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Smartphone Based Tele-Rehabilitation

Carlos Filipe Ribeiro Ferreira

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Carlos Filipe Ribeiro Ferreira
Dissertação de Mestrado apresentada à
Faculdade de Ciências da Universidade do Porto em
Ciência de Computadores
2013

Smartphone Based Tele-Rehabilitation

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Departamento de Ciência de Computadores
2013

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Dedicated to my parents

Acknowledgements

First of all, I would like to thank all of the support of my supervisor Vânia. She was really helpful and friendly and when I needed the most she was always there. The knowledge and experience she shared with me was crucial to a work with higher quality standards. I am very grateful for that. I would also like to thank my supervisor at Department of Computer Science Prof. Luís Lopes because he demanded constant updates of my work and that was a decisive factor for me to not to loose track of time. I also thank him for his comprehension and for the right words at the right time. I thank both of them for revisions, comments and suggestions that improved my thesis greatly.

I am grateful to therapist Dr. Hélder Campos and Eng. Rui Neves for their cooperation and important contributions to this thesis. Their input was tremendously important and their availability and sympathy should be recognized.

I would also like to thank Prof. Inês Dutra for her sympathy and support, in the beginning of my internship interviews. I would like to thank most of the teachers who were part of my academic career and that contributed to my academic and personal growth.

I would like to give one special thanks to my parents who always made everything easier in life for me and allowed me to dedicate myself exclusively to my academic degree. I am very grateful for all their love and teachings. I thank my brother for being in my mind, even when he was not present and I thank my girlfriend Joana for making me see my value and my place in this World and for making me happy. Without all of them, everything in life would be way harder to accomplish.

I would like to thank mainly to Jaime but also to Paulo, Fábio, Bruno Ferreira, Bruno Aguiar and a few others for their support and companionship, that made the Fraunhofer internship a remarkable and enjoyable experience.

At last but not the least, I would also like to thank every friend I made at the Faculty of Sciences of Oporto University for their laughs, companion and support. From among them, I would like to emphasize my thanks to Miguel, Mario, Luis, Alexandra and Ramalho.

Abstract

Cardiovascular diseases are very punishing to their victims. Stroke survivors have to adapt their routines to the partial or total loss of control over one or more parts of their bodies. That lack of control can go from the lack of sensibility, to locomotion problems and to the lack of proprioception, that is loss of the sense of orientation of one's limbs in space.

To overcome some of the difficulties caused by the disease, patients have to undergo physiotherapy. It is commonly realized by traditional methods or with the assistance of mechanical support or virtual reality. Motivation is one of the most contributive factors to their recovery and the need of preparation and of a consequent travel to an health facility, to perform physiotherapy can be one factor that contributes to an increased emotional exhaustion. If physiotherapy could be carried out in the comfort of home, with appealing exercises that would motivate the patients, they would likely show a better emotional response and an increased commitment in recovery. The growing dissemination of smartphones made the concept of smartphone based tele-rehabilitation possible. Tele-rehabilitation is the rehabilitation that is carried out by patients without the physical presence of a therapist. The later receives feedback of the progress of patients remotely. In the most industrially developed countries, almost anyone owns a smartphone and Android is the most widely employed mobile operating system. Besides that, these devices possess sensors with high capabilities, that can be used to implement training exercises.

This thesis aims to explore the concept of a cheap alternative to the traditional methods, that can be both motivational and intuitive and that allows patients, in a more advanced phase of recovery, to carry out their physiotherapy at home, or wherever they feel more comfortable. We evaluate what smartphone technology can do for physiotherapy and how it can influence patients recovery. We show that it can constitute a low cost alternative to the available solutions on the market and that it has an evident potential to be used in practice. We also developed an application prototype utilizing this technology that has been used already in preliminary tests.

Resumo

As doenças cardiovasculares são muito punitivas para com as suas vítimas. Quem alguma vez sofreu um acidente vascular cerebral (mais conhecido como AVC) e sobreviveu, pode melhor do que ninguém comprovar esse facto. Os sobreviventes de AVCs têm de adaptar as suas rotinas ao facto de terem perdido o controlo total de uma ou mais partes do corpo. Essa falta de controlo pode ir desde a falta de sensibilidade, às dificuldades de locomoção e à falta de proprioceção, que é a capacidade de determinar onde está determinada parte do seu corpo no espaço.

Para superar muitas das dificuldades decorrentes da doença, os pacientes têm que realizar fisioterapia. A motivação para a recuperação é um dos fatores que mais contribui para a recuperação dos pacientes e a necessidade da preparação e consequente deslocação para um estabelecimento de saúde, para realizar a fisioterapia, pode ser um fator que contribui para um maior desgaste emocional. Se a fisioterapia pudesse ser realizada no conforto do lar, com exercícios apelativos que motivassem os pacientes, verificar-se-ia, da parte deles, uma melhor resposta emocional e um maior empenho na recuperação. A crescente disseminação dos smartphones tornou o conceito de tele-reabilitação, baseada em smartphones Android, possível. Tele-reabilitação é a reabilitação que é executada pelos pacientes sem a presença física do terapeuta, recebendo o seu feedback remotamente. Nos países mais desenvolvidos, é fácil de encontrar quem possua um smartphone e o Android é o sistema operativo móvel mais utilizado. Para além disso, estes dispositivos possuem sensores de grandes capacidades, que podem ser utilizados para os mais diversos fins.

Esta tese procura explorar o conceito de uma alternativa aos métodos tradicionais existentes, que seja barata, motivadora, intuitiva e que permita aos pacientes, numa fase mais avançada de recuperação, realizarem a sua fisioterapia em casa, ou no local que desejarem. Avaliamos o que a tecnologia dos smartphones Android pode efetivamente realizar e de que forma pode influenciar a recuperação dos pacientes. Mostramos que esta pode constituir uma alternativa de baixo custo quando comparada com as soluções atualmente existentes no mercado e que tem um evidente potencial para ser utilizada na prática. Desenvolvemos também um protótipo de uma aplicação, utilizando esta tecnologia, que já foi utilizado em testes preliminares.

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Chapter 1

Introduction

1.1 Motivation

Stroke is well known for being one of the most disabling diseases of our time. Stroke survivors often have to live with at least a part of the body that he or she has lost full control of [1]. In the year 2012 there were 2995 registered records of stroke occurrences in Portugal [2]. In Europe, Japan and United States, this disease is the third leading cause of death [3]. As long as the patient has the money and the time to go to a clinic or a hospital, he or she can still be treated. The problem here is the need of leaving home and going to a medical facility. Therefore, to comply with the treatments and therapies, the patient needs to be motivated. We are in a technological era that has the means to allow rehabilitation at home, so why not use it? It can do that by allowing remote communication with a therapist or by providing all the tools and/or applications a patient needs to perform his/her rehabilitation on his own. If this is done correctly, it can be motivational, add positive outcomes and really help patients in their recovery [4]. Smartphones are becoming increasingly cheaper and are more accessible to more people. They also possess powerful sensors that can help patients perform physiotherapeutic exercises. Even if patients continue to perform physiotherapy with a therapist, they can still repeat the rehabilitation exercises at home, with the help of this technology, in order to achieve better outcomes.

1.2 Goals and Potential Benefits

The motivation behind this thesis is the relief of the burden of stroke patients. That can be done if the rehabilitation exercises can become enjoyable while still being appropriate and if the rehabilitation can be performed at home, without the need of frequent trips to the therapist. The objective is to create an upper limbs smartphone based stroke rehabilitation application, that can provide a relaxed experience and that at the same time is well built to contribute greatly to users impaired limbs recovery. Android smartphones are cheap and possess inertial sensors that can be used to develop rehabilitation and assessment tools. An application like this has the ability to provide health care services to patients with limited access and substantial needs. They will be able to access a platform with an extensive range of possibilities of recovery that has a great potential of growth. Android smartphones are an ubiquitous technology, so even at clinics they can be used to add a motivational factor to their practices [5]. Including a few physiotherapeutic exercises in the form of an intuitive application, also means rehabilitating more movement inhibitions in less time than a conventional therapy would, with the help of the therapist or with expensive big robotic devices.

1.3 Report's structure

This thesis starts with a brief literature review about stroke, it's causes and consequences and typical treatments used in rehabilitation. The investigation about stroke allowed writing about its statistics of incidence in the World and about the most known symptoms of the disease. This section also includes some healthy habits that can be adopted by anyone and positively contribute to the prevention of the disease.

The Prototype Development chapter details the methods and the used technologies in the development of the prototype. It explains how the communication between the client and the server is carried out, justifies the choice of the selected physiotherapeutic exercises and presents some preliminary results of the developed system.

The thesis ends with a critical discussion and with a brief description of future work.

Chapter 2

Stroke and Rehabilitation

Health is undeniably one of the biggest worldwide concerns of people. No one can really be happy without being healthy. Thus, finding new methods of treatment that can smooth the effect and the impact of diseases in the quality of life is a relevant matter to everyone.

On the other hand, we live in a time when fast development and dissemination of technology is a fact, e.g., there were never so many cellphones and laptops in the hands of so many people. This advent of technology can be of some help to the health sector, since it creates new possibilities and methodologies to help in the treatment of patients.

The first section of this chapter will explain the stroke disease as well as its causes, consequences, incidence, risk factors and possible ways of prevention. The second section will be focused on the rehabilitation of stroke victims, i.e., a literature review about traditional and technology based methods of upper limbs rehabilitation will be presented and explored.

2.1 Stroke

2.1.1 Definition

A stroke is a cardiovascular disease. It is a neurological deficit that is a consequence of a sudden rupture or blockage of a cerebral artery. When that rupture/blockage happens, the brain cells the artery feeds with oxygen and nutrients, start to die quickly and the part of the body that region of the brain controls stops working [1]. The brain is one of the most metabolically[1] active organs and because of that it requires a continuous supply of oxygen and nutrients (energy) [6]. It is the second most oxygen demanding human organ and uses almost 20% of the total energy consumption of an adult [7, 8]. A stroke may occur for two reasons, lack of blood supply to the brain or hemorrhage [1]. To be categorized as a stroke, the neurological deficit has to be persistent for 24 hours [9].

2.1.2 Hemorrhagic and Ischemic Stroke

An **hemorrhagic stroke** is the form of stroke that is a consequence of the bleeding that results from the rupture of a blood vessel. This type of stroke may occur in the area between the brain and the thin tissues that cover it or inside the brain. The released blood from the rupture may result in a decreased supply of oxygen to the brain and create an irritant effect on the brain nervous tissue and vasculature[2]. A continued bleeding may also result in an increased intracranial pressure that may diminish even more the blood flow to the brain. This is the most dangerous kind of stroke and it occurs on only ten to fifteen percent of the cases [10].

An **ischemic stroke** is the type of stroke that results from a restriction in blood supply to the brain. That lack of blood flow may be caused by a blockage of an artery or a vein in the brain or by an embolus[3] that traveled to the brain. Furthermore it may occur due to cardiac arrest or arrhythmias or from a weaker heart pump. This is the kind of stroke that affects most of the patients [10].

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[1] Referring to metabolism. Metabolism is the sum of the physical and chemical processes in an organism by which its material substance is produced, maintained, and destroyed, and by which energy is made available.

[2] The brain blood vasculature consists of a highly branched vessel network that is tailored to efficiently deliver oxygen and nutrients to each brain region.

[3] An abnormal particle circulating in the blood.

2.1.3 Incidence

Strokes are the principal cause of long-term disability and twenty five percent of the strokes occur on people younger than 65 years old [11, 12]. Stroke is the third leading cause of death in the United States, Europe and Japan. Each year 750000 people have a stroke and from those, 200000 don't survive [3].

Last year in Portugal, there were 2995 records of stroke occurrences. The majority of the calls to the National Emergency Number were made at the 30th-44th minute mark since the symptoms could begin to be observed and more than 70% of the calls were made after 30 minutes of the occurrence of the symptoms [2]. The longer the victim waits between the appearance of the symptoms and getting medical assistance, the bigger the consequences will be to the patient health [13]. In Portugal, the appearance of stroke symptoms is not associated with a quick health care seeking behavior [2].

2.1.4 Risk factors and Prevention

The classical stroke risk factors are: diabetes, high cholesterol, hypertension and smoking but there are several more [14]. Risk factors can be divided into two different groups: those which can be controlled or treated (controllable risk factors), and those which cannot be changed (uncontrollable risk factors). According to the American Heart and Stroke Associations[4] and to the National Stroke Association[5] those factors are [15, 16]:

Table 2.1: Stroke risk factors.

Controllable Risk Factors	Uncontrollable Risk Factors
high blood pressure	age [a]
high cholesterol	gender
atrial fibrillation[b]	race[c]
artery diseases	family history
sickle cell disease (or sickle cell anemia)[d]	previous stroke, TIA[e] or heart attack
coronary heart disease or heart failure	sex [f]
smoking	
diabetes	
poor diet	
atherosclerosis	
problems of circulation	
alcohol abuse	
inactive life style and obesity	

[a] The chance of having a stroke approximately doubles for each decade of life after age 55.

[b] A heart rhythm disorder.

[c] African-Americans have an higher risk of death from a stroke than Caucasians do.

[d] A genetic disorder that mainly affects African-American and Hispanic children.

[e] Transient ischemic attacks (TIAs) are seizures that have similar symptoms to strokes but no lasting damage.

[f] Strokes are more common in men.

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[4] http://www.strokeassociation.org

[5] http://www.stroke.org

In spite of depression being considered a consequence of major importance of stroke, at least one study stated that the relation between them is bidirectional [17]. Depression is mutually a risk factor and a consequence of stroke seizures. To have a risk factor doesn't necessarily mean having an high risk of having a stroke. To evaluate the percentage of risk of a stroke seizure in a human being risk stratification schemes are used. They are built using the known risk factors of a certain disease in a scoring system to assist physicians evaluating a patient. For each risk factor points are summed and the more points a patient gets, the higher risk is ascribed. They are used mainly to identify high risk patients and treat them accordingly and to avoid submitting low risk patients to certain therapies that may be too severe. Several Stratification schemes exist to classify patients into low, moderate and high risk groups. The most used stratification scheme is $CHADS_2$ because of it's simplicity. This scheme's name comes from the risk factors it comprises and the score it assigns to them (Table 2.2).

Table 2.2: $CHADS_2$ (*extracted from Gillis, A. et al. (2011)[18]*).

Risk Factor	Score
Congestive heart failure	1
Hypertension	1
Age greater or equal than 75 years	1
Diabetes	1
Stroke/TIA/thromboembolism[a]	2
Maximum score	6

[a] Thromboembolism is the formation in a blood vessel of a clot that breaks loose and is carried by the blood stream to plug another vessel.

According to Marfatia, R. (2012)[19] this scheme is limited because it excludes some known risk factors "which could improve the classification of "truly" low risk patients". To improve the identification of patients risk group and the choice of appropriate treatments to each individual case, physicians may use a modification of this scoring system named CHA_2DS_2-VASc that uses similar scores and incorporates the same risk factors with just few more (Table 2.3).

Table 2.3: CHA_2DS_2-VASc (*adapted from Gillis, A. et al. (2011)[18]*)

Risk Factor	Score
Congestive heart failure	1
Hypertension	1
Age greater or equal than 75 years	2
Diabetes	1
Stroke/TIA/thromboembolism	2
Vascular disease	1
Age from 65 to 74 years	1
Female	1
Maximum score	10

The $CHADS_2$ scheme associates patients that obtain scores greater or equal than 2 points to the high risk category of having a stroke, the patients that obtain 1 point to the intermediate risk category and the score of 0 to the low risk category [20]. However, it considers only a few risk factors that limit the judgment of risk, so in patients with a $CHADS_2$ score of 1 point CHA_2DS_2-VASc can be used to differentiate them [21]. The CHA_2DS_2-VASc assigns a patient to a risk category with the same criterions as the $CHADS_2$ system[22].

The FAST acronym is used to simplify and help people remember the signs of a stroke. The individual letters mean (F)face, (A)arms, (S)speech and (T)time. If the face has fallen on one side or if one can't smile or raise both arms and keep them both there or articulate speech or understand what people say, it's time to call the national emergency number [13]. If someone is having a stroke and recognizes the signs, the wisest thing to do is to hurry and call the emergency number. The faster it is done, the more consequences to the patient may be prevented.

Prevention can be carried out by anyone who is willing to change his or her lifestyle. A healthy lifestyle reduces the risk of stroke. Everyone who is at risk of stroke should be evaluated for stroke risk factors and his or her lifestyle. Some of the habits people in this situation should embrace are: a healthy balanced diet, intake only adjusted to age quantities of sodium, practice of moderate exercise (more than 150 minutes per week), weight control, limit the alcohol consumption and consider alternatives to birth control and hormone replacement therapies [23].

2.1.5 Symptoms and Consequences

Most of the people that survive a stroke are left with some kind of impairment and one third of them is affected by long term disability [24]. About fifty percent of stroke survivors are left dependent of others in their daily activities [25].

All of stroke symptoms appear suddenly and according to the National Stroke Association they are [26]: "numbness or weakness of face, arm or leg especially on one side of the body; confusion, trouble speaking or understanding; trouble seeing from in or both eyes; trouble walking, dizziness, loss of balance or coordination and severe headache with no known cause".

Strokes can affect individuals at physical and cognitive/emotional levels. The physical consequences of an acute stroke are [27, 28]:

- visual disturbances;
- paralysis of the throat muscles that may interfere with the swallowing process (technically known as *Dysphagia*);
- voice disorder (*dysphonia*);
- the muscles of the mouth, face and respiratory system may become weak, move slowly or not move at all (*dysarthria*);
- complete or partial loss of language function including ability to understand, speak, read and write (*sysphasia*);
- reduced and lack of control of muscle strength;
- loss of sense of orientation of one's limbs in space (*proprioception*) that may result in difficulties of driving, typing on a keyboard or putting food into the mouth without breaks;
- lack of coordination and balance;
- reduced joint stability that decreases mobility;
- altered gait pattern;
- stiffness and tightness of muscles;
- decreased or nonexistent ability to raise the front part of the foot;
- pain;
- incontinence;
- fatigue.

The known psychological effects of stroke are [27, 28]:

- diminished motivation, energy and alertness;
- personality changes;
- loss of cognitive function or thinking abilities (also called *vascular dementia*);
- disorder of a person's ability to speak and comprehend language;

- depending on the part of the brain the strokes occurs in, the short and long term memories may be affected;
- sudden changes of humor;
- depression.

From these consequences, the ones that have a bigger impact in the upper limbs mobility and functionality are: visual disturbances, reduced muscle strength, proprioception, tightness of muscles, pain, fatigue, diminished motivation, vascular dementia and depression. Depression is one consequence of major importance because it impacts greatly the life of the patients, slowing down their recovery. It affects 25 to 79% of the patients, it can result in a diminished will to participate in rehabilitation and slows down functional recovery, social integration and long-term improvements [29].

2.2 Rehabilitation

The goal of stroke rehabilitation is to restore the common brain functions that are needed in daily routine. Examples of everyday activities it tries to improve are: walking, talking, perform housework and meal preparation. Rehabilitation aims to provide patients the self-confidence and the independence they need to their everyday life [24].

Depending on the degree and type of damage, different rehabilitation treatments may be undertaken. The rehabilitation after stroke must be a continuous process of several sessions of treatments and of continuing staff and patients/families/carers education. To achieve the best results, rehabilitation should be performed supervised by a multidisciplinary team composed by a physician, a nurse, a physiotherapist, an occupational therapist and a speech therapist [30]. This team must be aware that the timely completion of proper therapy and treatments can make the brain recover significantly from the injury, and that a longer rehabilitation period improves functionality and therefore the patients' quality of life [31, 32].

To suggest the best rehabilitation treatment to a patient, it is wise to conceive a rehabilitation management plan. The framework in Figure 2.1, is one of the available frameworks that indicate the path of decisions, in accordance to the patient health status, the physicians should follow [33].

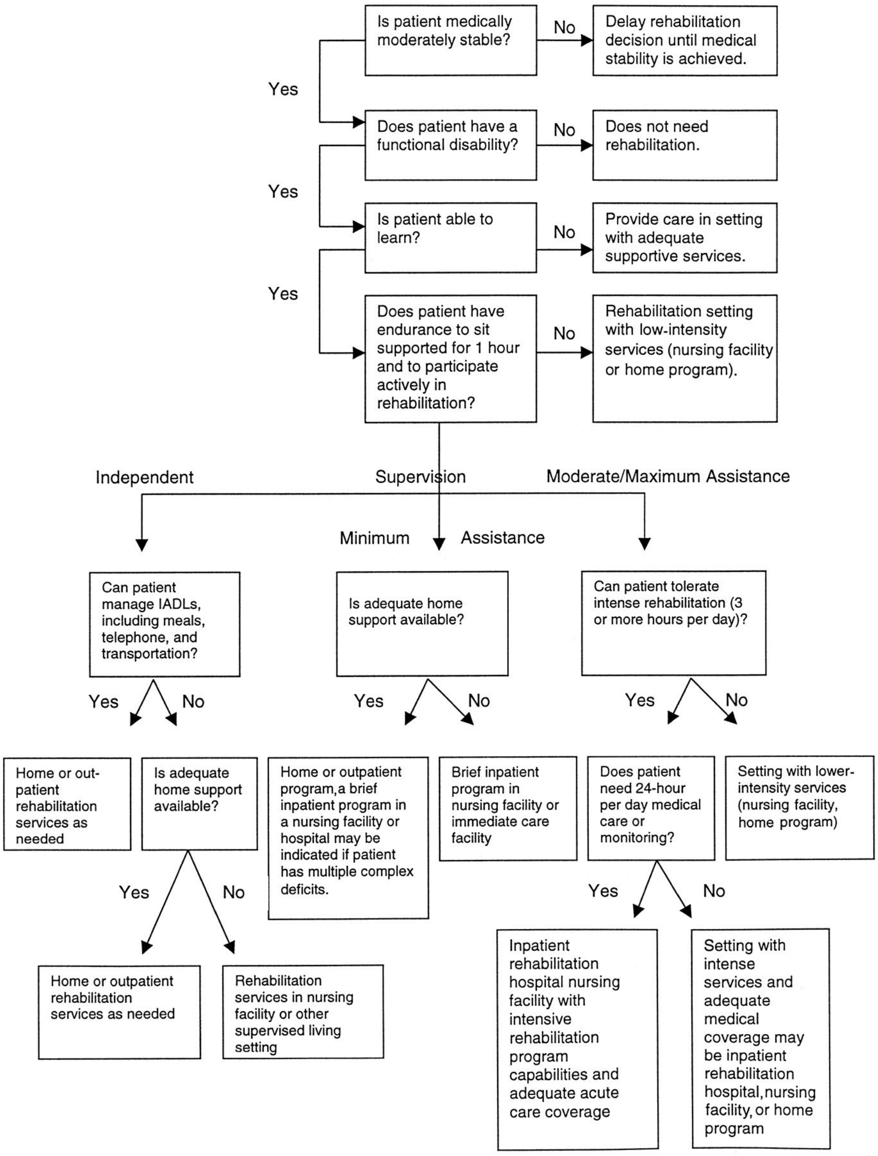

Figure 2.1: Framework for rehabilitation decisions after stroke (figure extracted from David, A. et al. (1997)[33].[7]

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[7] IADLs = Instrumental activities of daily living.

Patients should now be assessed for the degree of their impairments, in order for a detailed rehabilitation program to be developed [34]. This evaluation reflects what the patient can do, apart from the opinion of the physician about it. There are a few reliable stroke assessment scales available at “The Internet Stroke Center”[8]. The assessment scale is chosen according to the type of impairments the physical therapist wants to evaluate. One example of one of those scales is the NIH Stroke Scale (The National Institutes of Health Stroke Scale) that measures the level of stroke severity. According to this scale, some tests must be done to evaluate: the level of consciousness, the gaze, the visual fields, the facial paralysis, the upper limb motor capacity, a possible unilateral cerebellar lesion, the sensory capacities, the speech language, the speech articulation and the inattention of patients [35]. In the end of the tests, the score of the patient determines the level of the neurological deficit. There are scales dedicated to assess the upper extremity functioning or that have at least on section of tests dedicated to it. Some of them are: the Brooke Upper Extremity Functional Rating Scale, the Jebsen Hand Function Test [36], the Action Research Arm Test, the Fugl-Meyer Assessment [37], the Patient-Rated Wrist Evaluation, the DASH (Disabilities of the Arm, Shoulder and Hand)[38], the Rivermead Motor Assessment [39] and the Action Research Arm Test [40]. They evaluate activities of daily living and difficulty in changes of position like standing or sitting, with physical tests (with or without external tools) or with surveys.

2.2.1 Upper limbs rehabilitation

Delden, A. et al. (2009)[41] stated that “About 80% of all stroke survivors have an upper limb paresis immediately after stroke, only about a third of whom (30 to 40%) regain some dexterity within six months following conventional treatment programs.” Impairments in the upper limbs are often permanent and disabling and affect greatly the quality of life [42]. Upper limbs deficits are common among stroke victims, so the more innovative therapies that can exploit new methods of treatment and perchance achieve better rehabilitation outcomes the better. Rehabilitation of the upper limbs is the type of rehabilitation that will be the focus of this thesis. So, methods, principles and treatments of the upper extremity rehabilitation will be discussed in more detail in this subsection. They will be presented according to the work developed by Oujamaa, L. et al. (2009)[43]. The upper limbs rehabilitation goal is to lead patients to achieve their most possible positive functional outcomes, so they can recover their independence in their daily living routines.

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[8] http://www.strokecenter.org/professionals/stroke-diagnosis/stroke-assessment-scales

Traditional treatments

Practice and feedback are important in the outcomes of motor skill learning. There are two types of feedback, the inherent and the artificial feedbacks. The inherent feedback is the perceptual information felt while performing a task. The artificial feedback, like the name suggests, it isn't obtained from a natural source. It is the feedback that is obtained from external sources, such as a therapist, a biofeedback process or a timer.

A single two-hour application of **electric somatosensory**[9] stimulation of a paralyzed hand, is demonstrably effective in the improvement of motor functions. Even without physical training, two hours of stimulation achieved functional gains that lasted less than 24 hours. If a session of this stimulation is given to a patient before a rehabilitation training session, it will boost the motor training effects. Another kind of hand stimulation used in stroke rehabilitation is thermal stimulation. During a session of it, the patients are encouraged to take their impaired arm away when they feel an uncomfortable sensation. It is proven that this treatment enhances the recovery of motor functions.

Electroacupuncture, the acupuncture technique where a small electric current is passed between pairs of needles, is also a treatment that enhances the upper limb functional improvements in early stroke rehabilitation.

Mirror therapy creates an illusion of a perfect upper limbs synchronization and can improve motor capacity and autonomy. The achieved improvements last for six months after the conclusion of the therapy.

Constraint-induced movement therapy is applied breaking down an arm function task into simple tasks, that must be repeated several times and that increase in difficulty, at the same time the patient improves in functional performance. Flanagan, S. et al. (2012)[44] stated that cortical activity is thought to reflect the biomechanical properties of movement (e.g., force or velocity of movement). Constraint-induced movement therapy makes persistent modifications to the cortical activity.

Mental Imagery training is performed at the first and the third person views. If patients perform an imaginary movement, the mental imagery training is being executed from the first person point of view, but if they are just spectators of a mental representation of their actions, the training is being performed from a third person view. When mental imagery is performed after physical rehabilitation exercises, it improves arm function capabilities.

The frequencies used in a **magnetic stimulation** have different effects in the cortical excitability. E.g., a frequency above five hertz makes the cortical excitability easier, while a

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[9] The somatosensory system comprises sensations such as touch, temperature, proprioception, pain and muscle strain/tension.

frequency of only one hertz reinforces the cortical inhibition. After a single rTMS (repetitive transcranial magnetic stimulation) performed with a ten Hz frequency, the precision and execution speed of the patients performing tasks is immediately improved. Also, with a twenty minutes transcranial **electrical stimulation**, with the current of one milliampere, on patients who had had an ischemic stroke, the paretic hand function may improve significantly. The effect of this therapy disappears after ten days.

It has also been proven that the **anesthesia of the healthy upper limb** leads to motor improvements in stroke patients.

Classic rehabilitation training consists in non-standardized physiotherapy and occupational therapy treatments. The basic training has a duration of 10 hours (30minutes per day, 5 days a week, during one month). In cases of moderate motor impairment, it is estimated that 25 rehabilitation hours will be enough to efficient rehabilitation. The classic rehabilitation therapies proposed until today are: neuro-muscular stimulation, robot therapies and virtual reality.

Neuro-muscular electrostimulation stimulates the nervous fibers in their path between muscles, placing electrodes on muscles' motor points[10]. These stimulations are used in order to achieve painless full range of movements. One challenge in upper extremity stroke rehabilitation is the patients' control of wrist and finger extensors.

Electromyography stimulation is a therapy that makes electrical recordings of the muscle activity caused by voluntary movements of the patients and assists them, allowing full extension of movements. This technique when used alone and applied once per minute, ninety times a day, for four days in a two week period, improves wrist and fingers extension, as well as dexterity in patients with moderate physical disabilities.

Although constraint induced therapy increases use and function of the upper limbs, it is not widely employed in clinics because patients must fulfill certain prerequisites. They must be highly motivated and must not have cognitive disorders or be at risk of falling. They also have to be able to voluntarily extend the long fingers, at least ten degrees and the wrists for at least twenty.

When the evaluation of capabilities of patients is finalized, is when the positive effects of the stroke rehabilitation begin to directly affect them. Investigations conducted until today, obtained positive effects in the execution of some exercises in stroke rehabilitation. The exercises that are now used by therapists, are those who have obtained better results in those studies. The most common impairments caused by stroke were already displayed in the previous section.

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[10] Motor points are locations on the body surface where nerves controlling skeletal muscles lie close to the skin. A minimum amount of electrical stimulation, at this points, will easily excite this portion of the muscle

Not all treatments are adequate to counteract a given impairment. According to the Australian "Clinical Guidelines for Stroke Management 2010"[45] the recommended therapies/treatments to the most common impairments are shown in Table 2.4 and the recommendations to the principal difficulties of post-stroke patients are shown in Table 2.5.

Table 2.4: Recommendations of treatment for stroke impairments (*adapted from "Clinical Guidelines for Stroke Management 2010"[45]*).

Impairment	Recommendations
Visual disturbances	The use Fresnel Prism glasses[a] and computer-based visual restitution training.
Dysphagia	Positioning, therapeutic manoeuvres or modification of food or fluids and 1 of the following: therapy targeting specific muscle groups or thermo-tactile stimulation or electrical stimulation.
Sysphasia	Constraint-induced language therapy, the use of gesture, supported conversation techniques and delivery of therapy programs via computer.
Decreased or nonexistent ability to raise the front part of the foot	Ankle-foot orthoses[b], which should be individually equipped.
Dysarthria	Biofeedback[c] or a voice amplifier to change intensity and increase loudness, intensive therapy aiming to increase loudness, the use of strategies such as decreased rate, over-articulation or gesture and oral musculature exercises.
Complete or partial loss of language function	Constraint-induced language therapy[d], the use of gesture, supported conversation techniques and delivery of therapy programs via computer.
Unilateral impairment	Simple clues to draw attention to the affected side, visual scanning training[e], prism adaptation[f], eye patching[g] and mental imagery[h] or structured feedback.

[a] Glasses with fresnel prisms incorporated in the lens.

[b] A brace, usually made of plastic, that is worn on the lower leg and foot to support the ankle.

[c] Biofeedback is a technique that measures bodily functions and gives the patient information about them in order to train him/her to control them.

[d] Constraint induced therapies have three principles. A constraint (a patient must avoid some compensation), a forced use (the use of the impaired part of the body is required) and a massed practice (the patient must use the impaired part during all of the treatment). In the case of constraint-induced language therapy, the patient must avoid gesturing, writing, drawing or other compensatory strategies, he/she must communicate only by talking and must endure the therapy 2 to 4 hours a day.

[e] Training of the visual scanning capability. Visual scanning is the ability to actively find relevant information in our surroundings quickly and efficiently.

[f] Therapy that consists in putting patients looking through prisms that optically displace the visual field.

[g] An eye patch forces the unpatched eye (the weaker eye) to work harder so the vision improves.

[h] Patients imagine themselves performing an action without actually performing it.

Table 2.5: Recommendations of treatment for difficulties in performing ADLs (Activities of Daily Living) (*adapted from "Clinical Guidelines for Stroke Management 2010"[45]*).

Difficulty	Recommendations
Sitting	Practice of reaching beyond arm's length while sitting with supervision/assistance.
Standing up	Task-specific standing practice with feedback.
Walking	Repetitive practice of walking and 1 or more of the following: mechanically-assisted gait, joint position biofeedback[a] and virtual reality training.
Standing	Standing practice with feedback.
Reduced muscle strength	1 or more of the following: progressive resistance exercises, electrical stimulation and electromyographic biofeedback[b] in conjunction with conventional therapy.
Upper limb activity	Constraint-induced movement therapy, repetitive task-specific and mechanical assisted training and 1 or more of the following: mental practice, EMG (electromyographic) biofeedback in conjunction with conventional treatments, electrical stimulation, mirror therapy[c] and bilateral training.
Fatigue	Exercise, good sleep patterns and avoidance of sedating drugs and excessive alchohol.
Stiffness and tightness of muscles	Conventional therapy (standardized interventions) or serial casting[d] when tailored interventions have failed.
Pain	Evidence-based interventions for acute musculoskeletal pain (for shoulder pain) or tricyclic antidepressants and anticonvulsants (for central post-stroke pain).

[a] Biofeedback is a treatment technique in which people are trained to improve their health by using signals from their own bodies.

[b] Biofeedback with electrodes or other sensors, that evaluate and record the electric activity produced by muscles.

[c] The impaired limb is placed inside a box of two mirrors, placed in opposite directions and then both limbs execute some exercises simultaneously. While doing the exercises the patient only sees the healthy limb and a reflection of it.

[d] It is treatment where a well-padded cast is used to immobilize a joint that is lacking full range of motion, that is attached and removed regularly. This process gradually increases the range of motion of the affected joint.

Physiotherapy is a component of major importance in post-stroke treatment that has been proven to have positive impacts on rehabilitation outcomes [46]. The choice of a stroke physiotherapeutic rehabilitation treatment and of methodologies of assessment of patients' impairments is made according to the experience obtained from practice and not from consulting research studies [47]. That option of physiotherapists may not result in the best case scenario of treatments for the patients. Patients may be submitted to therapies that are not the ones that will achieve the best results. The occurrence of abnormal or unwanted movements (compensations with non paretic muscles) is detected by the direct observation by the therapists.

Most of the methods discussed in this section are experimental and rely on known theories/approaches/treatments to support them. One thing to consider, to explain that fact, is that physiotherapists themselves don't usually give enough description in the content of the published treatments [48].

Other approaches to therapy

The existence of different theories behind the recurrent traditional methods of physiotherapy contributes immensely to the lack of establishment of standards. There are different schools of thought that consider their principles/theories the essential theoretical basis behind successful treatments. The lack of a standard is a big enough problem but a bigger problem arises when it is verified that a few of these strongly defended theories are inconsistent with reality and/or contradictory with principles from other schools of thought. The most common programs, theories and/or principles that are the foundation of the existing physiotherapeutic exercises will be presented below.

Community-based exercise programs

According to the North Carolina Division of Social Services[11] "A fundamental characteristic of community-based programs is that staff and families work together in relationships based on equality and respect." There are several types of community-based programs but that sentence summarizes what they have in common. These programs mobilize formal and informal resources to the community to support patients' health improvement, so they can become a cheaper alternative, that doesn't need one-on-one supervision and expensive equipments, to the ones established at clinical environments [49]. One example of a community-based exercise program in stroke rehabilitation is the one executed by Pang, M. et al. (2006)[50]. In that program, a sample of 63 post-stroke patients were divided in two stroke rehabilitation programs. One training program was to rehabilitate functions of the upper limbs and the

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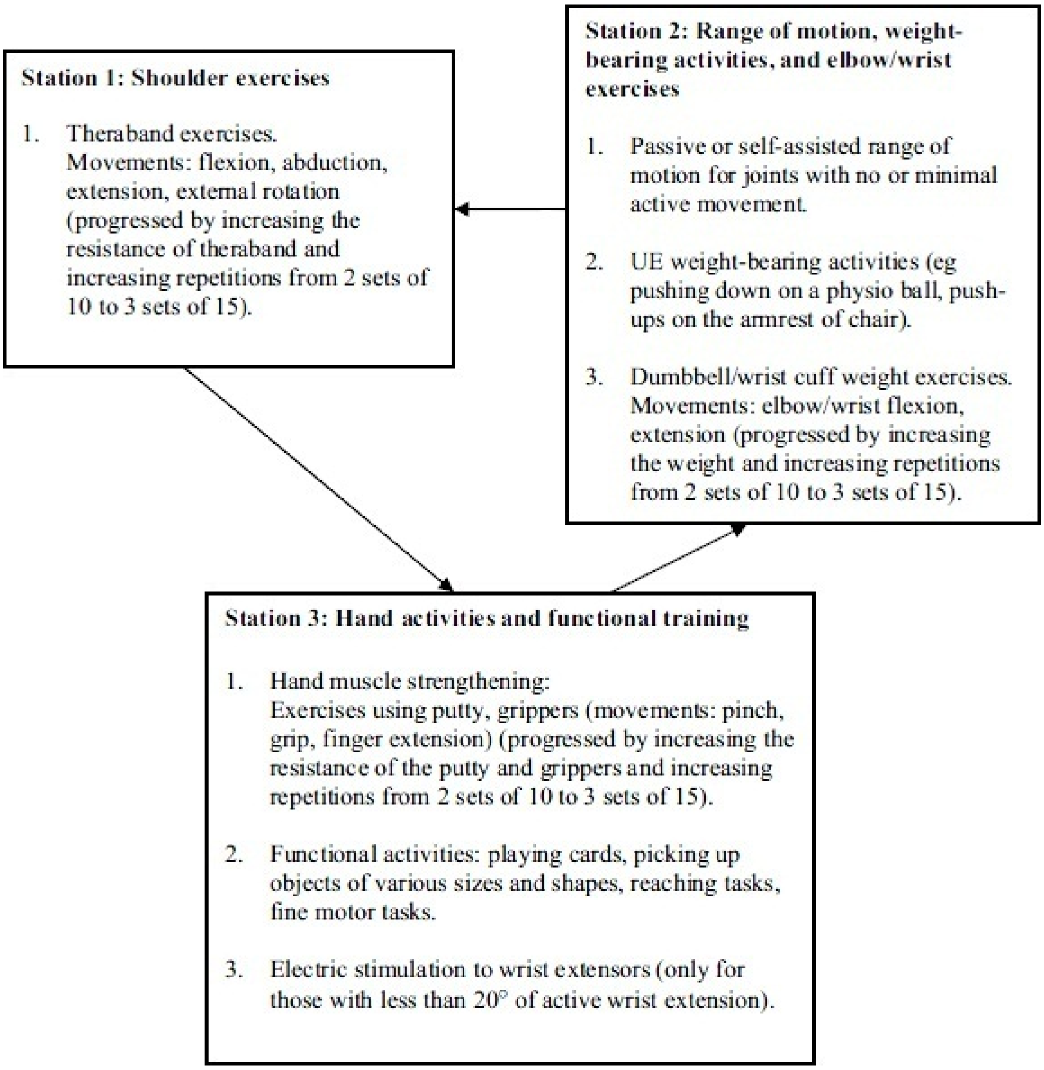
[11] http://www.ncdhhs.gov/dss/community/index.htm

other to rehabilitate the lower extremity of the body. The upper limbs rehabilitation program was divided in three stages. The first level of rehabilitation consisted in shoulder exercises of flexion, abduction, extension and external rotation with a theraband[12]. The second stage of rehabilitation consisted of hand muscle strengthening activities, functional training and electric stimulation for patients with less than 20° of active wrist extension. The last one, combined range of motion and elbow and wrist exercises with weight-bearing activities. All of the information provided in the article related to the exercises can be seen on Figure 2.2. The appliance of this methods in a community-based environment positively influenced upper extremity functions.



Station 1: Shoulder exercises

1. Theraband exercises.
   Movements: flexion, abduction, extension, external rotation (progressed by increasing the resistance of theraband and increasing repetitions from 2 sets of 10 to 3 sets of 15).

Station 2: Range of motion, weight-bearing activities, and elbow/wrist exercises

1. Passive or self-assisted range of motion for joints with no or minimal active movement.
2. UE weight-bearing activities (eg pushing down on a physio ball, push-ups on the armrest of chair).
3. Dumbbell/wrist cuff weight exercises.
   Movements: elbow/wrist flexion, extension (progressed by increasing the weight and increasing repetitions from 2 sets of 10 to 3 sets of 15).

Station 3: Hand activities and functional training

1. Hand muscle strengthening:
   Exercises using putty, grippers (movements: pinch, grip, finger extension) (progressed by increasing the resistance of the putty and grippers and increasing repetitions from 2 sets of 10 to 3 sets of 15).
2. Functional activities: playing cards, picking up objects of various sizes and shapes, reaching tasks, fine motor tasks.
3. Electric stimulation to wrist extensors (only for those with less than 20° of active wrist extension).

Figure 2.2: Exercises for the upper limb rehabilitation in a community-based study (figure extracted from Pang, M. et al. (2006)[50]).

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[12] A theraband is a flexible band that can help build muscle tone and flexibility without impact on joints.

Bilateral Arm Training with Rhythmic Auditory Cueing (BATRAC)

BATRAC is a conventional physiotherapy protocol with the principles of forced used and of repetitive and rhythmic bilateral training. A study conducted by Whitall, J. et al. (2000)[51] used a machine that incorporated these principles in the upper limbs rehabilitation. The patients sat at a table in front of the BATRAC device with: shoulders not flexed, elbows flexed about sixty degrees and wrists in the most natural position between flexion and extension. Figure 2.3 ilustrates the posture of a patient in front of the machine. After being comfortably seated, the patients must push the handles of the machine away, how much they can, and pull them back to the body with both arms. Movements must be interchangeably performed with both arms simultaneously and alternatively for five minutes. Every five minutes, the patients rested ten minutes. Having periods of rest that are twice as long as the period of exercises, might reduce conditioning effects, such as heart rate and blood pressure. The speed of the movements was determined in the first session, according to the criterium of the patient being able to comfortably perform the exercises for five minutes without stopping. All of the exercises were performed at the same speed during all sessions and timed by a metronome. In all of the tests, the patient has his/her blood pressure and heart rate measured to check if there is no cardiovascular reaction and if the heartbeat is not too fast.

Figure 2.3: A patient with a BATRAC device (figure extracted from Whitall, J. et al. (2000)[51]).

It is proven that BATRAC improves arm function in patients with stabilized upper limb impairments [52].

Bobath/ Neurodevelopment treatment

According to the International Bobath Instructors Training Association[13] Bobath is an approach that allows evaluations and treatment of patients with functional, movement and postural impairments, caused by a lesion in the central nervous system. It is not a static concept, it has evolved over the years. The creator, Karel Bobath said in 1986 that "The Bobath concept is unfinished. We hope it will continue to grow and develop in the years to come." It is tailored to the patients' needs and expectations and comprises knowledge from motor control and learning, neural and muscle plasticity, biomechanics and from the practice of current active therapists [53]. Presently, physiotherapists apply the Bobath's methods that consist in the voluntary enervation of muscles, in repetitive movements and in trying to reduce muscle tone[14] anomalies at the same time. Patients' movements must not be performed too quickly nor with too much strength for the treatments to achieve their desired goals. One of therapists biggest objectives is to achieve normal movement patterns that are essential to the quality of life of stroke survivors [54].

A training that incorporates these methodologies is the one proposed by Parry, R. et al. (1999)[48]. The treatment aims to the re-education of normal movements and comprises techniques such as relaxation, teaching about correct positioning of the upper limbs, stretching, massages, facilitated, passive and active movements, task oriented functional activities and an exercise where patients should hold still the impaired arm on a supporting surface. This treatment was effective only in patients with less severe impairments.

Proprioceptive Neuromuscular Facilitation (PNF)

Proprioceptive neuromuscular facilitation exercises have the goal of increasing the neuromuscular mechanisms stimulating proprioceptors[15]. Techniques of this kind have been used to increase the amplitude of movements of a joint, endurance and execution of vertical jumps. Two common types of techniques that embrace the PNF method are rhythmic stabilization training (RST) and combination of isotonic exercises (COI). Kofotolis, N. and Kellis, E. (2006)[55] conducted a comparison of the effects of two PNF programs in 108 women with

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[13] http://www.ibita.org

[14] Muscle tone is the contraction level of the muscles while they are relaxed. It is what makes muscles feel stiff even when they are at rest.

[15] Proprioceptors are sensory receptors that provide information about joint angle, muscle length, and muscle tension by responding to stimuli.

chronic low back pain. Both programs were a four week intensive exercise program and had the goal of improving strength, endurance, lumbar flexion-extension mobility and overall body control. The RST method combined alternating flexion-extension movements with some resistance and the COI schedule contained two resisted trunk flexions and maintained contractions of flexion-extension movements. After the training, both programs achieved an improved lumbar flexion, trunk flexion and extension and muscle strength and endurance, although only patients in the RST group improved the lumbar extension. Also, both treatments decreased disability and back pain.

Rood/ Sensorimotor approach

There's not much information regarding the Rood's treatment but Danion, F. and Latash, M. (2010)[56] stated that a Rood's treatment guideline pointed out that "normal development proceeds from stability in weight-bearing patterns to mobility in non weight-bearing patterns." In that guide, mobility built on stability is considered the best way of achieving motor evolution. Therapists that developed therapies based on Rood's methodologies used proximal-to-distal motor exercises, such as: throwing, hitting, jumping, and reach-to-grasp [57].

Brunnstrom/ Movement therapy

The Brunnstrom approach was developed by the Swedish physical therapist Signe Brunnstrom in the 1960s. In this approach the patient moves through seven different levels of motor control, as he/she regains some physical dexterity. In the first level, the patient's muscles are flaccid and he/she has no voluntary movement in the affected extremities and in the last one the patient's normal movements have completely returned to normal. Groups of muscles are co-activated in predictable flexion or extension patterns (synergies), through a wide range of movements. This approach encourages you to actively use these synergies and comprises techniques to facilitate movements. E.g., the elevation of the affected limb, above the horizontal line, causes an extension and abduction (separation) reflex of the fingers. When the patient isn't capable of moving the affected limb, movements are induced using reflexes, associated reactions and proprioceptive and exteroceptive (external stimuli) facilitations. When the patient can already execute voluntary movements, he/she is asked to hold contractions and to perform controlled lengthening and shortening contractions. As the patient progresses and shows less inhibition of movements and more voluntary control, the facilitation of movements is quickly reduced until is no longer needed. When no facilitation is needed, patients must repeat correct movements and practice activities of daily living. One exercise that is used at this stage of recovery is of trunk balance. The patient begins the exercise sitting, lifts the impaired arm by the unaffected one and executes trunk movements in all directions [58]. That exercise can be seen in Figure 2.4.

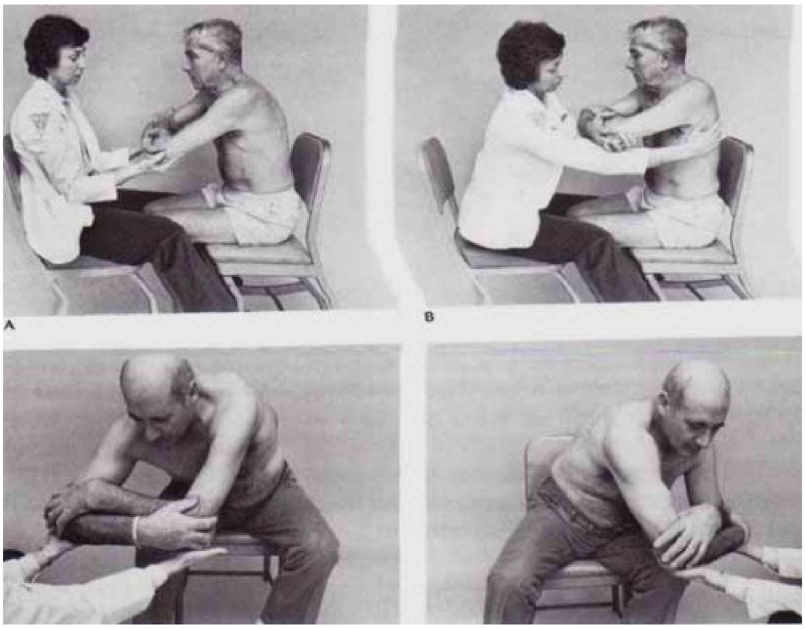

Figure 2.4: Trunk exercises of less impaired patients undergoing the Brunnstrom approach (figure extracted from Elsayed, E. [58]).

A study conducted by Ferraro, M. (2003)[59] showed that Brunnstrom arm training improves outcome in patients with chronic stroke.

Conductive education

Conductive education is a method that was developed by Janet Carr and Roberta Shepherd in the 1970s and that is used in the treatment of neurological deficits. In this approach a therapist teaches each patient how he/she should guide his/her movements in each individual task by using his/her own speech. Each task is divided in smaller tasks and the patients should be constantly verbalizing their own movements. The basic phenomenon that originated this theory is that an adult who experienced a neurological deficit may no longer know how to move and needs to relearn those movements [60]. According to Cotton, E. (1991)[61] some of the movements the patients should execute are retraction of the shoulder, flexion of the elbow and of the wrist and fisting of the hand. Ibid., they may be practiced in various positions: supine, sitting at a table, free sitting and standing. Other study conducted by Brittle, N. et al. (2008)[62] showed significant short-term effects of Conductive Education on self-reported physical function and well-being for people who suffered a stroke.

Motor relearning theory/ program/ Carr and Shepherd approach

The Australian physiotherapists Carr and Shepherd developed this method in 1980. It highlights the practice of functional tasks and the importance of patients relearning ADL. It comprises principles of learning and of biomechanical analysis of patient's movements and of tasks performed by them. This approach combines exercises from other methods that were already studied. It uses movements from the Bobath treatment such as holding, reflex inhibiting movement patterns, weight bearing, balance activities and many hand activities. It also comprises Rood's approach exercises like brushing, ice application, pounding, tapping and vibration. In addition to these exercises, it also uses EMG biofeedback to help decrease hypertension or to assist the contraction of certain muscles and mirrors to provide visual feedback that helps patients in self-correcting movements [60, 63]. Its effectiveness depends on the combination of therapies/methods it embraces.

Behavioral approach

Behavioral approaches are employed according to the belief that pain and disability are not influenced only by diseases, but also by psychological and social variables. These techniques are not physiotherapeutic exercises but are usually used in conjunction with them and with other treatment techniques. These methods include changes in the life style patients had before the stroke occurred. They can go from dietary changes for beneficial effects on brain repair, to exercise to increase muscular activity and weight loss. It is shown that exercise can have beneficial effects for brain reorganization and that a behavioral approach is also effective treating post-stroke patients who are in pain [64, 65].

Sensorimotor Integrative Treatment and the Functional Approach

The American Occupational Therapy Association[16] defined occupational therapists and occupational therapy assistants as the professionals that “help people across the lifespan participate in the things they want and need to do through the therapeutic use of everyday activities (occupations)” [66].

In the work conducted by Jongbloed, L. (1989)[67] two occupational treatments were compared, the Sensorimotor Integrative Treatment and the Functional Approach. The first one combines theories from therapies that were previously discussed in this subsection, such as Rood’s and Bobath’s. This approach considers that brain functions work together as one and that motor and sensory areas of the brain are interdependent, so if one of them is stimulated, it can influence the other. It aims for the treatment of the cause of the impairment, instead of trying to compensate or adapt to it. The rehabilitation exercises that incorporate the principles of this treatment should:

- Provide sensory stimulation: the patient must be actively involved;
- Make the activity meaningful: exercises should be planned so that they can be carried out by the patient(s) they are intended to and to motivate them;
- Use some kind of visual or auditory clues: clues can help patients cognitively organize the planning of their movements;

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[16] http://www.aota.org

- Facilitate the activities: patients should have a correct body posture in the execution of rehabilitation exercises, even when it's harder to execute them. Part of the job of a therapist is to facilitate movements of patients when that's needed in order for them to successfully accomplish their tasks.

The Functional Approach is focused in the practice of ADL, such as: dressing, grooming, bathing, taking care of personal hygiene, among others. Unlike Sensory Integrative Treatment, this therapy focuses on treating the symptom of the dysfunction instead of the cause of it. It has two major principles: compensation and adaptation. The therapist should find a solution to compensate for a patient's impairment and should adapt the environment of the patient to minimize the impact of such impairments. E.g., a compensatory help for a patient that is not achieving any significant returns of voluntary movements in the upper limbs, is teaching him/her one-handed techniques and providing assistive devices that can guarantee his/her independence in daily routine. An adaptation of the environment is, e.g., placing food, utensils and personal items next to the patient's unaffected side of the body, when he/she ignores half of his/her space.

In the same work conducted by Jongbloed, L. (1989)[67], the subjects showed significant improvements in meal preparation and in most of the sensorimotor integration tests[17] realized. There is no considerable difference in results between these two methods of treatment.

Rhythmic Auditory Stimulation (RAS)

Rhythmic Auditory Stimulation is a fairly recent approach in the rehabilitation of stroke that emphasizes on quality of movements. This approach generally comprises rhythmically practice of reaching, stepping, or walking, at the same time as an auditory cue (usually a metronome). It promotes motor learning and control and sensorimotor facilitation [68].

In a study conducted by Malcolm, M. et al. (2009)[68] a RAS training of two weeks was administered. Patients were seated at table with 28.7 inches (72.9 cms) of height, with their trunk in contact with it. That table had already secured a matrix template of 28 consecutive numbers separated by 6 inches (15.2 cms). In this approach the patient receives rhythmic auditory instructions to move between at least two numbers with his/her impaired limb. The difficulty level of the tasks was adapted to the degree of impairment of the patients. In this

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[17] Sensory integration tests evaluate how people use the information provided by all the sensations coming from within the body and from the external environment. Some examples of sensory integration tests are assessment of finger identification and imitation and sequencing of postures.

exercise, the therapist could request movements that encourage different movements from the patient, such as shoulder flexion/extension or shoulder adduction/abduction. Figure 2.5 illustrates a patient receiving this treatment.

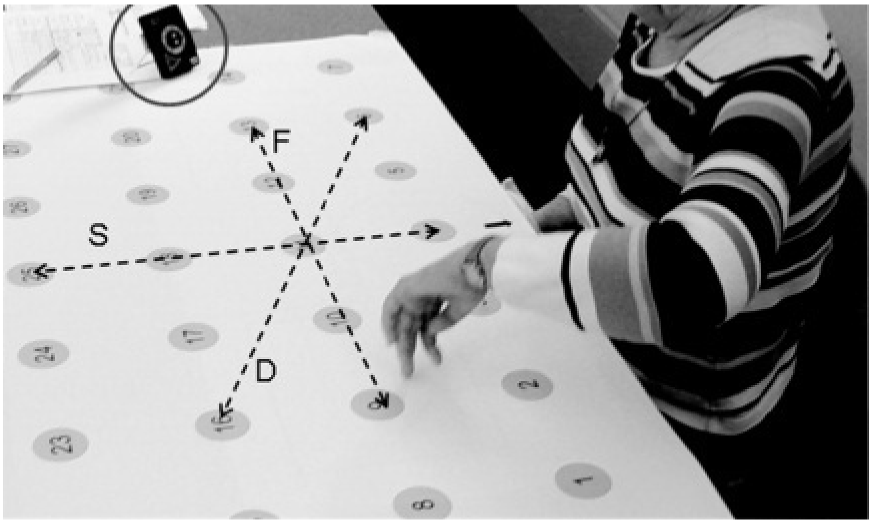

Figure 2.5: A patient seated at a table receiving a rhythmic auditory stimulation training (figure extracted from Malcolm, M. (2009)[68]).

This method achieved a reduction in the use of compensatory strategies and significant upper extremity functional gains by the patients. Summing up, it improved motor abilities that patients need in their daily routines.

2.2.1.1 Technology-based rehabilitation

The two major approaches of technology-based rehabilitation are robotic-assisted therapies and virtual and augmented reality and game based methodologies [69]. When technology began to be used in rehabilitation, the opportunity for tele-rehabilitation arose. Stroke tele-rehabilitation is the rehabilitation and support given to a patient by a practitioner, who is in a different geographical location (by telephone, email, teleconference, among others). The primary purpose of these types of therapies is to provide health care services to patients with limited access and substantial needs. They allow patients to benefit from services, more times than they would if they had to travel to an health facility, and therefore they attain better outcomes in their rehabilitation processes [4].

Robotic-assisted therapies

Nowadays there are several robotic devices being commercialized for upper extremity stroke rehabilitation. The motivation behind the investment in these technologies was the idea that, with the help of robotic devices, patients may perform some rehabilitation on their own, without the need to go to a clinic or the presence of a therapist [70]. Plus it has already been demonstrated in a research conducted by the MIT[18] that repetitive, goal-oriented, robot-assisted therapies can improve clinical outcomes. They can be active or passive and assist or resist movements and be adjusted differently on each section. Robot-aided movements are always of extension-flexion and pronation-supination of the wrist type. Their repetition increases voluntary motor capacities of the arm in severely impaired patients. These kind of therapies are used to help patients in exercises such as: trying to reach for something, bilateral movements and grasping of an object. There is also undergoing investigation related to the introduction of distortion in the feedback the patient gets with the use of a robotic device. It can be added to a computer screen or to a mechanic robot and aims to achieve correct movement counter-reactions from the patients. Robotic therapies are also being used to provide physicians with precise measures and evaluations of individual's functions, such as precision and force of patients in each movement. This kind of precise assessment can also be really useful in tele-rehabilitation providing appropriate and objective feedback to the physician on the other side of a screen [71].

One example of a robotic therapy for the upper limbs, that can be used in stroke rehabilitation, is the "Armeo Therapy Concept". According to research, brain recovery can be achieved through intensive and repetitive task-oriented movements. This therapy uses three different mechanical products to help patients fulfill those movements. Each one of these products is suitable to different degrees of impairments [72]. Figure 2.6 shows them in action.

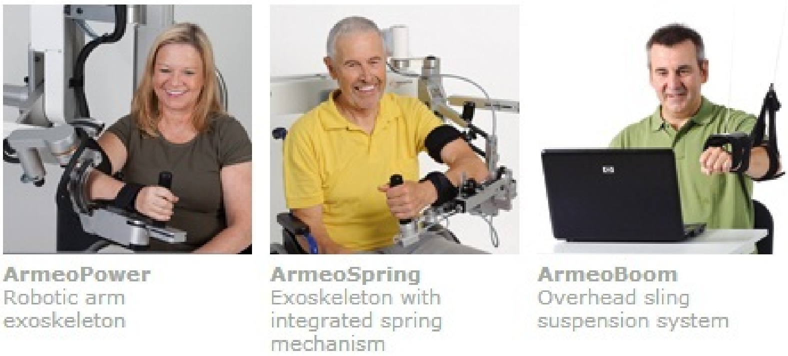

Figure 2.6: Armeo Therapy products (figure extracted from Hocoma AG (2013)[72]).

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[18] MIT stands for Massachusetts Institute of Technology.

Still, the robotic assisted rehabilitation is still very much confined to the clinical environment due to high complexity and cost [69]. The scientific evidence of appropriate methods to treat impairments after a stroke is limited and the benefits of robotic assisted therapies have not yet been proven as better than less expensive alternatives [70, 71]. Without substantial evidence, this methods will not be largely adopted in health facilities around the World [70].

For instance, in Portugal, the "Hospital Do Mar"[19] also makes use of technology in stroke rehabilitation. The hospital has computers that are moved by an articulated arm attached to patients beds, at their fully disposal [73].

Virtual reality therapies

Nowadays, the research in stroke rehabilitation focuses on virtual and augmented reality and game-based technology. Virtual reality methods increase the patients' motivation greatly because of the games usually associated with them and they might increase arm function capabilities. They can be used to provide feedback to a patient in robotic therapies.

There are several examples of developed systems that include these areas. To increase the motivation of a patient, the SWORD Tele-Rehabilitation system created by Bento, V. et al. (2012)[69] uses various games and visual interfaces to train different motor functions [69]. In Figure 2.7 we can see the look of the graphical interface of their airplane game, developed to train the range of movements of patients' upper limbs. The patient must avoid the obstacles that appear on the screen, controlling the altitude of the plane. He or she does so, by flexing or extending the shoulder. The game has several difficulty levels, increasing the speed of the plane on each one.

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[19] http://www.hrmar.pt

Figure 2.7: Airplane game graphical interface (figure extracted from Bento, V. et al. (2012)[69]).

A great example of an augmented reality entertaining stroke rehabilitation application is the one developed by Lee, R. and Tien, S. (2012)[74]. The system incorporates three different games. In one of the games, the patient will be a treasure hunter that has to find the key to open a door that leads to a treasure chest. After picking up the treasure, he or she needs to leave the room in a limited time period before it collapses. As the game progresses, the user will have to turn AR (augmented reality) markers placed on the floor, in front of the feet and on his left or right side of the body. The patient will have to stand for a few seconds, straighten the arms, put the palm on an AR marker and hold that position. He or she even has to walk ten meters, pick the treasure from the floor and come back to the chair where the game began. The score of this game is the total Motor Assessment Scale[20] items completed. This scale is used on all of the games and contains performance evaluations of moving from an inert position, sitting and walking and upper arm functions. The different steps of the game are shown in Figure 2.8.

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[20] The Motor Assessment Scale (MAS) is a task-oriented approach with a performance-based scale that was developed to evaluate everyday motor function in patients with stroke.

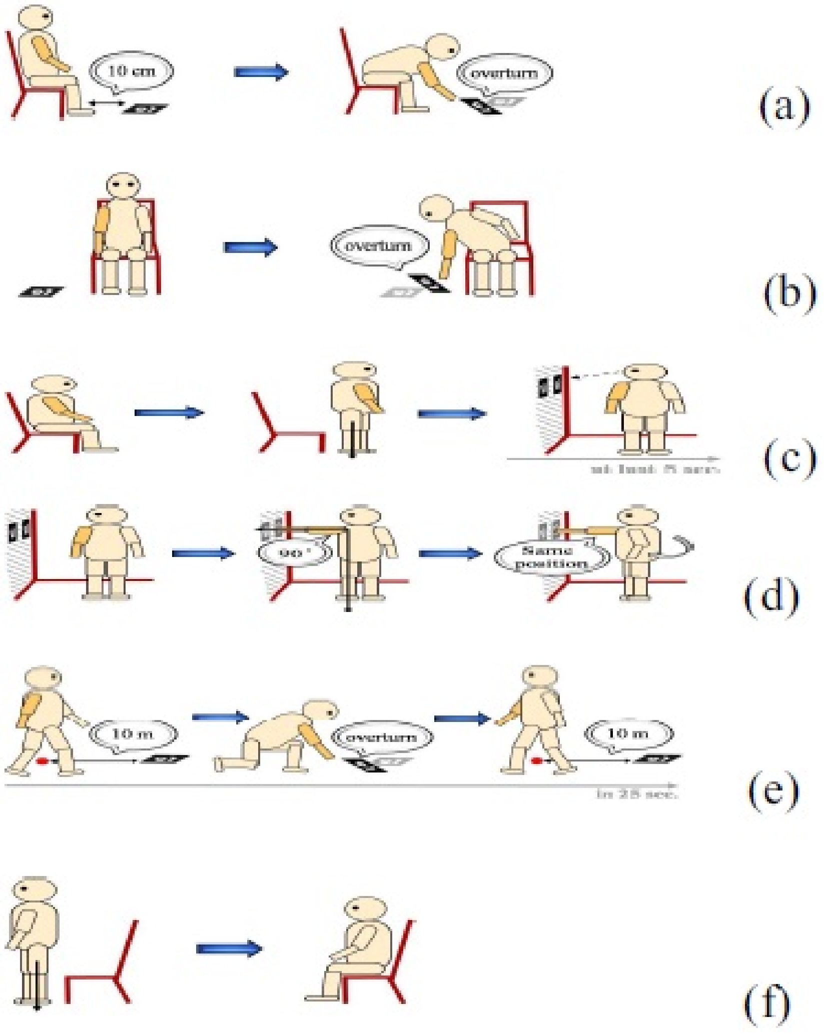

Figure 2.8: Treasure hunter augmented reality game steps (figure extracted from Lee, R. and Tien, S. (2012)[74]).

It has been studied that music with particular structures may be effective in reducing pain and anxiety and that listening to music contributes to a positive treatment outcome. The positive effects of music in a patient increase if he or she is listening to his or her favourite music [42]. Wijck, F. et al. (2012)[42] developed a music rehabilitation game, targeted to stroke victims with at least one affected arm. The game has a graphical interface with a set of round targets that are highlighted, accordingly to the beat of a current playing song of user's preference. The objective of the patient is to place a cursor, that appears on the screen, in the current highlighted round target, through the movement of his/her affected arm. The game can be adapted to each patient capabilities, e.g., by adjusting the distance between targets, the size of targets and the type of movement the patient must do to move the cursor. Figure 2.9 discloses the look of the game visual interface.

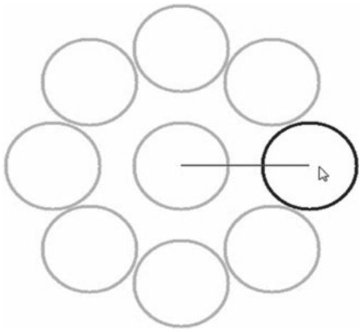

Figure 2.9: Visual interface of a music stroke rehabilitation game (figure extracted from Wijck, F. et al. (2012)[42]).

Multiple wearable inertial sensors

A few stroke rehabilitation systems also use multiple wearable inertial sensors[21]. Two examples of this kind of systems are the ones developed by Zhou, H. et al. (2005)[75] and Zhou, H. and Hu, H. (2005)[76]. Both of them make use of a comercially available sensor called MT9. The first one is an arm movement tracking system with a single MT9 inertial sensor, as can be seen in Figure 2.10. The data of the movement is gathered by a tracking algorithm. The second one is similar, but it is uses a more complex approach. It uses a MT9 sensor and three CODA markers[22] attached to an upper limb and therefore, more complex algorithms to gather the movement data. The upper limb with the markers and the sensor are shown in Figure 2.11.

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[21] Inertial sensors are devices that measure velocity, orientation and gravitational forces.

[22] They consist in an infrared light emitting diode powered and controlled by a separate small box that contains their electrical circuit and a rechargeable battery.

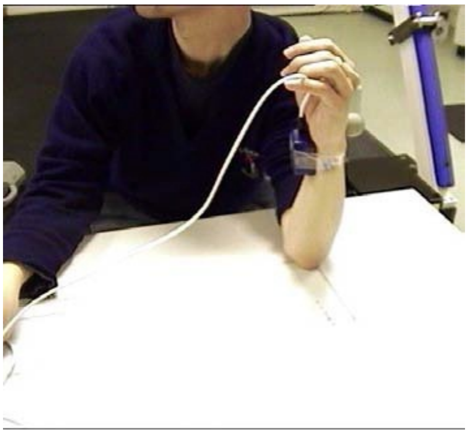

Figure 2.10: Mt9 inertial sensor attached to an arm (figure extracted from Zhou, H. et al. (2005)[75]).

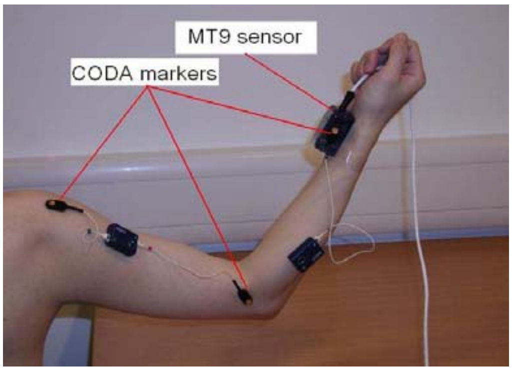

Figure 2.11: Mt9 inertial sensor and CODA markers attached to an arm (figure extracted from Zhou, H. and Hu, H. (2005)[76]).

2.3 Summary

There is a potential room for the use of smartphones in stroke rehabilitation because they are an ubiquitous technology and are loaded with powerful sensors. They are also simple to use and are able to establish a connection to therapists via phone calls, sms/mms and email. The simplicity of use increases their target audience and the possibility of sensing feedback to a therapist remotely allows the practice of physiotherapy wherever patients feel more comfortable. Smartphones are obviously cheaper than the current technological solutions because most people already possess one and even if they don't their prices keep on falling. Their sensors allow the assessment of some traditional physiotherapeutic exercises and provide the opportunity to take advantage of virtual reality.

Chapter 3

Prototype Development

This chapter describes the implementation of a prototype application for smartphones that is intended to be used in stroke physiotherapy. It will be introduced which sensors are available in Android smartphones, their capabilites and limitations and how they can be used to determine spatial orientation. After that a few biomechanics concepts will be provided, for a better understanding of the physiotherapeutic exercises that were chosen to be assessed by the application. This application works with an Android smartphone as a client and with a desktop/laptop computer as a server, so both sides will be explained in detail and the end result of the development will be clearly shown.

3.1 Smartphones and Sensors

Nowadays it is hard to find someone who doesn't feel the urge or the need to have a cellphone always in his/her possession. We are so used to communicate where and when we want, that leaving a cellphone behind, is like walking without something real essential like clothes or shoes. It is possible to acquire, for not much money, a smartphone that is a cellphone and also a smaller and cheaper computer with an Internet connection available.

At the end of 2011, there were 356 million cellphone users. That is about 69% of all Internet users [77]. In February of 2012, 46% of American adults owned smartphones and other advanced portable devices, such as tablets.

Smartphones are already adopted in a large scale and their prices keep on falling, making them more and more accessible to more people. Among mobile operating systems that exist today, there are two that stand out. They are Apple iOS and Google Android. Android is the most popular [5] and the one that comes with cheaper devices.

An application can be developed natively (on a specific platform) or on the web (available to all platforms). This application will be developed natively to Android. This means the application will only be available to an Android platform, but it also means full availability of all Android potential and features to the programmer. Nevertheless, Android is an open platform and can be used on any device if the device's company wants to do so. Android is also open source, so it is possible to see the code of existing applications. Still, there are several tutorials and forums available, in the world wide web, to help code developers [78]. All Android applications can be downloaded from a mobile application market (or application store) or from websites. Their prices range from free to over twenty euros. The biggest Android Market is owned by Google and it's called Google Play. The Android Markets contain more than 450000 applications ready to be downloaded. Right now, there is no approval process an application must endure to be accepted in the Google Android Market. If a developer wants to upload an application to the market, it will always be accepted [78]. In the future, the work developed during this thesis will be of great help to anyone who wants to develop a similar application to iOS.

The Android SDK (Software Development Kit) is a development tool that provides the libraries and the programming and debugging tools, the developer needs to build, test and debug applications. A ADT (Android Developer Tools) Bundle contains: Eclipse plus ADT plugin, Android SDK tools, Android Platform tools and the latest Android platform and emulator system image. It includes almost everything that's needed to develop an application from scratch. The programmer only needs to have some previous knowledge of the Java programming language [78, 79].

3.1.1 Inertial Sensors

The most meaningful sensors available in smartphones are the accelerometer, the magnetometer and the gyroscope. Accelerometers (TYPE_ACCELEROMETER in the Android API) measure tilt movements by sensing the amount of force applied trying to force the smartphone to move. If it is flat on a table, they display the values of gravity's acceleration. They measure acceleration in 3 axis and are used to determine the direction of the force applied to them and not which way the smartphone was tilted. They are susceptible to detect even minor movements like hand tremors. Magnetic field (accessible with TYPE_MAGNETIC_FIELD in the Android API) sensors (also known as magnetometers or digital compasses) measure the stability of the three dimensional plane by feeling the environment magnetic field force. They can tell where the screen of the smartphone is facing but they don't know if the device is upside down or not [80]. The gyroscope (accessible with TYPE_GYROSCOPE in the API) measures the rate of rotation [81]. When there's a magnetic interference in the environment, the magnetometer is not accurate anymore and when the smartphone is not resting on a solid surface, the accelerometer lacks precision. In those cases, the gyroscope is also used in order to a more accurate orientation of the phone to be obtained. The disadvantages with the use of gyroscopes is that they are prone to errors and a further treatment of the data collected is needed [82].

The Smartphone Reference Frame (or Device reference frame (DRF)) is the standard axis system that is used in the Android API for the accelerometer, the magnetometer and the gyroscope sensors and is shown in Figure 3.1. That system is relative to the screen of the smartphone in a vertical position with the screen facing the user [83].

Figure 3.1: Smartphone Reference Frame (figure extracted from Ayub, S. et al (2012)[84]).

3.1.2 Sensor Fusion

Sensor fusion is the combination of data collected from different sensors, and it aims to improve the quality of the measurements of each individual sensor [85]. One of the most important sensors that results from sensor fusion is the orientation sensor (can be accessed in the API by the method `getOrientation`). It is not a physical sensor, it is usually a software created one that gets its values by combining data from the magnetic and the accelerometer sensors. By being a combination of the mentioned sensors, it measures the orientation of the 3 axis plane, knowing exactly where the phone is staring at [86].

Nowadays, sensor fusion can also be performed in hardware. The first digital gyro with on-chip intelligent motion processing capability was created by InvenSense[1] in 2009. It is called MPU-3000^{TM}and it is small enough to fit any smartphone. It contains two I2C[2] interfaces, one to receive signals from other sensors, such as the accelerometer or the magnetometer and the other to transfer the extracted motion information to que host processor [87]. At the moment, the same company already has 6-axis (a 3-axis gyroscope plus a 3-axis

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[1] http://www.invensense.com

[2] A chip to chip interface that supports two wire communication.

accelerometer) and even 9-axis (a 3-axis gyroscope plus a 3-axis accelerometer plus a 3-axis compass) integrated circuits with an onboard processor that executes fusion algorithms and extracts motion information [88].

3.1.2.1 Complementary and Kalman Filters

As mentioned earlier, accelerometers are susceptible to detect minor movements and it is what they excel at. In more demanding applications, such as handwriting recognition or image stabilization, their performance and operation are limited. A clean signal from the accelerometer can only be acquired if the device is not in movement. Furthermore, when a smartphone is flat on a table, the accelerometer can not distinguish the different horizontal orientations. That's why the gyroscope comes in handy. Smartphones use it to take advantage of its 3 axis measurements of angular velocity[3], that are not provided by any other sensor. Gyroscopes measure the angular velocity of all movements carried out around the X (also called pitch axis), the Y (also called roll axis) and the Z axis (also called yaw axis). A gyroscope is prone to errors, but when combined with an accelerometer, fast and accurate pitch and roll measurements can be achieved [89].

So, what is the best approach to use the data collected from this two sensors? Colton, S. and Mentor, F. (2007)[90] discussed a few methods to do so. According to the authors, we can find the angle from the data of the accelerometer and the angular velocity from the data collected by the gyroscope directly (without treating the signals). That is the easiest way to use the data from the two sensors, but the end signal will have lots of noise and any horizontal acceleration would be detected. If the smartphone is on a moving platform, or if it is in the hands of someone who is walking, the accelerometer will detect those movements and will not isolate the movements of the smartphone itself. To work around this limitation of the accelerometer, a low-pass filter[4] can be applied to the signal collected from it, filtering out short duration accelerations. That leaves in the signal only longer duration accelerations, such as the gravity. The problem with relying in a low-pass filter is the lag it causes in the calculation of the inclination angle. The more frequencies are filtered, the more lag it gets. It doesn't mean it will usually affect the responsiveness of the smartphone, but it will for sure affect the stability of applications. To avoid using the accelerometer, we can use the gyroscope data only and apply to it a numeric integration to convert the angular velocity to orientation angles, that are (usually) calculated with the accelerometer's data. In this case, lag and short accelerations are not a problem but the gyroscope will not read an exact zero when stationary and that small error will be incrementally added to the calculations of the

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[3] The angular velocity is the ratio of the angle traversed to the amount of time required to traverse that angle. It can also be measured as the ratio of the velocity to the distance covered.

[4] The Android API lets programmers use an already implemented low-pass filter sensor that can be accessed with `TYPE_GRAVITY`.

angle, making them further and further away from the real measurements. An alternative to these methods is the appliance of the filter known as the ”Kalman Filter” to fuse the collected data from the sensors. It was introduced in 1960 by R. E. Kalman and it has been studied extensively. It is composed by a set of equations that make this a very good filter for this kind of applications [91]. The downside of it is that it is not applicable in a scenario where the sensors are in smartphones because it would kill processor time. A better alternative to the previous mentioned filters is a ”Complementary Filter”. It applies a low-pass filter to the data of the accelerometer and a numeric integration and a high pass filter[5] (to filter out long-term drift) to the data collected from the gyroscope. Then, it combines those two signals to extract the angle and finds the angular velocity directly from the gyroscope. Figure 3.2 shows an illustration of how this filter works [90].

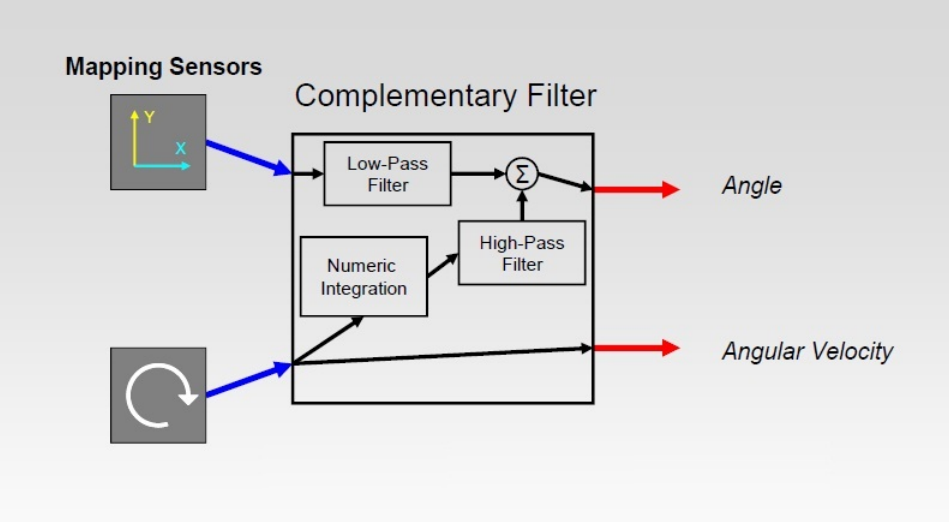

Figure 3.2: Illustration of a Complementary Filter (figure extracted from Colton, S. and Mentor, F. (2007)[90]).

This approach fixes the miscalculations of the gyroscope in the calculation of the angle and the unwanted noise and the short duration acceleration problem of the accelerometer. It also does it with much less lag than the appliance of the low-pass filter all by itself and it is not very demanding processor-wise [90]. This filter does not have any significant disadvantages, it just requires a bit more theoretical knowledge than the previous filters (except the Kalman) to be perfectly understood [90].

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[5] The Android API lets programmers use an already implemented high-pass filter sensor that can be accessed with TYPE_LINEAR_ACCELERATION.

3.1.2.2 Attitude Representation

Two of the most known methods to determine device orientation are the Euler angles and the Quartenions [92]. These methods are useful to a better understanding of the raw sensor data. For an easier interpretation of orientation of smartphones, from the data gathered by the sensors, they use the World Coordinates Reference Frame. In that coordinate system the X-axis points East, the Y-axis points North and the Z-Axis is the vertical direction. The World's Coordinate Reference Frame (or Earth Reference Frame (ERF)) is shown in Figure 3.3. This coordinate system is always static independently of the orientation of the smartphone. It is really useful when a programmer wants to know the movement executed by the smartphone in relation to the World [84]. E.g., if it is not only needed to know if the smartphone rotated but also to measure the angles it rotated in relation to the World horizontal and vertical lines.

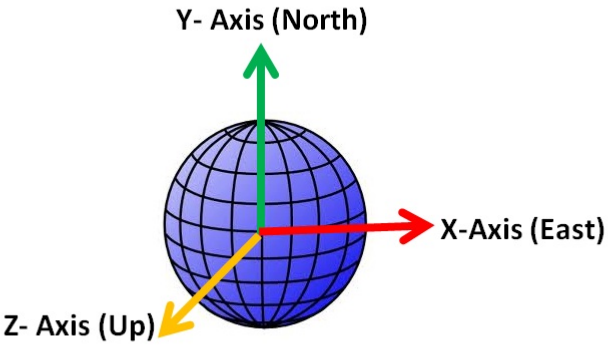

Figure 3.3: World coordinates reference frame (figure extracted from Ayub, S. et al (2012)[84]).

Euler Angles and Rotation Matrix

The Euler angles represent the rotation of each axis relative to the world frame of reference and require at least the combination of data of the accelerometer and the magnetometer to be added to a Rotation Matrix[6]. A Rotation Matrix can be built based on Euler angles, and is able to transform data received from the smartphone (i.e., in the smartphone coordinates) to the world coordinates. The Euler angles exist because of the existing principle that any rotation is defined by the combination of three successive rotations (one in each axis) [92]. The raw sensor data of the two sensors can be collected first and then added to the `getRotationMatrix` method to compute the rotation matrix. The Euler angles can be extracted

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[6] A rotation matrix is a matrix whose multiplication with a vector rotates the vector while preserving its length.

by the method getOrientation that receives as input the rotation matrix and returns the orientation angles in radians [93].

Euler angles are easy to understand but are less accurate than quartenions and are susceptible to a singularity called Gimbal Lock. That anomaly sometimes occur in the form of indistinguishability of changes of the first (yaw) and third angles (roll) when the second angle (pitch) is at some values [92]. E.g., for any pitch rotation greater than approximately 80 degrees, the yaw and roll rotation values start to increase, even without any movement realized over the Z and the Y axis, and they can't be distinguished anymore.

Quartenions and Rotation Vector

The quartenion is an alternative to represent the device orientation relative to the world [94]. A quartenion is a structure defined by q=[q1,q2,q3,q4]^T where q1 is the rotation angle and q2, q3 and q4 are the axis of rotation [95]. The rotation vector is a sensor fusion method of similar structure and is provided directly from the Android API as TYPE_ROTATION_VECTOR. Its values are calculated from the combined data of the accelerometer, the magnetometer and the gyroscope (if available) sensors. In the smartphone used in this thesis (Samsung Galaxy Nexus) the rotation vector is the result of sensor fusion made in hardware by InvenSense[7]. The rotation vector can also be converted to a rotation matrix calling the method getRotationMatrixFromVector and the orientation Euler angles can also be acquired with the method getOrientation [93]. The mandatory steps to access the values of a quartenion and to compute the Euler angles from a Rotation Matrix, that receives as input the values of the rotation vector, are shown below. The sensor service should be started and the sensor listener registered before of any sensor value change in the Android Life Cycle. Because of that, both operations were performed in the method onCreate that is the first method executed when a new Android Activity is called.

```
public void onCreate(Bundle savedInstanceState) {

         // starts the sensor service
        sensorManager=(SensorManager)getSystemService(SENSOR_SERVICE);

        // regists the rotation vector listener
        listener=sensorManager.registerListener(this,
        sensorManager.getDefaultSensor(Sensor.TYPE_ROTATION_VECTOR),
        SensorManager.SENSOR_DELAY_NORMAL);
        }
```

---

[7] http://www.invensense.com

```
// method that is triggered any time a sensor value changes
public void onSensorChanged(SensorEvent event) {

    if(event.sensor.getType()==Sensor.TYPE_ROTATION_VECTOR){

        // stores in variables the event values of the rotation vector
        // second parameter of the quartenion
        q2=event.values[0];
        // third parameter of the quartenion
        q3=event.values[1];
        // fourth parameter of the quartenion
        q4=event.values[2];

        // first parameter of the quartenion
        rotangle=Math.toDegrees(-2.0*Math.asin(Math.sqrt(
        event.values[0]*event.values[0]+event.values[1]*event.values[1]
        +event.values[2]*event.values[2])));

        // to use the quartenion method of rotation the code ends here
        // the following code is to extract the Euler angles
        // from the Rotation Matrix that receives as input the Rotation Vector

        // computation of the rotation matrix with the rotation vector values
        SensorManager.getRotationMatrixFromVector(rotMatrix, event.values);

        // stores in an array the Euler angles extracted from the rotation Matrix
        SensorManager.getOrientation(rotMatrix, orientationVals);


        // Get the Euler angles values from the array
        yaw=Math.toDegrees(orientationVals[0]);
        pitch=Math.toDegrees(orientationVals[1]);
        roll=Math.toDegrees(orientationVals[2]);
}
```

If the intention was to use accelerometer and magnetometer data directly to populate the Rotation Matrix, one listener to each sensor should be registered and the event values of both sensors sent to the Rotation Matrix, instead of those from the rotation vector.

The Rotation Vector has parameters that do not have a physical meaning and they have to have a quadratic unity norm to be considered a rotation. Using the Rotation Vector directly to determine device's orientation is slower than Euler angles but they are not prone to singularities. So it is wise to try to apply first an Euler angles method and to test if Gimbal Lock occurs in the application being developed. If it does, it is better to use the Rotation Vector directly instead [92].

3.2 Arm rotation exercises

3.2.1 Physiotherapy principles

The major conventional physiotherapeutic principles and practices that can and should be part of an upper limb stroke rehabilitation process were already presented in Section 2.2. From those, only a few can incorporate a smartphone in practice. The smartphone must be the only external device included in the therapies and for that sole reason weight bearing exercises, thermal, electric and magnetic stimulations, acupuncture, anesthesia, mirror therapy, constraint-induced therapies and bilateral arm training should be excluded from that list. So, only exercises that incorporate the remaining principles have a practical interest for this thesis and they are:

- progressive repetitive training;
- daily routine oriented exercises;
- rhythmic exercises;
- therapies that incorporate audible and/or visual feedback;
- therapies that possess a meaningful/motivational quality;
- virtual reality;
- fine motor tasks;
- repetition without repetition.

3.2.2 Biomechanics kinematics modeling

Cândido, P. et al. (2012)[96] defined biomechanics as “the science that studies the physical analysis of the movements of the human body from the point of view of mechanical laws”. To propose a rehabilitation system for the upper limbs and to talk about existing rehabilitation systems, it is wise to know the basic anatomy of an upper limb and to do a preliminary study of the basic movements it can carry out. From the perspective of this thesis, a correct placement of the smartphone is essential to not limit the movements of the patients and to gather the most appropriate data of the upper extremity movements to the application.

The term “upper limb” was used instead of the word “arm”, in the previous paragraph, because it has a different meaning. Anatomically speaking, an “arm” is not an entire upper limb, it is only the segment between the shoulder and the elbow. The segment between the elbow and the wrist is denoted by “forearm”. The arm and the forearm are covered by muscles in all their extent. The upper limb anatomy is shown in Figure 3.4. The ratio of the arm to the forearm plus hand is approximately 1 to 1.618 [97]. The same ratio is observed between the hand and the forearm [97, 98].

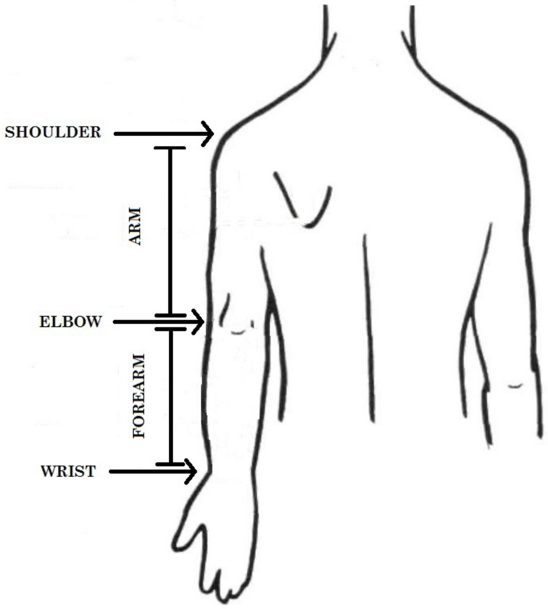


Figure 3.4: Upper limb anatomy (figure adapted from Taylor, C. (1955)[99]).

All of the following movements that will be explained, consider the most neutral/natural position of the upper limb (the position where it is not exerted any force to move it) as the initial position before any kind of movement. That initial position of the upper limbs is presented in Figure 3.5.

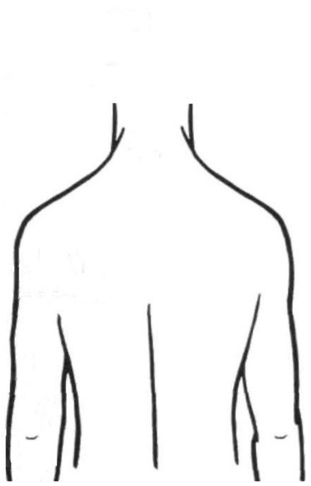


Figure 3.5: Neutral position of the upper limbs (figure adapted from Taylor, C. (1955)[99]).

There are two basic types of movements the shoulder can fulfill. It can be elevated or depressed (lowered) in a forty or ten degrees angles, respectively and it can be flexed onward or extended backward in twenty or fifteen degrees. That movements can be seen in Figure 3.6.

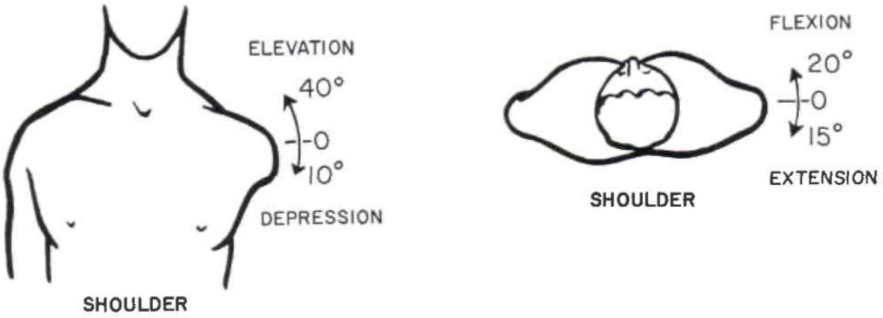


Figure 3.6: Basic shoulder movements (figure extracted from Taylor, C. (1955)[99]).

The arm and the forearm can both execute more types of movements than the shoulder. The arm can perform six different types of movements and the forearm can do four. An individual can also elevate or depress an arm. The elevation can be done to the maximum extent of 180 degrees and the depression can only be fulfilled in a 20 degrees range. An arm can also be flexed in 180 degrees or extended in 60 degrees. A flexion is not more than an frontal elevation and an extension a rear elevation. The medial (counterclockwise) and lateral (clockwise) rotations are also movements that can be carried out with an arm. They can be performed in an extent of 90 degrees (the medial rotation) and 20 degrees (the lateral rotation). These two types of rotations can be done with the forearm too, but they have different anatomical names. They are called pronation (counterclockwise rotation) and supination (clockwise rotation). The pronation can be done at a maximum of 90 degrees and the supination in 80 degrees. As the arm, the forearm can also be flexed or extended, but does that within a less amplitude. The flexion can be done until a 140 degrees. The extension is exactly the opposite motion of the flexion, so if the arm is already naturally extended, it can be said it is performed with the range of 0 degrees. Figure 3.7 shows all of the movements explained in this paragraph [99].

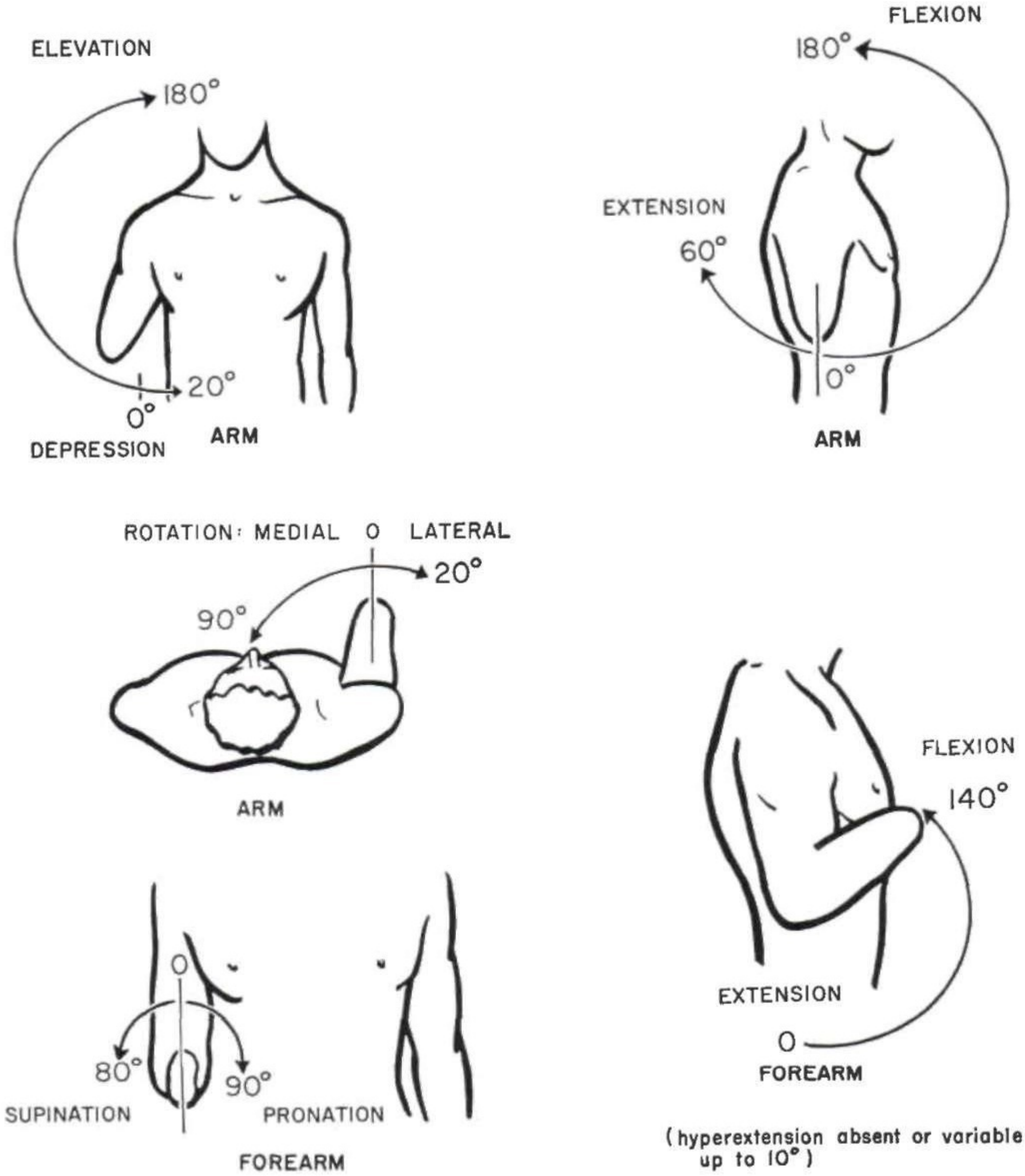


Figure 3.7: Basic arm and forearm movements (figure extracted from Taylor, C. (1955)[99]).

3.2.3 Possible exercises

The presented physiotherapy principles/practices, still allow the execution of some beneficial exercises for stroke victims. Some examples of exercises are: grasping objects of different dimensions, stretching the arms, moving something and trying to reach for something. Others may be extension/flexion or pronation/supination of the wrist, flexion of the elbow and flexion/extension, rotation and elevation/retraction of the shoulder, fisting of the hand and trunk balance exercises. Activities such as taking care of personal hygiene, brushing, playing cards or fine motor tasks can also play an important role in patients' recovery and be explored in games and/or virtual reality applications.

When a mechanical approach, such as the armeo therapy, is considered, the medial and lateral rotation of the forearm and of the arm and the flexion and extension of the arm can also be observed. When an extensive research within the most common assessment scales is executed, the evaluation of how much patients can elevate and retract the shoulder and how well they can pronate and supinate the forearm from different starting positions is also evaluated (e.g. in the Fugl-Meyer Assessment of Upper and Lower Extremity Motor Function[100]). The contact with a Hospital Pedro Hispano stroke physiotherapist confirmed that those movements must be rehabilitated and that forearm supination exercises are, among all exercises, the ones where patients achieve some of the quickest recovery rates.

3.2.4 Technology limitations and the choice of exercises

Movements that involve the measurement of an accurate distance, such as grasping or trying to reach for something, can't be properly implemented using only the available sensors of today's smartphones. Meters accuracy can be easily achieved, decimeters precision may be obtained approximately close to the exact values, but when centimeters or precision with more decimal cases is wanted, smartphone sensors fail relatively short because double integration of acceleration is required. Only movements that can be evaluated in angles of rotation can be perfectly assessed. Any exercise of the type extension, flexion, pronation, supination, elevation or depression can be correctly and accurately evaluated by a smartphone if it is attached to the segment of the body that is being rehabilitated.

The choice of exercises to the rehabilitation application was made according to:

- The capabilities of the smartphone hardware (sensors);
- The number of available smartphones (only one);
- The effectiveness of the exercise in the patient's outcome;
- The impossibility of patient's compensation of the assessed movement with an incorrect movement;
- The completeness, in regards of achieving the most different possible types of exercises, of the rehabilitation application.

The first choice was the supination/pronation of the forearm. This exercise was chosen because, like stated earlier, it is one exercise where patients achieve good and fast improvements. This also improves motivation. Patients can't also anatomically compensate the movement with other muscles, what makes the detection of incorrect movements fairly easier. That is important because the smartphone can only detect movements of the segment of the body it is attached to, e.g., if it is placed in the forearm and the wrist rotates, the smartphone can't detect that movement because it doesn't move accordingly. That situation is illustrated in Figure 3.8.

Figure 3.8: Wrist rotation to the left and to the right that can not be detected by the smartphone placed on the forearm.

The second and third exercises that were chosen were the flexion/extension and the medial/lateral rotation of the forearm. Both exercises can be compensated with the upper arm, but either way, the possible compensations are also valid and useful physiotherapeutic exercises. They are simple to evaluate with a smartphone and with them included, the rehabilitation application treats movements in all axis of rotation. All of technology limits and possible exercises were discussed in the presence of the therapist. The input he gave contributed immensely to the final choices. All of these exercises can be properly assessed by the smartphone attached to the forearm, in the same position.

3.3 Prototype Architecture

When a player performs physiotherapeutic exercises with a smartphone attached to the forearm, he or she keeps loosing track of the screen of the smartphone and looses important feedback. In order to provide appropriate feedback to the patients, the prototype requires client and server components. The smartphone works as a sensor and the games are run in the server and displayed on its monitor. That component should be a desktop/laptop because personal computers are really massified and already present in people's lifes for quite a few time now, avoiding the need of acquiring a specific device to perform physiotherapy. Most of them are also able to run this application with ease. The client is an Android smartphone. Each one has different components and duties in the application. The client side has the GUI, the sensors data extraction algorithm and Calibration Screens that gather the maximum capabilities of each patient to be used in the games. The server component incorporates the Game Engines, the Logging of patients performance in games and a simple GUI. If it has an available Wifi/GPRS/Ethernet connection to the Internet, the application sends data about patients' performance to a therapist. Both the client and server sides will be explained in detail in the following sections. The connection between the client and server components is made via bluetooth. An illustration of the prototype architecture is shown in Figure 3.9.

Figure 3.9: Prototype Architecture.

At the client side the smartphone used was a Samsung Galaxy Nexus with Android 4.2.2 and the bluetooth version was the 3rd. All of the graphical user interface was developed in individual xml (version 1) files. At the server side, the GUI was developed with the package javax.swing and the game engines with LWJGL (Lightweight Java Game Library). The logging was made directly in Java code. All code was developed in Eclipse 3.7.2 Indigo.

3.3.1 Bluetooth Connection

Wifi connections are really massified but the work being developed in this thesis is aiming to target a even broader audience. In the times we live in, there are still some people who do not have a wifi connection at home. Bluetooth exists in almost every computer. Even if it is not available in a certain computer, bluetooth adapters can be acquired for a really cheap price.

The creation of a bluetooth connection between an Android smartphone and a personal computer needs, just like any other connection, a client side and a server side. The client here is the Android smartphone and the server a laptop/desktop computer with a Java program running. The connection needs an UUID[8] and the mac address of the bluetooth card/adapter of the server. The Android developers webpage[9] recommends the use of the UUID `00001101−0000−1000−8000−00805F9B34FB` in this case scenario. To establish a connection in the Android API, there is only needed to create a socket using the method `createRfcommSocketToServiceRecord()` associated with the UUID of the connection as argument.

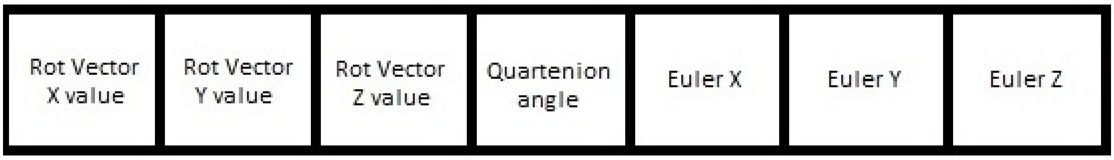
---

[8] UUID is a representation of a 128-bit and stands for Universally Unique IDentifier.

[9] http://developer.android.com/reference/android/bluetooth/BluetoothDevice.html

The connection on the server side is established using the method StreamConnectionNotifier.open( ) on a URI of the form *“*btspp:*//localhost:” + uuid +“;name=Name of the Server”.* After that, if there is a connection, it must be accepted with the method acceptAndOpen(). To send data from the Android smartphone, a byte[] sequence must be written to the outputstream of the socket and to receive it, in the server side, the inputstream of the connection already open must be read and the byte[] sequence converted to a human readable format, such as a sequence of Floats.

The message sent starts with the 3 rotation Vector components and the first angle of a quartenion. The Euler angles of which axis end the stream. The Message format is shown in Fig 3.10.



Rot Vector X value	Rot Vector Y value	Rot Vector Z value	Quartenion angle	Euler X	Euler Y	Euler Z

Figure 3.10: Message format.

In this work, the used version of bluetooth is the third because the Android core API doesn't support the fourth version, yet. At this moment in time and even though smartphones are already hitting the stores with bluetooth 4 compatible hardware, the version 4 (low energy) is working only with third party libraries supplied by the smartphone manufacturer. The smartphone used in this thesis is the Samsung Galaxy Nexus and it is does not have official bluetooth 4 support from Samsung.

3.3.2 Client Side

GUI

The graphical user interface could have been created in Java, but it was created entirely in xml files. The development of the GUI in the xml files allowed a separation from the code of the interface and of the actual code of the application. The xml version used was the 1st and the encoding “utf-8”. The Android API provides different layouts that can be used. The layout used in all Android activities was the TableLayout and the different graphical elements were grouped in rows..

Android Sensor Data Retrieving

To test what is or what are the best sensor(s) to evaluate certain movements, the values collected by the sensors were saved to a file and a small Python script was ran to visualize their data with a line chart. An example of one of those charts can be seen in Figure 3.11. This example is related to the raw data extracted from the gravity sensor (a low-pass filter applied to the accelerometer) while the smartphone was rotated over the Y axis. The green line represents the force of gravity in the Y axis and the red and blue lines the acceleration of gravity in the Z and X axis respectively.

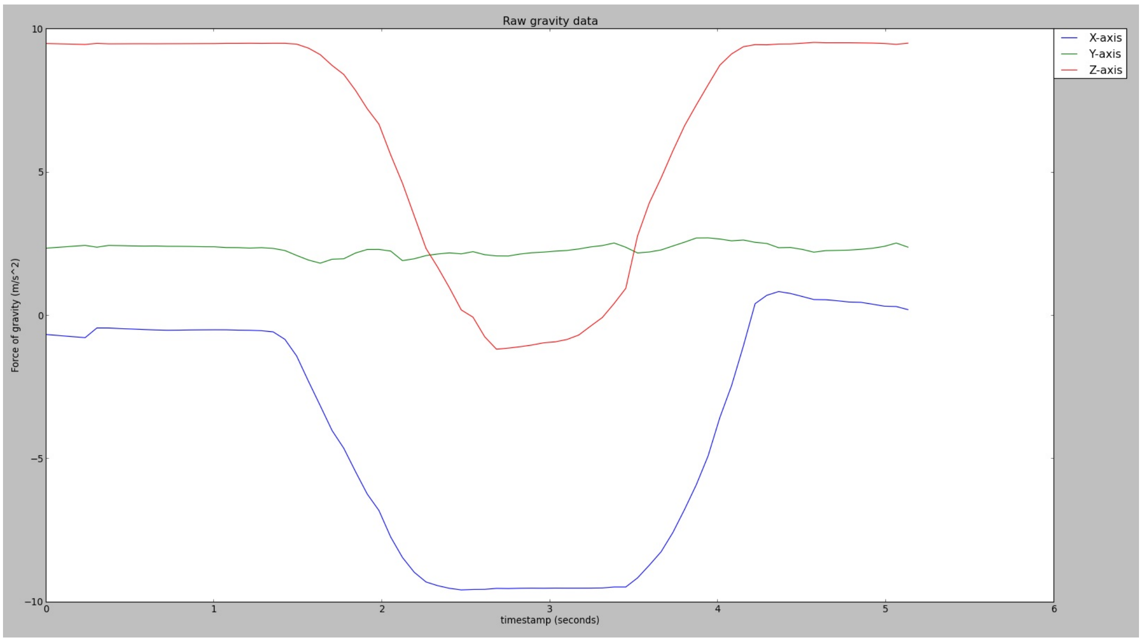


Figure 3.11: Line chart of raw gravity data.

The sensor delay rate used in the application is always the `Normal` speed. It is more that enough to a responsive action on the screen. If a faster mode of data retrieving is used, the 3D models of the Server component always take a little time to stabilize before they begin to move smoothly and in line with the smartphone movement. There is also another problem involving choosing faster gathering speeds, such as Game or Fastest. The bluetooth connection is dropped after a few minutes, if the data from the sensors is being sent at a faster speed than the Normal delay rate. To test how many samples are collected from a sensor, at Normal speed, the data of the accelerometer was saved to a file with the correspondent timestamp. With just smooth movements, the smartphone used (a Samsung Galaxy Nexus) collected 154 samples in only 10 seconds. That is close to a frequency of 15 Hertzs. If the smartphone remained still on a table, the sensor rate would be slower, because the event that produces each sample is the method `onSensorChanged`. That name appears from the fact that, sensor values update only when there is a change in their values. With the smartphone still on the table, the only values that would be being gathered would be noise from the sensor.

Android calibration

It was decided to develop the rehabilitation prototype in the form of a few games that can increase motivation and positively influence patient's recovery. These games will be controlled by the smartphone and will be displayed on the server monitor.

In the application, the first screen that appears is the main menu. It allows patients to choose which game they want to play. A print screen of the main menu, taken with the smartphone, is presented in Figure 3.12.

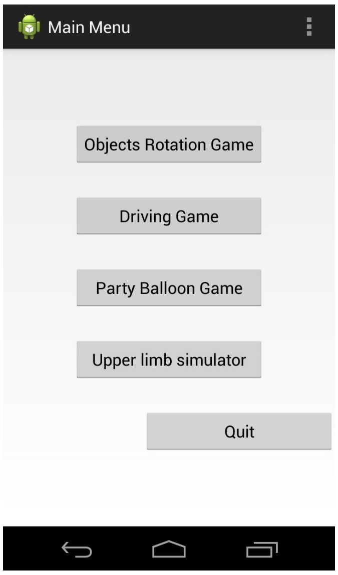


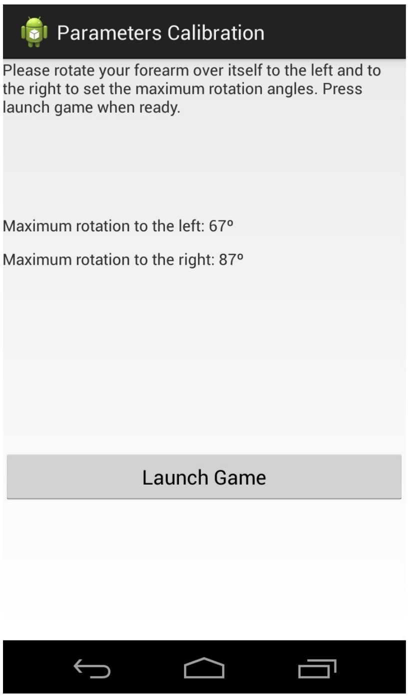
Figure 3.12: Application Main Menu.

Before rushing into games, the patient has to follow some instructions given by the smartphone client side of the application. They instruct the patient how he or she should attach the smartphone to the forearm with the help of a bracelet. A screen capture of that screen is shown on Figure 3.13.

Please place the smarpthone on the forearm with the screen pointing upwards and the palm of your hand pointing downwards as shown in the picture. Press 'Next' when ready.

Figure 3.13: Application instructions screen.

When the patient presses the 'Next' button a calibration screen appears. That screen depends on the game the patient chose on the main menu. The calibration phase is really important because that's when the application adapts the game's difficulty, to the patient's impairment, ensuring a proper physiotherapy that's adapted to each individual. It sets the maximum range of rotation, in degrees Celsius (rounded to the nearest unit), a patient can execute in a certain axis, in both ways. The axis of rotation it evaluates depends on the game already chosen. If it is the “Objects Rotation Game”, Roll rotations (pronation/supination exercises) are evaluated, if it is the “Driving Game”, Yaw rotations (medial and lateral rotations) are evaluated and if the chosen game is the “Party Balloon Game”, the Pitch rotations (flexion/extension movements) are evaluated. Each calibration screen contains the appropriate instructions, of the movement that should be executed, for the patient the follow. It also evaluates in real time the maximum rotation executed for each side. An example of one of these screens, is the calibration for the “Objects Rotation Game”, that is illustrated in Figure 3.14. After placing the bracelet in the forearm as instructed, the patient should rotate the forearm as in Figure 3.15.



Please rotate your forearm over itself to the left and to the right to set the maximum rotation angles. Press launch game when ready.

Maximum rotation to the left: 67º

Maximum rotation to the right: 87º

Figure 3.14: Application instructions screen.

Figure 3.15: Left and right rotations over the Y axis.

Three different approaches can be used to implement the assessment of the maximum amplitude of rotation. One of them uses one sensor only, other uses two and a third one uses two or three sensors (if the smartphone has a built-in gyroscope). Although it is wise to test the lowest number of sensors that can be used to effectively program and save battery life, the calibration screens are used for only a few seconds and the precision of measurements is greatly improved with the use of more sensors. In this application and in all calibration screens, Euler angles that are extracted from a rotation matrix that receives the data from the rotation vector are used.

The base of all games are the calibration screens. They are really important tools that establish the difficulty of each game. If they are not measuring the angles accurately, they can be ruining the whole smartphone rehabilitation concept of this application. To correctly validate those screens, one rotation over all different axis were executed and a photo of the initial and final positions were taken. After each rotation the smartphone is returned to the initial position. In those pictures, the real angle of rotation is measured and is readily compared with the value of rotation the smartphone shows on the screen. All photos were shot from a fixed spot, with the help of a tripod and all angles were measured in the photos with the software MB-Ruler[10].

To measure the rotation over the Y axis, the smartphone was placed with its back on a table, in the same position as in the calibration screen of the "Objects Rotation Game", and was slightly rotated to the right. Figure 3.16 shows the initial position of the smartphone and Figure 3.17 illustrates how much it was rotated.

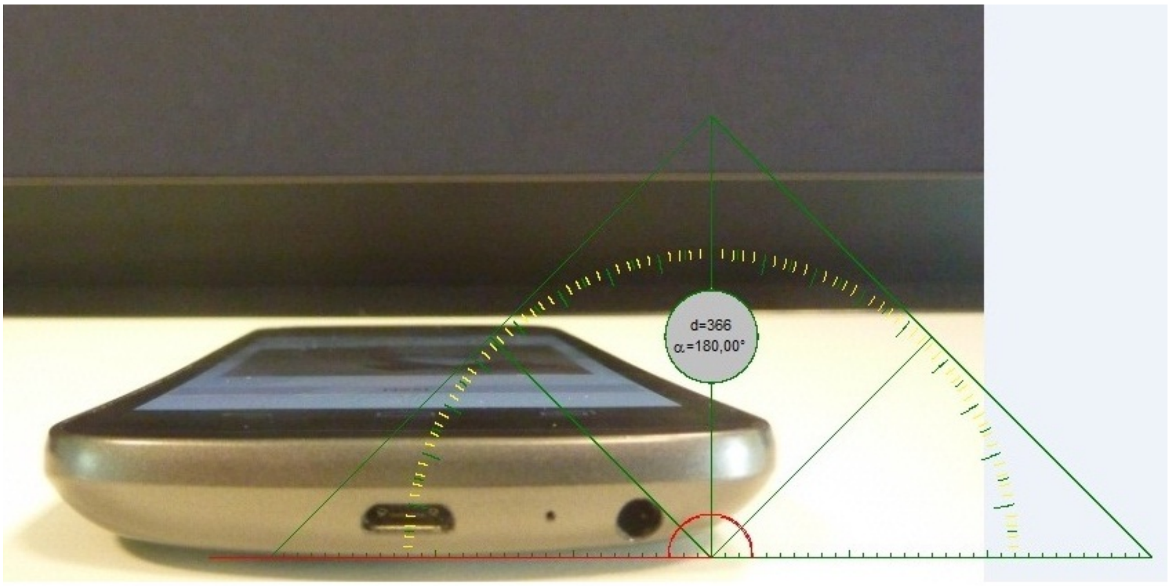


Figure 3.16: Initial position before a rotation over Y.

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[10] http://www.markus-bader.de/MB-Ruler

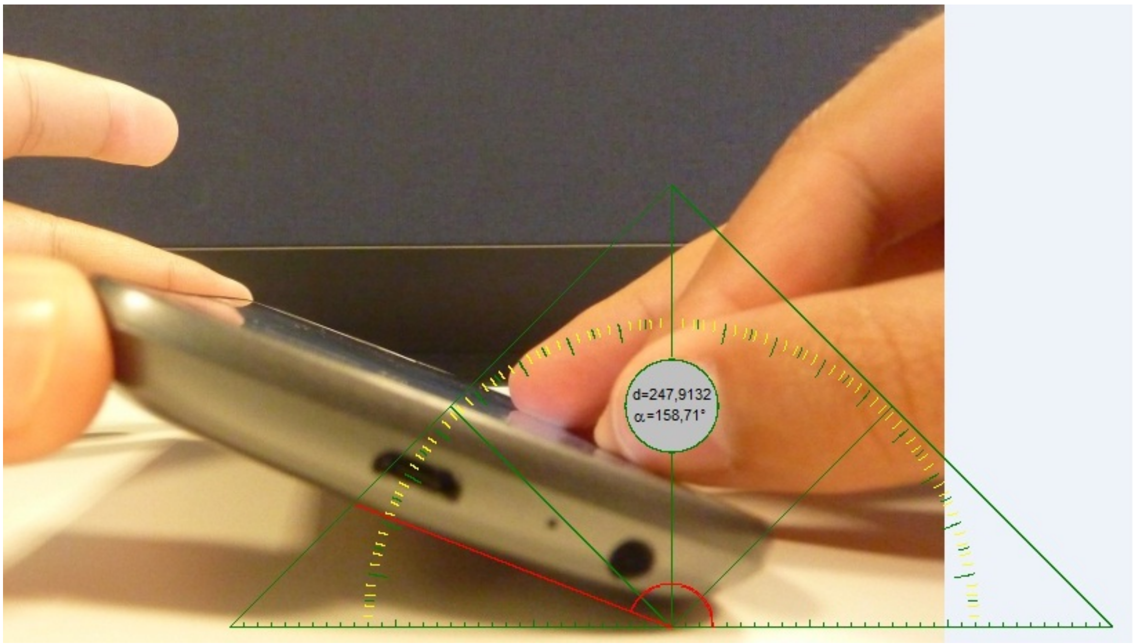
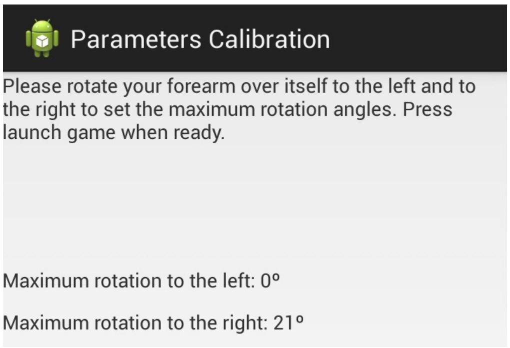


Figure 3.17: Spot where the maximum rotation to the right was reached.

At the initial position, the center of the bottom of the smartphone was exactly in one of the green lines of reference of MB-Ruler, i.e., at 180 degrees. When it rotated, the angle measured is of 158,71 degrees. That means the smartphone rotated approximately 21 degrees. That's exactly the maximum amplitude of rotation the smartphone detected to the right. That can be seen in Figure 3.18.



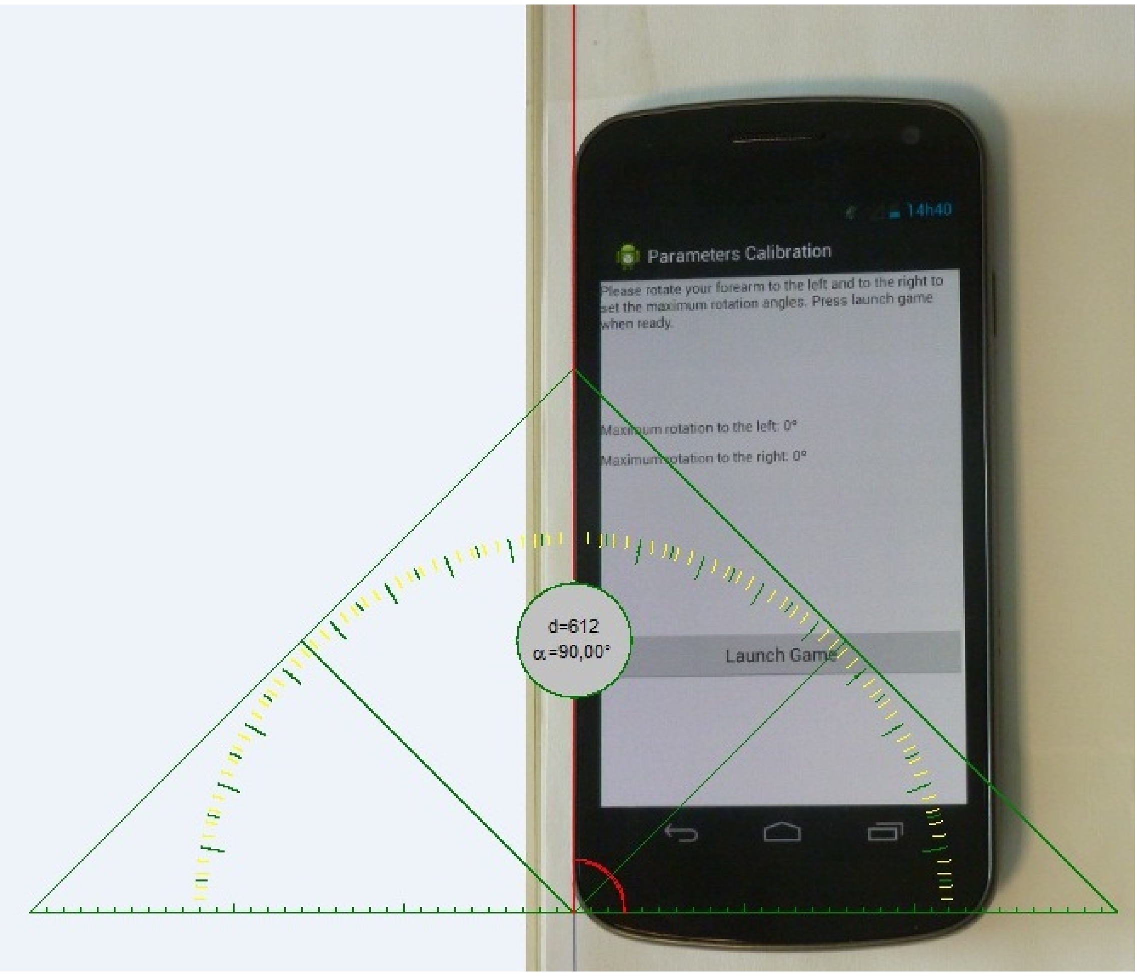
Please rotate your forearm over itself to the left and to the right to set the maximum rotation angles. Press launch game when ready.

Maximum rotation to the left: 0°

Maximum rotation to the right: 21°

Figure 3.18: Maximum rotation to the right measured by the smartphone at the first experiment.

The second experiment was made to evaluate the rotation over the Z axis, that is measured in the calibration screen of the "Driving Game". In the first experiment, the smartphone had a natural line of reference, the table, but to evaluate the rotation over the Z axis, the introduction of an exterior line of reference was required. To do that, a page that contained only a vertical line was impressed. The smartphone was placed in contact with that line and it became the reference of the initial position. That can be seen in Figure 3.19. The smartphone was rotated to the right and a second photo was shot. The final position of the smartphone can be seen in Figure 3.20.

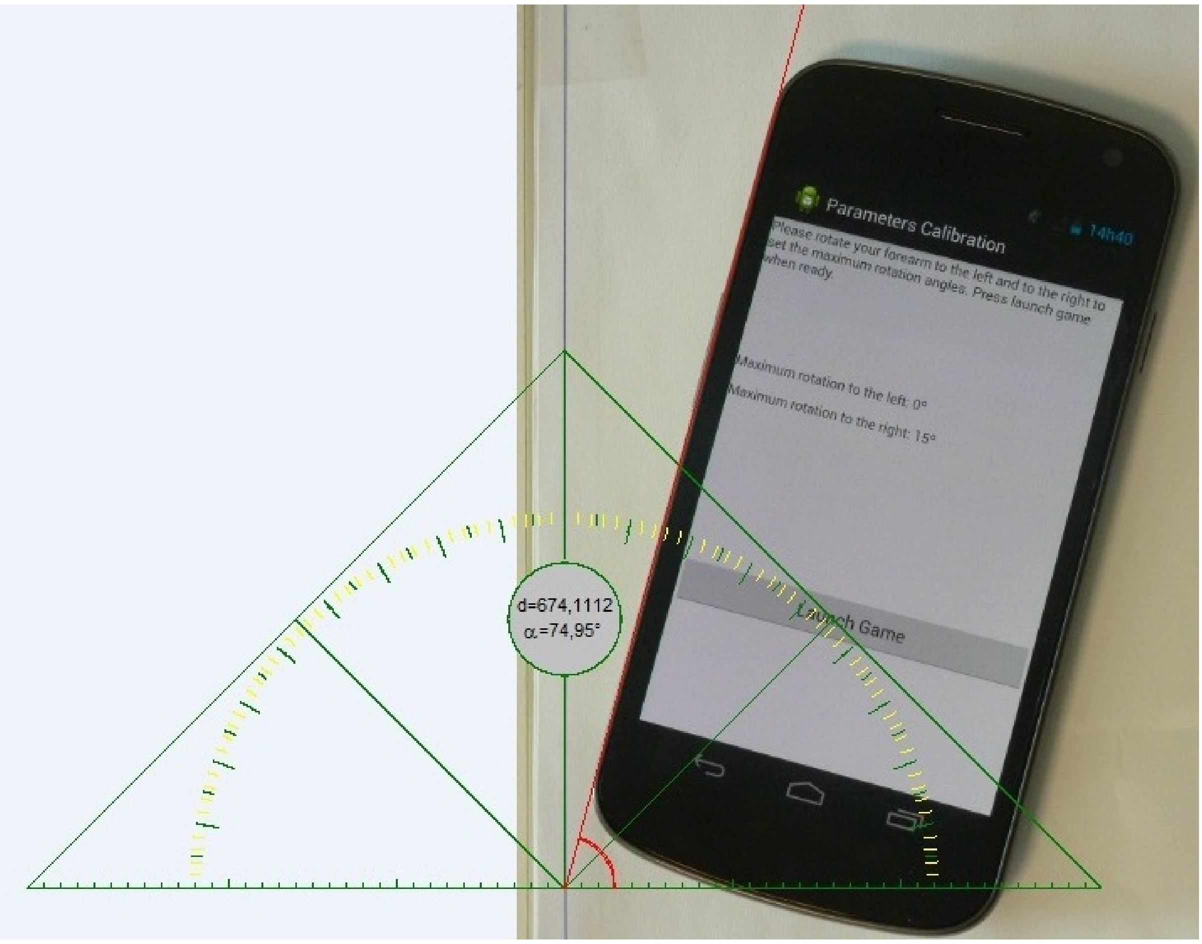


Please rotate your forearm to the left and to the right to set the maximum rotation angles. Press launch game when ready.

Maximum rotation to the left: 0°

Maximum rotation to the right: 0°

Figure 3.19: Initial position before a rotation over Z.



Please rotate your forearm to the left and to the right to set the maximum rotation angles. Press launch game when ready.

Maximum rotation to the left: 0°

Maximum rotation to the right: 15°

Figure 3.20: Photo of the maximum rotation to the right in Z.

Both photos are self-explanatory. The smartphone rotated from 90 to 74,95 degrees Celsius. That makes it approximately 15 degrees of rotation and that is exactly what was measured by the smartphone.

The calibration screen of the "Party Ballon Game" was also assessed with the smartphone lying down on a table. The horizontal reference is the table and the smartphone is rotated downwards (the bottom of the smartphone is rotated upwards). The smartphone has a round surface that made the settlement of the initial reference harder, but the same point was evaluated in the initial position and after the rotation. The defined initial position is shown in Figure 3.21 and the final rotation in Figure 3.22.

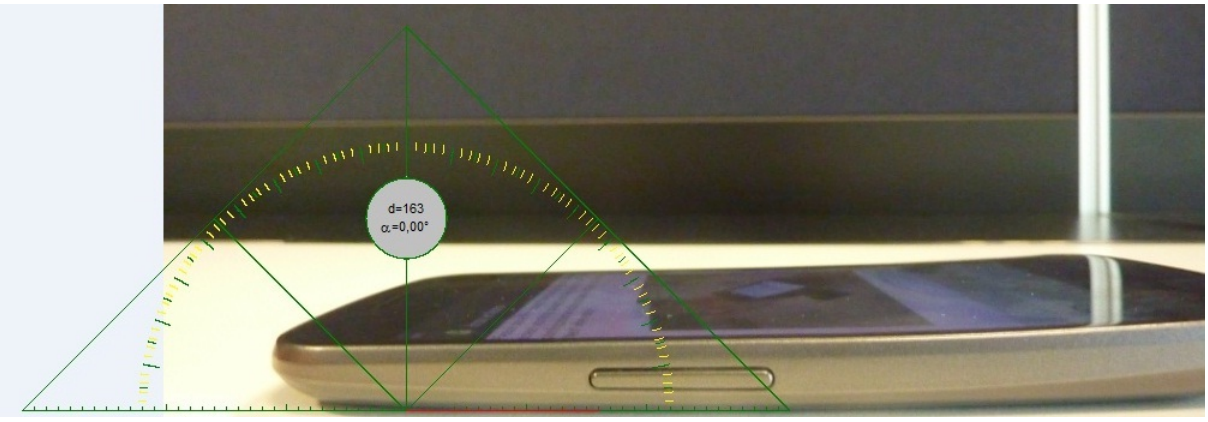


Figure 3.21: Initial position of the smartphone before a downward rotation.

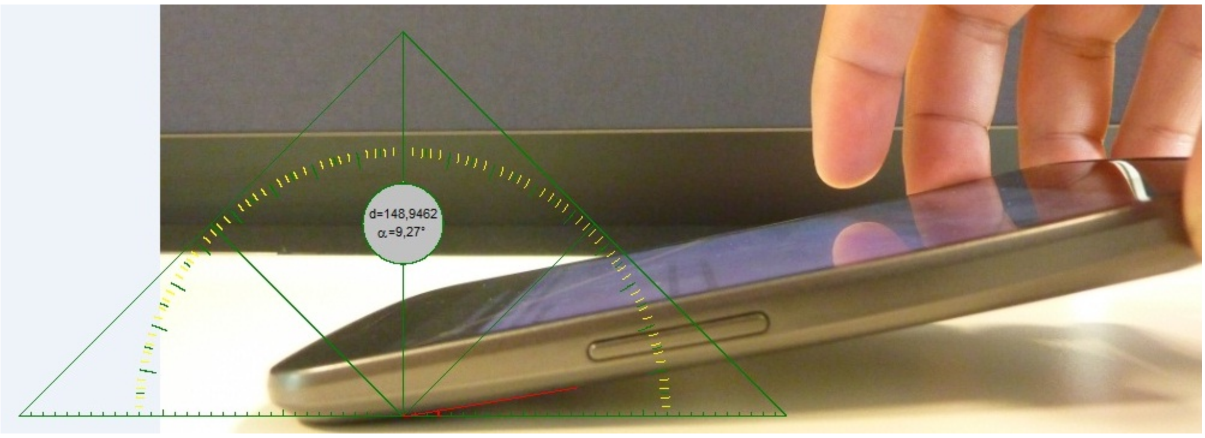
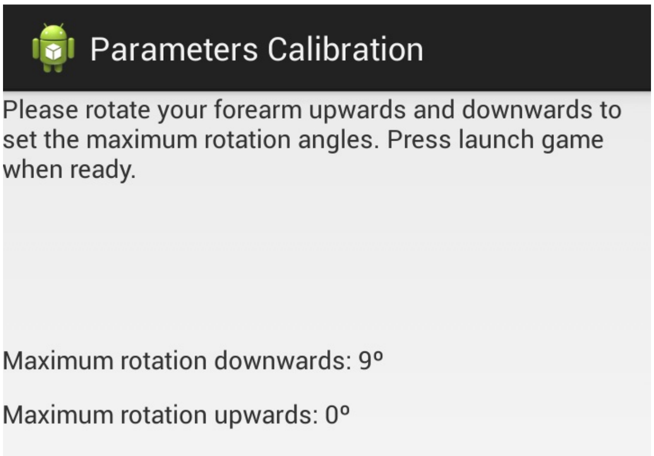


Figure 3.22: Final position of the smartphone after a rotation over the X axis.

MB-Ruler marked about 9,27 degrees of rotation in the X axis and a screenshot of the smartphone showed 9 degrees Celsius of maximum rotation. That can be seen in Figure 3.23



Parameters Calibration

Please rotate your forearm upwards and downwards to set the maximum rotation angles. Press launch game when ready.

Maximum rotation downwards: 9º

Maximum rotation upwards: 0º

Figure 3.23: The smartphone sensors measured the maximum rotation downwards of 9 degrees.

In spite of only the best tries of all 3 experiments have been considered, they might still be susceptible to some minor errors caused by hand trembling and by some lack of precision (perhaps on the experiment over the X axis). However, for this type of application, the values measured by the smartphone didn't need to be exactly correspondent to reality. Even if they deviated two or three degrees from the exact value, it wouldn't make no difference in the recovery of the patient. In this case and even with a little deviation that could be happening but that doesn't appear to be there, the measurements of the smartphone are showing excellent results.

3.3.3 Server Side

Simulator

The simulator runs effectively with the smartphone attached to the forearm or to the upper arm. In that case, a model that could resemble a segment of a real upper limb, on virtual reality, would be appropriate.

The application incorporates a simulator that contains a 3D model of a segment of an arm, where different rotation methods can be tested. The visual interface of the simulator, allows the choice of rotating over each individual axis or over all of them at the same time. This simulation is important because it validates visually, the implemented rotation methods in the 3 axis.

Initially, an attempt to reproduce movements of an upper limb, representing the two segments (forearm and arm) was made. The increased difficulty of doing that effectively is the fact that the smartphone is placed in only one segment of the upper limb and the other segment has to be virtually reproduced. What was thought to be possible was to reproduce only certain movements, that could be the only ones a person could do if on a certain position. The range of movements anyone can execute depends on the position he or she is on and they can be easily limited if a starting position to run the simulator is imposed. That attempt used an elbow represented with an articulation with 2 DOF (DOF stands for degrees of freedom and the 2 means only two axis of rotation available) and a shoulder with 3 DOFs (rotations available in all axis). The forearm was moving fine by itself because the smartphone was attached to it. The problem was on the upper limb. The following problems occurred:

- it is not possible to detect when an arm is stretched with only one smartphone;
- it can be simulated with an angle that works as a threshold but not on the full range of motion;
- the upper limb can't move in a realistic manner because of Gimbal lock.

The first two were already explained when the choice of exercises were made, but the third needs an enlightenment. To be realistic, the arm should pronate/supinate slightly when the forearm executes a medial/lateral rotation. That is easily implemented, but if the forearm is flexed to more than 80 degrees, Gimbal lock occurs and the arm starts to rotate, when it shouldn't be moving. In other applications, that do not need certain movements, a simulator like this could be implemented, but that is not the case of this application, where certain important physiotherapeutic movements, like the flexion of the forearm, can't be reproduced.

Considering only what can be done, the final simulator resulted in a single segment that started on the shoulder and that ended on the hand. That segment is when the already explained rotation methods are tested. The representation of the arm, used in the simulator, can be seen on Figure 3.24.

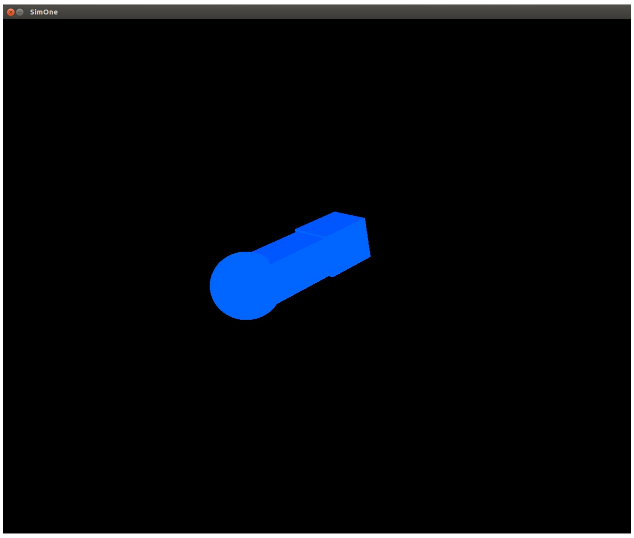


Figure 3.24: Simulator arm moving on the screen.

3D Models

How fast and which sensors are being used to move the models in the application, were already explained. What was not told was, which models are being moved. The intention is to reproduce on the screen what is really happening in reality, so the creation of a 3D representation was needed. A search for the possible Java solutions were carried out. To create 3D graphics on the screen, the first choice was the Java2D API. It was chosen because it is easier to use than the Java3D and OpenGL alternatives, to anyone who doesn't have any experience with any of them. Drawing in 3D could be easily simulated with 2D lines, but representing 3D rotations were not what a 2D API would do easily. After a few days of tests, it became obvious that a change of direction was necessary. The next step was the Java3D API[11]. It is really easy to use but the same problem was being faced, the 3D rotations. They could be done, but were not that intuitive and like it was stated before, the physiotherapy with a smartphone is really dependent on them. Because of that, the supervisor of the project decided it was better to use OpenGL instead. In the short run, with only a few days of work, it was easily verified that OpenGL rotation methods were really the simplest to use so far. Facing that evidence, LWJGL (a lightweight OpenGL Java game library)[12] became the final choice in this project.

There are several ways of creating 3D models. Polygons can be used to quickly draw geometric figures and are useful in situations where it isn't needed a realistic representation

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[11] http://www.java3d.org

[12] http://www.lwjgl.org

of real life. The simulator of this application is only used to test rotation methods and no patient will ever use it in physiotherapy. In this case, a polygon representation is quick to draw and there is no need for anything more real. The representation on the screen, just has to give a general idea, of an arm moving, to the programmer.

In the rehabilitation games, instead of drawing, it was decided to import already created models. These models can be created in softwares like Maya[13] or Blender[14] and most of them are a lot more realistic than what could be drawn quickly. There is no need to "re-invent the wheel" if existing models can be used. That could easily become a really time consuming task that is not the main goal of this thesis. To incorporate them in game, a parser of .obj files was created. This extension of models was chosen because they are a common exported file type of 3D modeling software. They have several types of definitions such as vertices, normals of the vertices and faces. Each line starts with a letter or with a pair of letters that are short names of those definitions, and are followed by the coordinates of where they are drawn on the screen. In this project there was no need to use texturized models, so they were discarded.

Euler angles and quartenions

When it is necessary to rotate over only one axis, the Euler angles were used because they get the job done in a really simple way. They were extracted by the method `getOrientation` that receives as input the rotation vector. To use them, it is only needed to call the method `glRotate`. In this application the floating point version of that method is used. The call of it is `glRotatef(angle, axisx, axisy, axisz)`. The method receives as input the Euler angle and the proportion that each axis rotates from that angle, with two decimal cases from 0 to 1. E.g., if it is wanted to rotate 90 degrees over the Z axis, it just has to be called `glRotatef(90, 0, 0, 1)`. When there is a need to rotate over all axis, using the rotation vector directly is a better choice because of the lack of singularities.

In the games that incorporate the chosen physiotherapeutic exercises, the methods of rotation used are the methods tested in the simulator. The only exception, is the "Objects Rotation Game", where the rotation over all axis is executed with Euler angles because it's needed to always compare the current angle to the initial angle, for the action to always occur on the center of the screen. The singularity doesn't happen in game, because the dangerous angles are never reached. The user doesn't need to rotate that much to move the model on the screen, and even if it decides to do it, it doesn't matter because the model stays locked at the border of the screen.

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[13] http://www.autodesk.com/products/autodesk-maya/overview

[14] http://www.blender.org

Like mentioned earlier, the euler angles and the rotation vector are both represented relative to the World Coordinates Reference Frame. The representation of models in OpenGL, uses the same coordinate system [101]. That system of coordinates is shown in Figure 3.25.

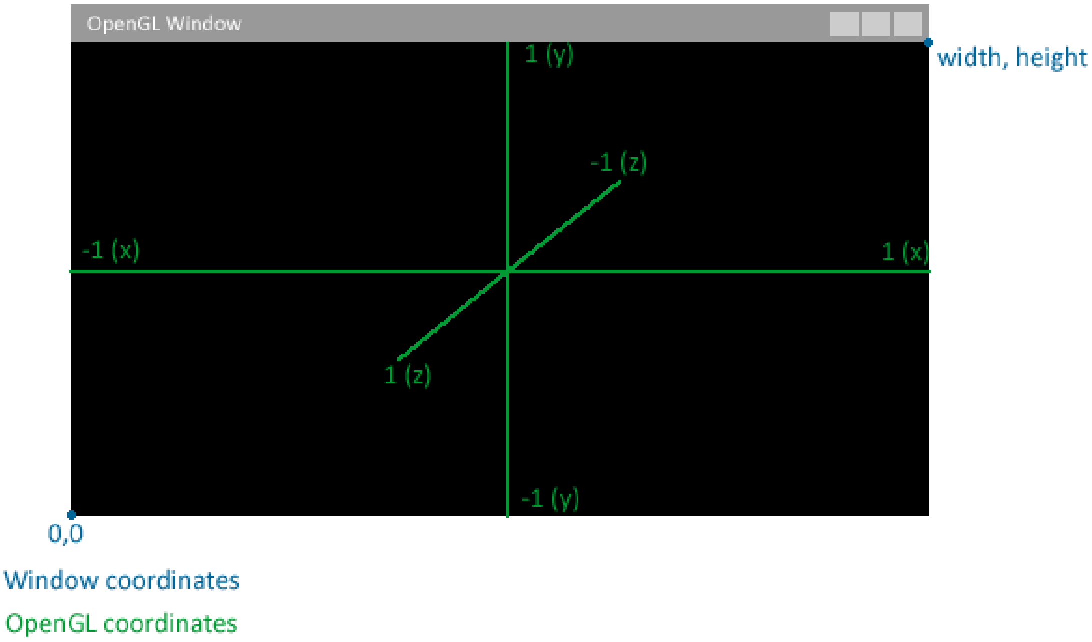
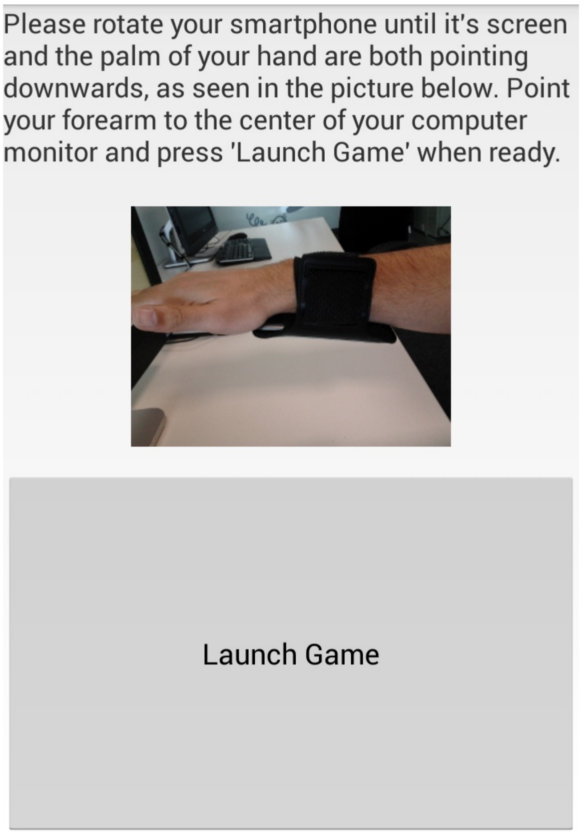


Figure 3.25: OpenGL coordinate system (figure extracted from the LWJGL Wiki[101]).

Objects Rotation Game

This game incorporates medial and lateral rotations, flexion and extension movements, supination and pronation of the forearm and even includes fine motor tasks. It constitutes the first real evidence that the concept of smartphone based tele-rehabilitation works and has potential to be implemented in practical work. This game is also one of the most complete games, that can be created specifically to the rehabilitation of stroke because it demands movements in all axis from the patient.

To be played, right after the calibration screen, the patient has to rotate the smartphone in the forearm until its screen and the palm of his/her hand are both pointing downwards. When the smartphone is in that position, the patient has to point the forearm to the center of the computer monitor and press the "Launch Game" button. The next step after calibration is a screen that explains all those steps for who is playing the game. A screenshot from that screen is shown in Figure 3.26.



Please rotate your smartphone until it's screen and the palm of your hand are both pointing downwards, as seen in the picture below. Point your forearm to the center of your computer monitor and press 'Launch Game' when ready.

Figure 3.26: "Objects Rotation Game" smartphone placement instructions.

As the smartphone is upside down, when the button to launch the game needs to be pressed, an appropriate size of the button to facilitate that action and a notorious bip sound to give feedback to the user were taken into consideration and introduced in this screen. The game begins with a hand model representing the patient's hand, in the center of the screen. In it, three different randomly selected objects appear (a door, a bird's cage and an waterer). Taking in consideration the therapist feedback, the models chosen were real objects that the patient can find in his daily routine. To make progress in the game, the patient has to place the hand on top of the model on the screen and rotate the wrist over itself. The door and the cage must be opened and the water from the waterer must be dumped. The door and the cage open with the maximum calibrated rotation to the right and the waterer disappears only when it is rotated with the maximum previously set rotation to the left. Anytime that happens, the model on the screen disappears and other model is rendered. This game deliberately demands for more rotations to the right than to the left because patients generally have more difficulties in the supination of the wrist than in the pronation exercise. In the beginning of the game the score is 0 and for each successful rotation 1 point is added to the score of the player. All models of the game can be seen in Figure 3.27:

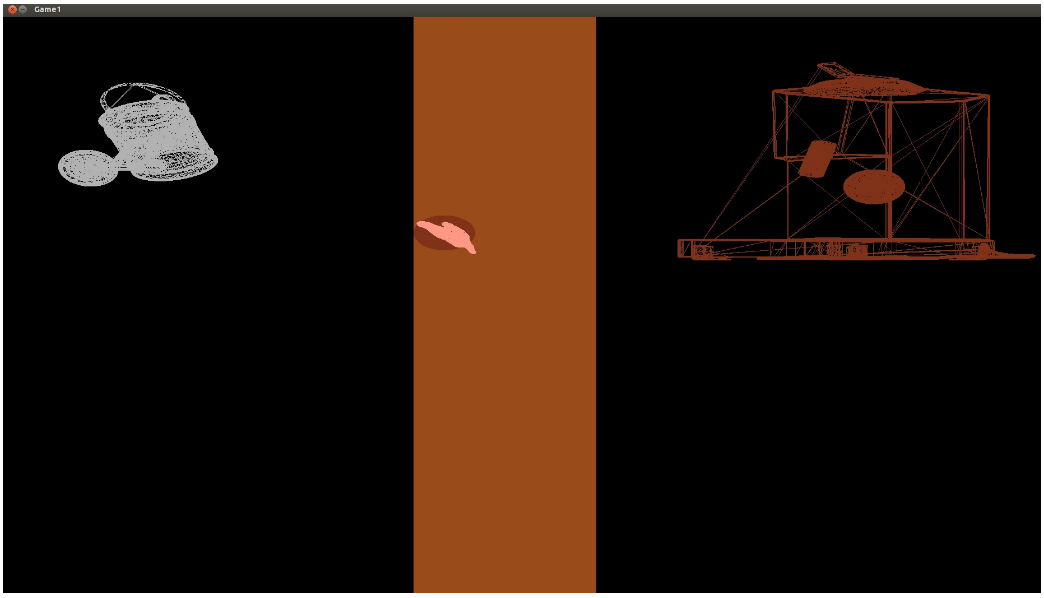
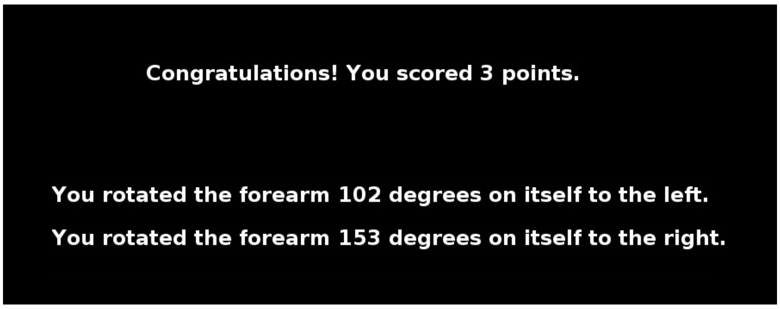


Figure 3.27: Visual interface of the "Objects Rotation Game".

The hand model rotations over the Y axis are a reproduction of the rotations from the real hand and the smartphone aligned with the horizontal line is considered the initial position (where the application assesses 0 degrees of rotation). When a patient reaches the needed amount of rotation to surpass an object, a sound that most resembles that movement is played. E.g., when the door is opened, a sound of a door being opened is heard. The game ends after 60 seconds. When the time ends, the score of the patient and the maximum rotation degrees he/she could execute over the forearm to the left and to the right is displayed. An example of that final screen is shown in Figure 3.28.



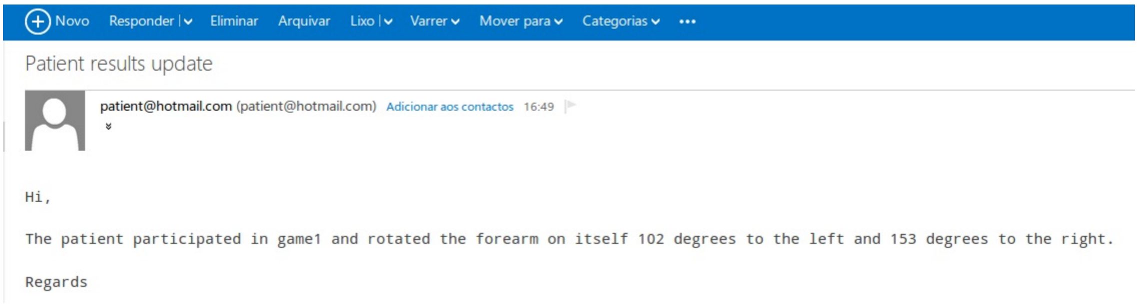
Congratulations! You scored 3 points.

You rotated the forearm 102 degrees on itself to the left.

You rotated the forearm 153 degrees on itself to the right.

Figure 3.28: "Objects Rotation Game" final screen.

The maximum rotation angles, that are collected in real-time while the game is running, are also sent automatically via email when the game ends. The implementation of this functionality adds the possibility of sending patient's results to any therapist, for him/her to follow the patient's progress. In the case of the "Objects Rotation Game" and of the previous final screen, the email is displayed in Figure 3.29:



Patient results update

patient@hotmail.com (patient@hotmail.com) 16:49

Hi,

The patient participated in game1 and rotated the forearm on itself 102 degrees to the left and 153 degrees to the right.

Regards

Figure 3.29: Email received from the patient right after he/she finishes playing the "Objects Rotation Game".

To center the hand on the screen, when the game begins, the initial rotations over Z and X are established as the center of the screen. For the hand to move, the current angles of both axis have to be subtracted, in real time, to their initial angles.

Driving Game

This game is specialized in the physiotherapy of the medial and lateral rotations of the forearm/arm.

The "Driving Game" consists of a 3D animation of a car that is controlled by the patient. He/she has to avoid roadblocks that appear randomly on the left and on the right side of the road. To play this game, the adopted position of the smartphone in the calibration phase must be maintained and the user has to point to the center of the desktop/laptop monitor to launch the game. At the moment the game is launched, the rotation over the Z axis of the patient's arm is considered the center of the screen. A screen that appears in the application after the calibration, turns the bluetooth on and provides all the instructions patients need to know, to be able to start the game on their own. It is possible to steer the car to the left or to the right, tilting the phone to the left or to the right, over the Z axis. The blocks appear in a ratio of 5 on the left to 3 on the right, to force patients to rotate the forearm more times laterally. That is done because post stroke patients usually show more difficulties in the lateral movement than in the medial rotation. The car is represented by a 3D .obj model that was imported with the parser, the berm and the central white lines of the road are drawn with polygons and the block obstacle was created with another imported 3d model. The visual interface of the game can be seen in Figure 3.30.

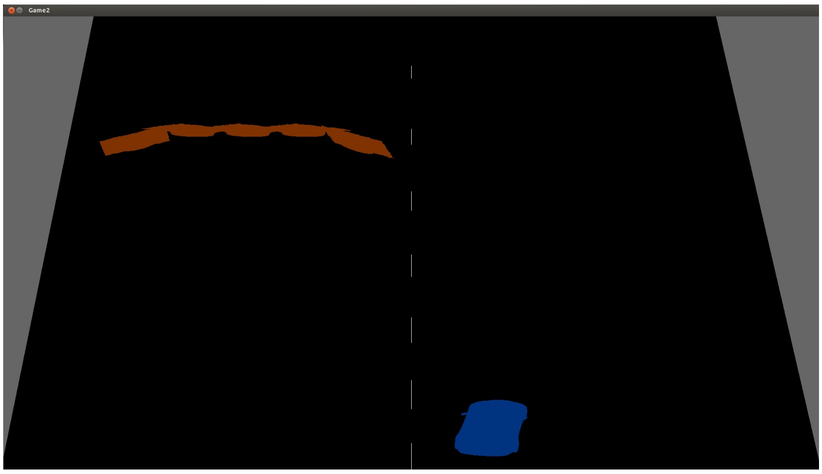


Figure 3.30: Visual interface of the "Driving Game".

The game is calibrated in a way, that patients with more impairment, are able to move the car, the same distances as patients with less loss of movement. The game gives gradually less steering sensibility as the degree of difficulty of the patient (detected in the calibration phase) decreases. When the car hits the block, a car animation starts and a crash sound is heard. That gives visual and sound feedback to patients and adds a motivational quality to the game. The game starts with 100 points. For each contact with a block, the patient loses 1 point. The game ends after 60 seconds. When the time ends, a score screen is displayed. It shows the score of the patient and the maximum rotation degrees he/she could execute over the Z axis.

The maximum rotation angles, are also sent automatically via email when the game ends. An example of an email message that the hypothetical therapist could receive, when a patient finishes playing the "Driving Game": "Hi, The patient participated in game2 and rotated the forearm 47 degrees to the left and 54 degrees to the right".

Unlike the "Objects Rotation Game", to center the car on the screen, there is only needed to find the initial position of the car over the Z axis. To do that, the current angle over the Z axis has to be subtracted to the inital angle over the same axis, when the game begins. Throughout the game, the gathered angle is always subtracted to the initial angle to ensure the car always moves from the center of the screen.

Party Balloon Game

This game concern is the flexion and extension of the forearm/arm. As in the "Driving Game", this game is also specialized in only one type of movement. They were created with the goal of extending the smartphone based tele-rehabilitation concept to patients who can not physically execute a more complete game like the first one. Even if they are more severely impaired in some other movements, they can still access games that have a higher motivational factor, to rehabilitate themselves.

The "Party Balloon Game" is a basic 2D game where the player has to move a party balloon up or down to catch arrows that appear from the right of the screen. The game is calibrated like the previous games, but this time the maximum extension and flexion of the forearm are measured. The game visual interface is shown in Figure 3.31.

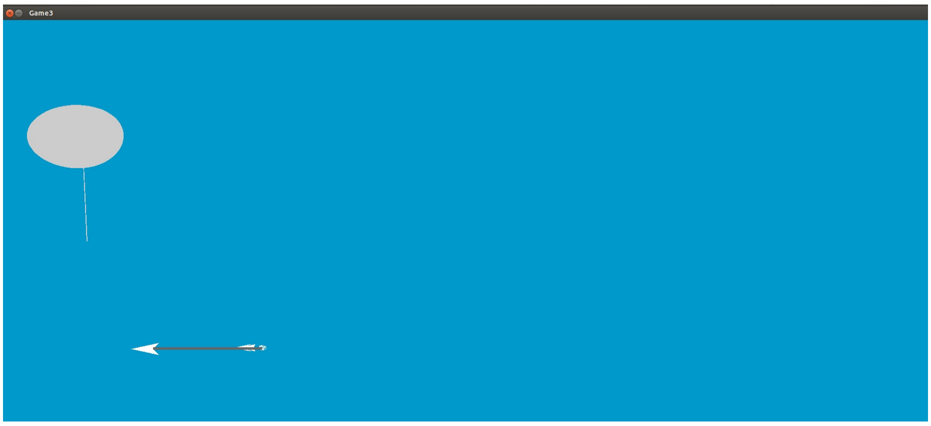


Figure 3.31: Visual interface of the "Party Ballon Game."

To play this game, as in the "Driving Game", the adopted position is the same of the calibration phase and the user has to point to the center of the desktop/laptop monitor before launching the game. This time, the balloon will be in the left side of the screen and not in the center of it like the car. The player needs to point to the screen because the application still places the balloon model vertically centered, establishing the initial vertical position of the patient's forearm as the center of the screen. To move the balloon up, the patient has to flex the forearm and to move it down, he/she has to extend the forearm. When it is hit by an arrow a balloon splash sound is heard and the model blinks. The score of the game follows the same rules as the "Objects Rotation Game" and it is shown in the end, together with the maximum angles of flexion and extension of the forearm. An email that contains that piece of information is also sent to the therapist.

3.3.4 Test

The opportunity for a patient to test the application, who was released from hospitalization 2 weeks before, arose. This particular patient still has to be monitored in periodic consultations with his therapist, but he already recovered autonomy in his activities of daily living. He feels no more pain and his movements feel more natural, although they are still not fluid and are made with a bit of difficulty.

A small demonstration of the application was realized to introduce it and the therapist confirmed the real need to rehabilitate the movements it assesses. Only then the patient started to play the games. Everything worked like it was meant to and he seemed quite satisfied and motivated through the tests. On the "Objects Rotation Game", it became evident that he was realizing physiotherapeutic exercises because he really needed to extend the rotation of the forearm, to his maximum range, to rotate the objects on the screen. On the "Driving Game", his reactions were sometimes not fast enough but most of the roadblocks were dodged and the general satisfaction grew. The "Party Balloon Game" was easier than it should be, but a quick fix of a parameter, made the movement of the balloon a lot harder to perform and he was already having a challenge hitting all arrows on the screen. He couldn't decide if he preferred the less intrusive view of smarphone, that implied a change of position from the calibration to the actual game, of the "Objects Rotation Game" or the intuitive, but more intrusive view, of the smartphone on the other two games.

In the patient's opinion, the concept has a lot of potential and the proof of it is well adapted to the goal. The calibration screens allow a persistent difficulty level, over all of the patients' recovery process, and the implemented games proved themselves to have a motivational character that is really important in the tedious, repetitive and non motivational routine of rehabilitation. The games developed are also interesting, they are appealing and naturally adaptable to each individual patient and ensure the continuation of a more traditional treatment at home. They also have a broad target audience because they use tools of increasingly widespread access. He was impressed with the technology capability and with the lack of bugs and full functionality of the proof of concept application.

Chapter 4

Conclusions

4.1 Critical Discussion

The work developed in this thesis followed well defined steps. It began with the Background Work research about Stroke and Android sensors. It was followed by the Android programming learning phase and with the analysis of the data collected from the sensors. The next step was the exploration of different available methods to represent orientation of objects, in relation to the World, from raw sensors data. To give the appropriate feedback to the user, the Android bluetooth client and Java server implementations were the obvious next steps and the research about how to represent 3D models on the screen followed. Having that previous work concluded, the games could be developed in accordance to the knowledge acquired in the Background Work and with the direct contact with a physiotherapist, to constitute an usable and motivational proof of the title concept of the thesis. The final phase was the realization of tests that validated all of the thesis fulfilled work.

The work developed was inspired by the desire to have a general, broad-covered overview and empirical description of how a smartphone can be used in effective practice, in the rehabilitation of those who need the most. The goal of this thesis is to provide a cheaper and a motivational alternative to stroke patients, with a certain degree of recovery, so they can rehabilitate themselves, without the need of traveling to an health facility. That was not totally accomplished, because the use of only one sensor does not allow the detection of all movements used in physiotherapy. However, information on why it is not possible and how it could be resolved was provided, so the work was extensive and explicit enough to become a really useful knowledge base to future researches, in the same area. Regarding what a single device can do, a few examples that make use of and illustrate all of its capabilities were shown.

The use of a smartphone in rehabilitation is a practical solution. It is easy to use what is already in the pocket and there is no need to buy expensive devices that would affect the household savings. In addition to that, even if a cheap solution, that doesn't involve smartphones, can be implemented, using one is still more convenient and less intrusive than using various sensors spreaded throughout the body. However, the use of a smartphone doesn't come without the cost of some capabilities.

Using only one device/sensor automatically means being able to evaluate all rotations, of the segment it is placed on, but it also implies not being able to evaluate/simulate certain movements. The biggest limit of the one device/sensor approach is the impossibility of simulating complete limbs, that possess more than one segment that moves differently from the others. This drawback makes the detection of some movements not possible. E.g., if the smartphone is placed on the forearm, it is not possible to detect the stretching of the arm or if the elbow moved and if the smartphone is placed on the upper arm, it is impossible to measure any movement of the wrist or the pronation/supination and flexion/extension of the forearm. Like any individual sensor, the measurements of the smartphone are also dependent of the quality of the sensors. If they were better (less prone to noise), it could be possible to suppress a few of these handicaps, simply by measuring accurate traveled distances in centimeters with the accelerometer[1].

The use of multiple sensors has the advantage of being able to assess more movements, but has the disadvantages of a bigger expense and of a more intrusive use that requires bigger times of preparation to single therapy sessions. How many sensors are used depends on what the therapy aims for and what are the monetary resources of patients.

4.2 Future Work

The application developed is just a proof of a concept, so a lot of what was created can be improved and optimized. The graphical interface should be assessed by designers, to be adapted to an elderly target audience. Different levels of difficulty can be introduced into the current games. More games should be added and receive plenty of graphical enhancements. An idea of one, is the creation of a split screen with a virtual trainer, on one side of the screen, and a 3D representation of the patient on the other side. The trainer could execute correct movements and the patient should try to mimic them. Proper tests with several smartphones should also be carried out. The feedback the therapist receives can be more detailed. He/she can receive line/symbols charts of movement and position of the patient's limb during a game. This information can also become available in an web interface that is

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[1] More accurately with the gravity sensor, that applies a low pass filter to the accelerometer, filtering out frequencies that correspond to peaks of quick movements.

connected to a database. A wifi alternative, to those patients who don't possess a bluetooth adapter and already have Internet via wireless at their disposal, can also be provided. The same work can also be made available to iOS and Windows Phone.

The use of only one sensor is the cause of a lot of restrictions, in the concept of smartphone tele-rehabilitation, addressed in this thesis. So, the use of multiple inertial sensors is a natural extension of this work. They can be small auxiliary sensors or even two smartphones. With only one more smartphone, placed on the upper arm, the range of movements that can be assessed, in the upper limbs, grows tremendously because the programmer regains access to the two major segments of that part of the body. There is no need to use other smartphone, a small inertial sensor can be combined with the smartphone, and because they are cheap, the best of both worlds, can be achieved.

Appendix A

Acronyms

ADT - Android Developer Tools

AR - Augmented Reality

BATRAC - Bilateral Arm Training with Rhythmic Auditory Cueing

CHADS_2 - Congestive heart failure, Hypertension, Age greater or equal than 75 years, Diabetes and Stroke/TIA/thromboembolism

$\text{CHA}_2\text{DS}_2\text{-VASc}$ - Congestive heart failure, Hypertension, Age greater or equal than 75 years, Diabetes, Stroke/TIA/thromboembolism, Vascular disease, Age from 65 to 74 years and Female

COI - Combination of Isotonic Exercises

DASH - Disabilities of the Arm, Shoulder and Hand

DOF - Degrees of Freedom

DRF - Device Reference Frame

EMG biofeedback - Electromyographic biofeedback

ERF - Earth Reference Frame

FAST - Face, Arms, Speech and Time

GPRS - General Packet Radio Service

GUI - Graphical User Interface

IADLs - Instrumental activities of daily living

I2C - Inter-Integrated Circuit Communications

iOS - Iphone Operating System

LWJGL - Lightweight Java Game Library

MIT - Massachusetts Institute of Technology

NIH Stroke Scale - National Institutes of Health Stroke Scale

OpenGL - Open Graphics Library

PNF - Proprioceptive Neuromuscular Facilitation

RAS - Rhythmic Auditory Stimulation

RST - Rhythmic Stabilization Training

rTMS - Repetitive transcranial magnetic stimulation

SDK - Software Development Kit

UUID - Universally Unique IDentifier

Wifi - Wireless Fidelity

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