real world has many advantages and no occurrences of cyber sickness in impaired populations have been reported to date in VR motor abilities training. There is always a risk, in either situation, of patients traumatizing themselves by performing false movements during exercises, which is taken into account by creating real-time instructions with trainer's videos.

4. Session Exercise Demonstration

Our platform recognizes direct straight and cyclic movement patterns, with processor-light programming techniques and great effectiveness. These robust techniques provide real-time recognition of the movement state on the joints of interest, whenever they move up, down, right, left, backwards or towards the Kinect sensor. Through this method on a direct straight or cyclic movement patterns, repetitions are counted and grade is calculated.

For exercises with joints of interest making a direct straight movement pattern, such as Figure 9, the corresponding minimum and maximum path levels are detected. This technique results in a movements counter for each joint of interest and mobility error calculation by comparing both tracked movement patterns, in a manner to diagnose a mobility dysfunction from right to left hand or foot movement and draw the attention of the doctor. In an exercise with joints of interest making a cyclic movement pattern, such as Figure 10, the corresponding path per semicircle in each dimension is detected. This technique results in a circle counter for each joint of interest and circularity error calculation by comparing horizontal and vertical diameters. The direct straight and the cyclic movements are committed in any two of the three dimensions, depending on each exercise's instructions. All exercises are designed to be tracked with the patient's body direction facing the Kinect device.

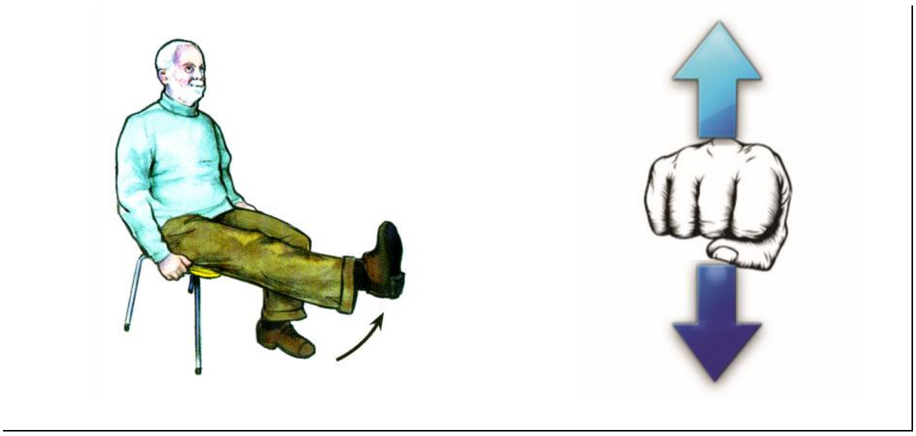

Figure 9 – Exercise Example with a Direct Straight Movement Pattern

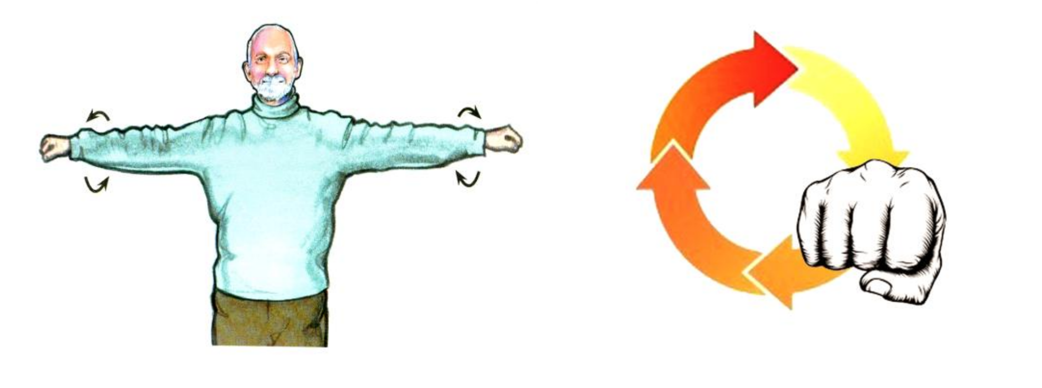

Figure 10 – Exercise Example with a Cyclic Movement Pattern

Mathematical analysis was made in two stages including performance and result stage on both movement patterns. On direct straight movement pattern, minimum and maximum joint dimensions are inspected while patient performs an exercise. For example, at above exercise at Figure 9, foot joint is inspected during performance and minimum and maximum joint dimensions are identified. Average distances between those values over 10 repetitions are concluding to a normalized smooth result as shown below:

$$\Delta y\_mobility = AVG\ (max(y) - min(y))\ \text{over 10 repetitions}$$

This distance is calculated only in Y dimension ignoring the other two, because X-Z dimensions have no shifting interest. At result stage, the patient has completed the required repetitions and patent's mobility is checked as a diagnosis measurement by both feet to detect motor disabilities of a patient from left to right foot and compare results in a long-time manner.

At performance stage on a cyclic movement pattern, minimum and maximum joint dimensions are inspected while patient performs an exercise. For example, at above exercise at Figure 10 hand joints are inspected during performance and minimum and maximum joint dimensions are identified. Average distances between those values over 10 cycles are concluding to a normalized smooth result as shown below:

$$\Delta y = AVG\ (max(y) - min(y))\ \text{over 10 cycles}$$

$$\Delta z = AVG\ (max(z) - min(z))\ \text{over 10 cycles}$$

These distances are calculated in two dimensions ignoring the third one, because at this specific exercise, cycle is executed in Y-Z dimensions during patient's performance having no shifts on X dimension. Minimum and maximum joint dimensions are inspected in both Y and Z dimensions and semicircles are instantly detected. At result stage, the patient has completed the required repetitions and circularity is checked as a diagnosis measurement comparing minimum and maximum in both vertical and horizontal dimensions. Circularity is measured at the circles made by both hands to detect motor disabilities of a patient from left to right side as shown below:

$$Right\_Circularity = Right\_\Delta y / Right\_\Delta z$$

$$Left\_Circularity = Left\ \_\Delta y / Left\ \_\Delta z$$

Graphical User Interface (GUI) is designed to serve simplicity, flexibility and demonstration purposes considering dynamic thresholds, console responses, GUI menu buttons, current exercise number, joints in 3D space, trainer instructions and patient's skeleton real-time video (see Figure 11).

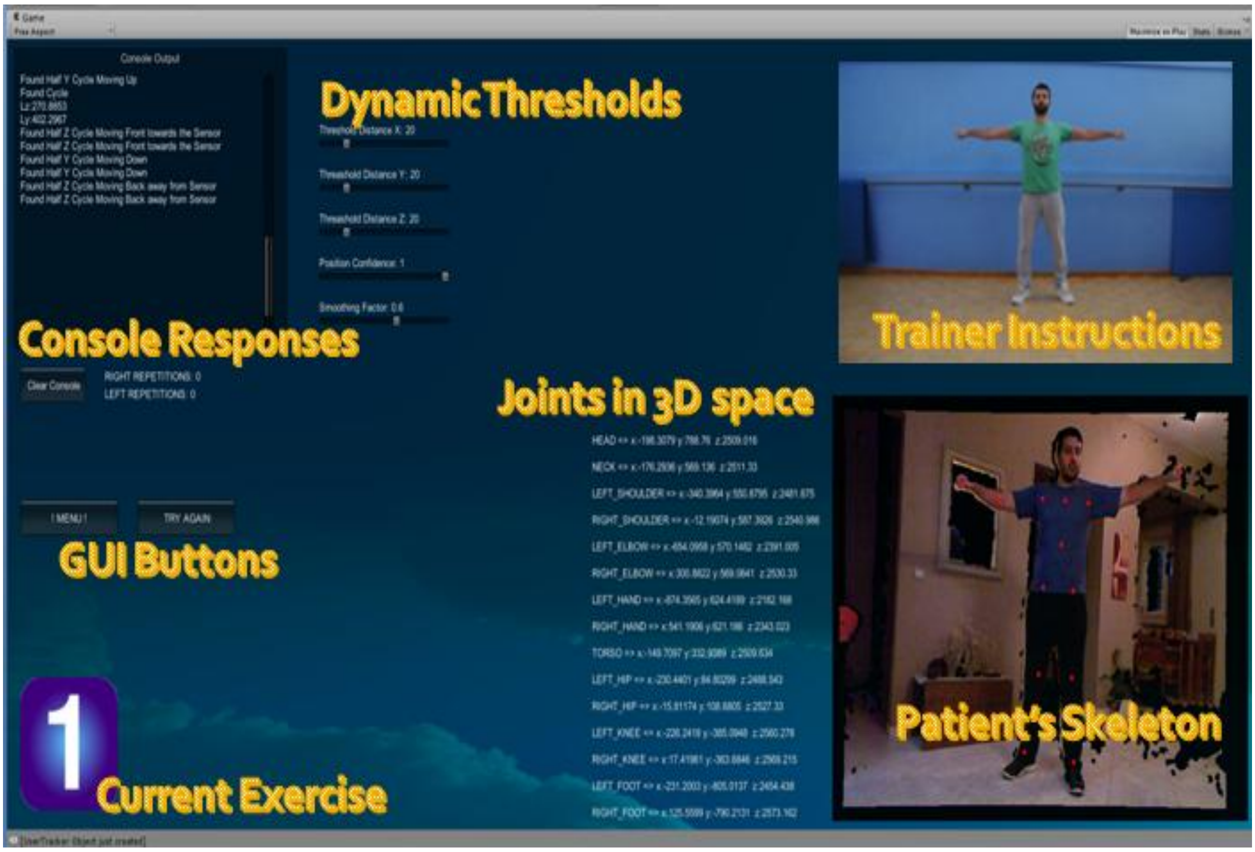

Figure 11 – Real-Time Performance Interface Components

Meaningful to note is that dynamic thresholds are implemented as adaptability properties of each exercise. Joint thresholds are programmed to expunge undesirable small movements of tracked joints in terms of accuracy. Smoothing factor is stabilizing noisy joint movements and confidentiality threshold ensures that joint positions are considered to be tracked with confidence by platform's middleware. These thresholds are optimized for each exercise and loaded when each exercise starts from external configuration file, because each patient's performance space and lighting can vary and might need some adaptation.

Exercise 1 is completed when 10 repetitions of both hands are performed as shown at Figure 12 below. Repetitions are meant to be cyclic movements of hand joints on Y-Z dimensions and exercise stance is standing.

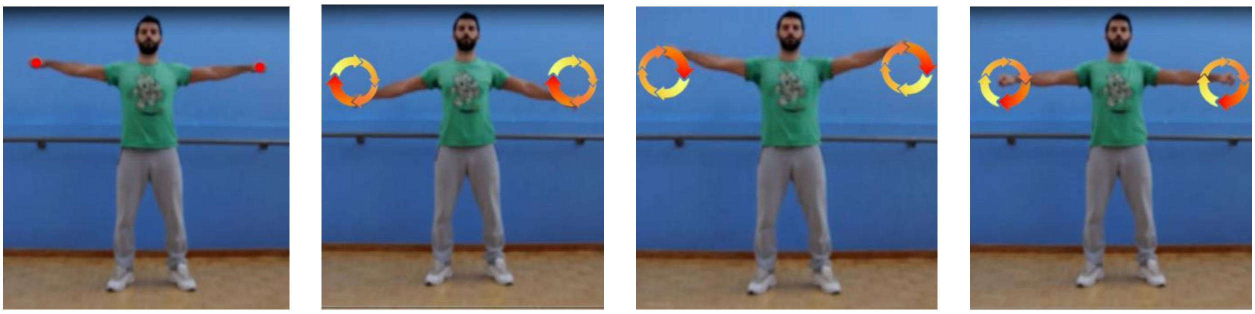

Figure 12 – Exercise 1: cycles with both hands

Exercise 2 is completed when 20 repetitions are performed, 10 of each hand one by one, as shown at Figure 13 below. Repetitions are meant to be cyclic movements of hand joints on Y-Z dimensions and exercise stance is standing.

Figure 13 – Exercise 2: each hand cycles

Exercise 3 is completed when 10 repetitions are performed as shown at Figure 14 below. Repetitions are meant to be direct straight movement of hip joints on Y dimension and exercise stance is standing.

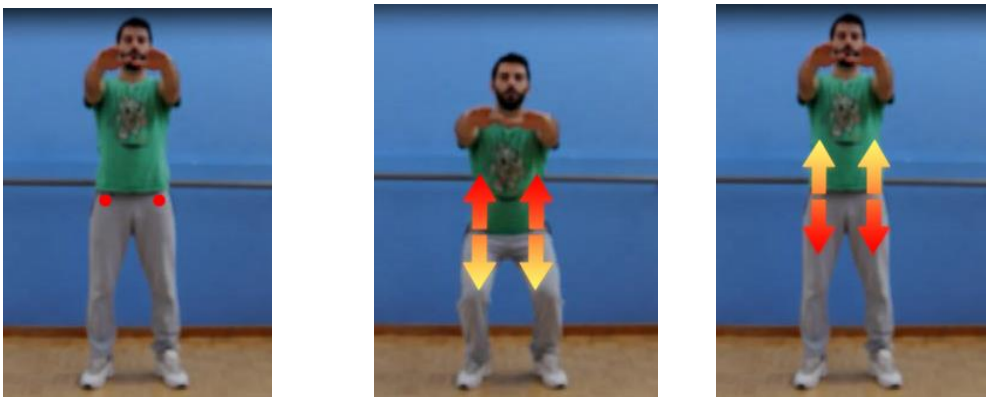

Figure 14 – Exercise 3: hip up & down

Exercise 4 is completed when 10 repetitions are performed as shown at Figure 15 below. Repetitions are meant to be cyclic movements of hip joints on X-Z dimensions and exercise stance is standing.

Figure 15 – Exercise 4: hip cycles

Exercise 5 is completed when 10 repetitions are performed as shown at Figure 16 below. Repetitions are meant to be direct straight movement of elbow joints on Y dimension and exercise stance is standing.

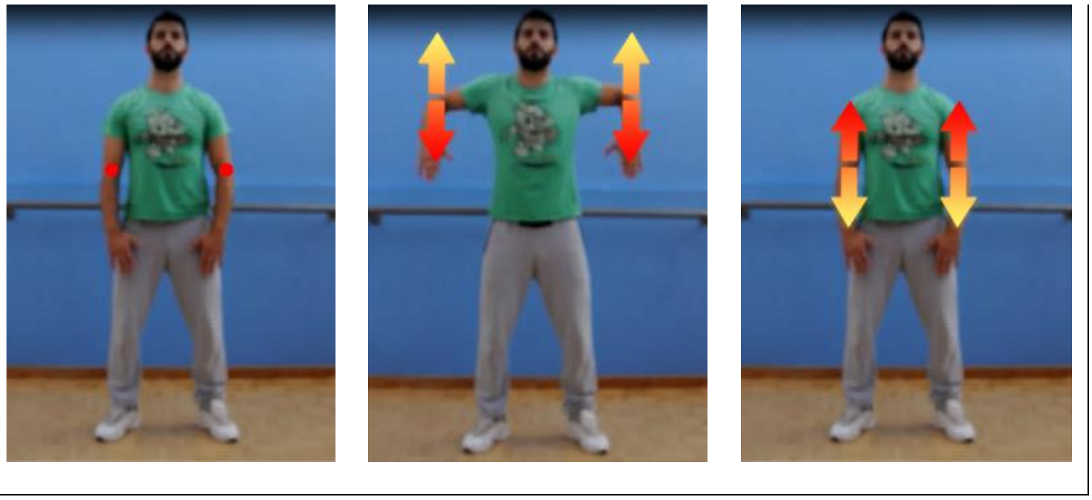

Figure 16 – Exercise 5: elbows up & down

Exercise 6 is completed when 10 repetitions are performed as shown at Figure 17 below. Repetitions are meant to be cyclic movements of both hand joints on Y-Z dimensions; exercise stance is sitting and best performed with a stick.

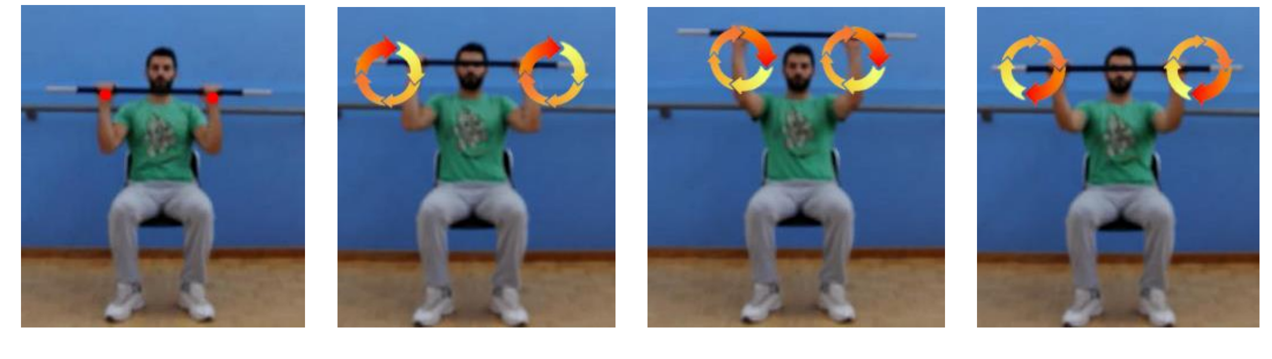

Figure 17 – Exercise 6: stick cycles

Exercise 7 is completed when 10 repetitions are performed as shown at Figure 18 below. Repetitions are meant to be turn and turnabout cycles of hand joints as 8-figure movements on Y-Z dimensions; exercise stance is sitting and best performed with a stick.

Figure 18 – Exercise 7: stick 8-figure

Exercise 8 is completed when 10 repetitions are performed as shown at Figure 19 below. Repetitions are meant to be direct straight movement of hand joints on Y dimension; exercise stance is sitting and best performed with a stick.

Figure 19 – Exercise 8: stick up & down

Exercise 9 is completed when 10 repetitions are performed as shown at Figure 20 below. Repetitions are meant to be direct straight movement of elbow joints on Z dimension and exercise stance is sitting.

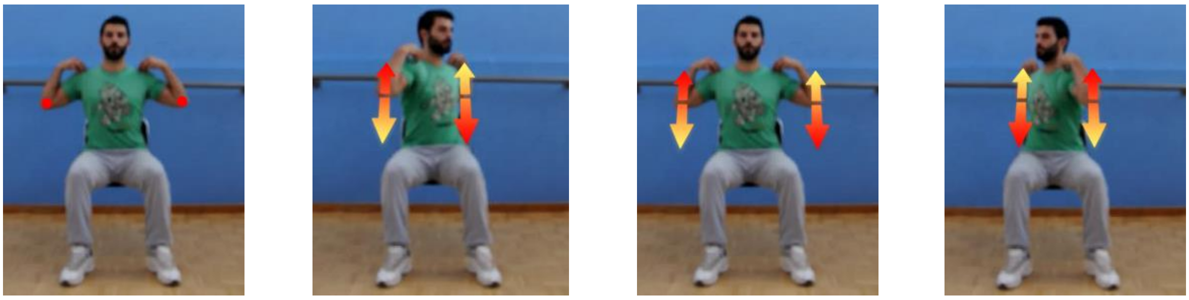

Figure 20 – Exercise 9: elbows back & front

Exercise 10 is completed when 21 repetitions are performed, 10 of each foot one by one, as shown at Figure 24 below. Repetitions are meant to be direct straight movements of foot joints on Y dimension and exercise stance is sitting.

Figure 21 – Exercise 10: feet up & down

Meaningful to explain is that when hand joints are mentioned, joints 8 and 11 of skeletal model (see Figure 3) are considered. Similarly, hip joints are considered to be joints 9 and 10, elbow joints are considered to be joints 5 and 7 and foot joints are considered to be joints 14 and 15 of skeletal model.

After an exercise is completed, grade is calculated and shown to monitor, while recorded video stream as ".oni" video file and skeletal frame data as text file are stored as mentioned (see Figure 6). These two functionalities are currently disabled in demonstration version of current project. Then, user is encouraged to continue to the next exercise until all exercises in the daily set prescribed by his doctor are completed. Regarding the installation of our platform, our project was successfully exported from Unity3D as a standalone executable application in terms of directness. This means that any user desiring to use our platform does not have to install Unity3D game engine. However, he is obliged to install Microsoft Kinect device drivers, OpenNI v2 and Nite middleware. This installation procedure should take very few minutes and after that, double-clicking on project's executable icon is enough to get started with the physiotherapy exercises performance in a daily routine.

5. Discussion and Future Work

Patients with neurological disorders are known to benefit from physical practice, which improves mobility and functional independence through increased muscular strength, flexibility and balance control. The present thesis aims to contribute to the development of a virtual rehabilitation platform tailored to PD patients which offers daily physical exercise, while storing medically useful skeletal joint data providing long-term performance progress of each patient.

The most significant contributions of the proposed platform is that it offers a mobile and easily setup rehabilitation platform that can be used at a patient's home, at a physiotherapist's establishment or at hospital. We investigated the capability to utilize both standing and seated exercises in order to obtain accurate skeleton data measurements, which is a very valuable and objective diagnostic criterion, to be used for assessing long-term disease progress diagnosis, accompanied by the detailed response of patients to PD-specific drugs. Modularity, adaptability and simplicity of this platform provide a solution to patients' having transportation problems, communicating with their doctor, physiotherapist and trainer, in a more objective and long-time manner.

While being capable to 3D space skeletal join data, joint orientation can be extracted through mathematical calculations or Unity3D ready functions. For example, we can make a decent assumption on the angle of patient's head direction (see Figure 22). These orientation functions were not accurate enough for medical usage, while, on the other hand, custom functions made with mathematical calculations proved to be resource-hungry techniques. The Law of Cosines helps calculate the angle between joints and the largest angle calculable 180.

When calculating the angles between the joints, an additional point is needed to determine the angles from 180 to 360. From the skeleton tracking data, we can draw a triangle using any two joint points. The third point of the triangle is derived from the other two points. Knowing the coordinates of each point in the triangle means that we know the length of each side, but no angle values. By applying the Law of Cosines (see Figure 23), the value of any desired angle can be obtained. Calculations on the joint points give the values for a, b, and c. The unknown is angle *C*, which can be obtained by the formula: $C=\cos^{-1}((a^2+b^2-c^2)/2ab)$. The gestures detected by Kinect sensor are integrated to the keyboard controller for playing games. The experimental framework calculates each gesture done by the patient and generates virtual keyboard commands. These functions could be extremely useful for exercise performances and a very good example based on body angles is the physical rehabilitation a project mentioned on 2.2 Chapter (Related Technologies) called InfoStrat ReMotion360 (see Figure 24). At that project 2D skeleton is recognized instead of 3D skeletal joint data, which gives less information about patient's stance, position and distance from the Kinect device. Also, in one repetition goal is achieved when angle degrees are reached, having no repetitions counter and no grade estimation as in current project.

Although recognizing the capabilities of orientation functions, our platform takes advantage less resource-hungry techniques to identify direct straight and cyclic movement patterns, referring to exercises with more repetitions. These techniques are simpler but still very accurate and they also provide real-time recognition of the movement state on the tracked joints, whenever they move up, down, right, left, backwards or towards the Kinect sensor. Through this method on direct straight or cyclic movement patterns, repetitions are counted and grade is calculated.

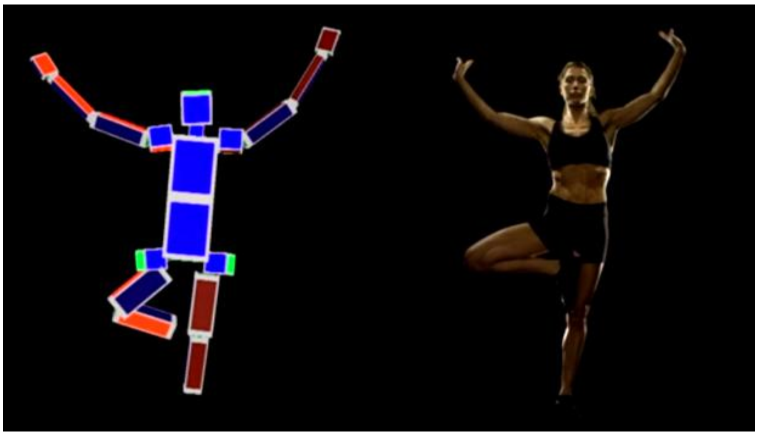

Figure 22 – Demonstration of Skeletal Joint Orientations

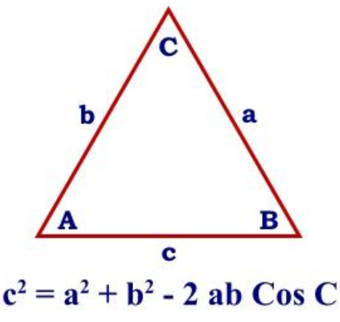

Figure 23 - Law of cosines

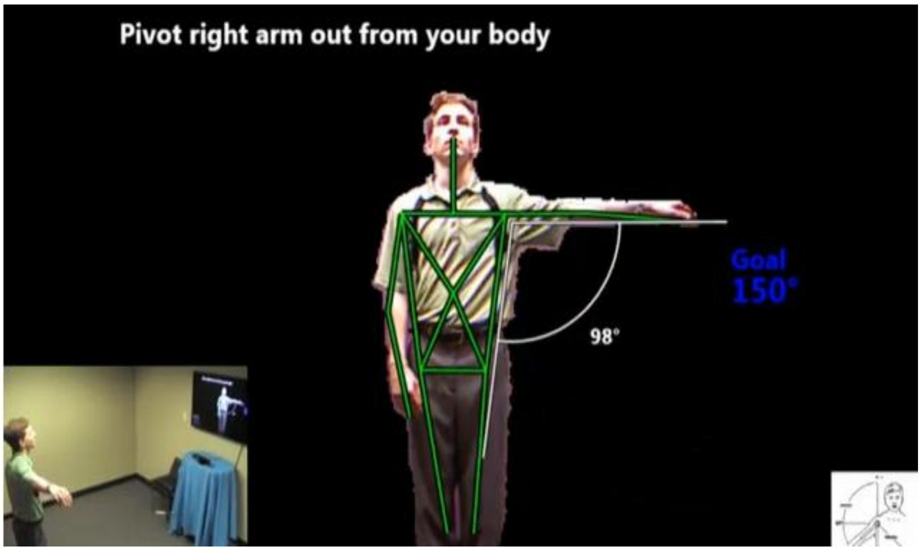

Figure 24 – Body Angles from InfoStrat ReMotion360 Project

In cases that there is no keyboard or mouse, or they cannot be used, we can either employ other Microsoft Kinect applications that manage gestures or sound commands recognition for Microsoft Windows functions.

This platform is intended to be modular and adaptable to offer real-time rehabilitation opportunities to various sub-groups under the large category of patients with neurological disorders. Within a common virtual environment it will offer rehabilitation programs tailor to specific sub-populations such as stroke recovery patients, athletes etc.

A real-time feedback mechanism, in the form of encouragement and corrective suggestions as an extra feature could be incorporated during the execution of the exercises, which can be either privately automated or administered live from a connected physical therapist during a live session.

An attending physician could be able to assemble an exercise schedule tailored to a specific PD patient from a pool of available exercises. These schedules may be updated by the physician on a timely basis and depending on disease progress to provide patient-customized schedule of exercise sets.

Moreover, support of physical therapists on-call could be provided as an extra safety measure, especially for patients in severe stages. A physiotherapist could then be remotely available to join a patient's exercise session through the platform. A patient could invite a therapist for advices or directions in a live remote session. Alternatively, based on the performance of the patient, the platform could automatically suggest the patient to invite a physiotherapist. A connected physiotherapist could be able to see the patient's performance and give real-time instructions and feedback. Moreover, this functionality could also be used as an emergency call for reducing the risk of home injuries.

The multivariate space embedded in the exercise structure can be exploited to study the possibility of training the system to be used as a real-time progress assessment tool. This process will demand close collaboration with experienced physicians to identify the telltale signatures of a motor impairment and device exercises intended to bring these up with the least amount of error. Subsequently, the system should be able to offer a standard assessment program to arrive to the same results with a known error assessment. As a result, an individual suspected of having a motor impairment can follow through an initial screening by the platform and will be instructed to carry out a number of exercises. Skeletal data from each activity can be stored from many patients and used to arrive to a diagnosis with a confidence level. Furthermore, stored skeletal data accompanied by the current medication should be available for the doctor at a hospital server as patients' history progress with the corresponding drugs.

Our platform could also provide appropriate feedback if significant error deviations are evidenced, either in form or in timing delay. That could be shown to the patient on-screen in some easily understood format (e.g. coloring a section of screen space at the region of the deviation) as a real-time automatic correction of patient's performance. To end with, the patient's skeleton data stream could be stored for each exercise performed and uploaded to a hospital server at the end of an exercise session to support complete remote storage of patient's treatment report.

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