Pós-Graduação em Ciência da Computação

"Improvement of Computational Rehabilitation Support Systems Based on Virtual and Augmented Reality: Clinical Similarity and Biomechanical Movement Recognition"

Por

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Tese de Doutorado

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RECIFE, (2015)

Universidade Federal de Pernambuco
CENTRO DE INFORMÁTICA
PÓS-GRADUAÇÃO EM CIÊNCIA DA COMPUTAÇÃO

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"IMPROVEMENT OF COMPUTATIONAL REHABILITATION SUPPORT SYSTEMS BASED ON VIRTUAL AND AUGMENTED REALITY: CLINICAL SIMILARITY AND BIOMECHANICAL MOVEMENT RECOGNITION"

Este trabalho foi apresentado à Pós-Graduação em Ciência da Computação do Centro de Informática da Universidade Federal de Pernambuco como requisito parcial para obtenção do grau de Doutora em Ciência da Computação.

ORIENTADOR(A): ***Profa. Veronica Teichrieb***

RECIFE, (2015)

Catalogação na fonte
Bibliotecária Jane Souto Maior, CRB4-571

D111i Da Gama, Alana Elza Fontes
Improvent of computational rehabilitation support system based on virtual and augmented reality: clinical similarity and biomechanical movement recognition / Alana Elza Fontes Da Gama. – Recife: O Autor, 2015.
184 f.: il., fig., tab.

Orientador: Veronica Teichrieb.
Tese (Doutorado) – Universidade Federal de Pernambuco. CIn, Ciência da computação, 2015.
Inclui referências e apêndices.

1. Ciência da computação. 2. Realidade virtual. 3. Realidade aumentada. 4. Reabilitação. I. Teichrieb, Veronica (orientadora). II. Título.

004 CDD (23. ed.) UFPE- MEI 2015-53

Tese de Doutorado apresentada por **Alana Elza Fontes da da Gama** à Pós-Graduação em Ciência da Computação do Centro de Informática da Universidade Federal de Pernambuco, sob o título "**IMPROVEMENT OF COMPUTATIONAL REHABILITATION SUPPORT SYSTEMS BASED ON VIRTUAL AND AUGMENTED REALITY: CLINICAL SIMILARITY AND BIOMECHANICAL MOVEMENT RECOGNITION**" orientada pela **Profa. Veronica Teichrieb** e aprovada pela Banca Examinadora formada pelos professores:

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Visto e permitida a impressão.
Recife, 23 de fevereiro de 2015.

____

Profa. Edna Natividade da Silva Barros

ACKNOWLEDGEMENTS

The opportunity to work my PhD in an area different from my origin was challenging and enriching. To cross all these process of learning and growing a lot of people participated directly or indirectly. I would like to use this space to thank them.

The PhD is not an individual work as some people use to think. It is a team work. Without a great team to support you it becomes a very arduous duty. Due that I would like to thanks the Voxar labs (www.cin.ufpe.br/~voxarlabs) team by all help provided on this work. They were not only my work partners but my programmer teachers. More than a team, Voxar is a family which I am grateful in been part of it. Inside this family I would like to thank specially Thiago Menezes and Lucas Figueiredo which worked directly in this work generating ideas and helping in solving problems.

I happily thanks vt, also known as Veronica Teichrieb, first by accepting me in this family, even without knowing before, and also by all support provide by her, professionally and personal.

Since it is an interdisciplinary work we also needed support and helpful professionals in the Physiotherapy area, and all this was provided by the Applied Neuroscience Laboratory (LANA) team (www.ufpe.br/lana). I would like to thanks you all, and especially Professor Katia Karina Monte Silva and the researchers Adriana Baltar, Deborah Marques and Maíra Sousa, by helping on the system idealization and also in providing a welcoming space to test the systems. In this aspect I also want to thanks Professor Lucas Ithamar, who in name of UFPE Physiotherapy School Clinics, allowed access to apply the tests in patients, and thanks all volunteers which make this work possible.

During my PhD work I had the great opportunity to perform an internship to the Technische Universität München (TUM). I am grateful in this enriching opportunity to the Professor Nassir Navab by accepting to be my co-advisor and by allowed me in his group (campar.in.tum.de). There I was very well received at the Narvis group, and I would like to thanks all, especially Pascal Falllavollita by all support provided.

The internship was possible due the CAPES scholarship from the "Programa de Doutorado Sanduiche no Exterior" (PDSE). This PhD work was also supported by the FACEPE PhD scholarship. I am grateful to these two institutions by the financial help.

To finish I would like to thank all the people which support me outside of the science world. First I would like to thank my love and partner, Artur Lira Dos Santos, which supports me in all aspects of my life. He inspires me to be the best what I can be. I also thank my family and friends who are always cheering for me and by understanding my absence during all the process. My mom, Albaneide Dias Fontes Da Gama, which always helps, motivates and gives me positive energy, my father, Professor Alfredo Arnóbio de Souza Da Gama, which is my reference as father, scientist and professors, and my brothers and sister, Arnóbio José, Ana Elisabeth and Aldo Henrique, and brother and sisters in law, which are always in my side motivating and helping me. Finally, I would like to thank my nephews and nieces whose smiles recharge my energies to work.

Thanks you all who helped and helps me. I am very grateful.

RESUMO

Tradicionalmente, o processo de reabilitação é lento e repetitivo levando a uma alta taxa de evasão de pacientes. Com o crescimento das tecnologias interativas como Realidade Virtual (RV) e Realidade Aumentada (RA), diversos sistemas têm sido desenvolvidos com intuito de motivar pacientes a realizar exercícios. A maior parte dos sistemas incluem movimentos de alcançar, pegar e colocar objetos, ou seja, movimentos genéricos para treino de amplitude ou exercícios de equilíbrio para membros inferiores e tronco. O objetivo desse trabalho é realizar o aprimoramento de sistemas interativos de suporte à reabilitação motora, tornando – os mais relacionados à prática clínica.

Para auxiliar na identificação de requisitos, foram realizadas reuniões com fisioterapeutas. Dentre os requisitos identificados, um dos principais é a possibilidade de interagir com o sistema com movimentos que são realizados na rotina clinica e com a flexibilidade de permitir ao terapeuta escolher entre estes movimentos. Nesta tese é proposto um novo método de reconhecimento que analisa o movimento de acordo com os parâmetros padronizados na biomecânica. Para contemplar os movimentos funcionais, que são também utilizados na prática clínica, foi desenvolvido o método de reconhecimento por checkpoints, onde os movimentos funcionais podem ser cadastrados pelo fisioterapeuta ou pelo paciente e utilizados para controlar as aplicações.

Também foi desenvolvida uma biblioteca de análise de movimento com os dois métodos propostos para permitir que eles possam ser usados em diferentes aplicações. Essa biblioteca foi então integrada ao Ikapp, um sistema desenvolvido para reabilitação motora, e fornece informações como amplitude e qualidade do movimento. No sistema foram incluídos os demais requisitos listados, como uso do método de reconhecimento em uma aplicação interativa para motivar o paciente no exercício, uso de configuração para dar flexibilidade ao fisioterapeuta para escolher características do exercício, como, por exemplo, amplitude máxima do movimento e precisão requerida na execução, e produção de relatório para avaliação futura. Outro importante requisito é a possibilidade de orientar e corrigir movimentos durante sua execução. Isso foi permitido com o uso da biblioteca de reconhecimento de movimentos que fornecia informação da qualidade do movimento e dos erros que estavam sendo realizada, informação essa que possibilitou o retorno visual.

Utilizando a biblioteca de reconhecimento de movimento integrada ao Ikapp foram desenvolvidos um sistema de RV e um de RA. O reAIRbilitation é um jogo que permite controlar um avião por meio de movimentos biomecânicos ou funcionais. Mensagens de como corrigir o movimento são fornecidas na tela junto com mensagem de áudio. A aplicação de RA desenvolvida foi o mirrARbilitation, onde objetos para induzir o exercício são posicionados na tela de acordo com a posição do usuário e a amplitude de movimento desejada na terapia. Informações e imagens demonstrando as execuções erradas fornecem orientações para correção de movimento.

Ambos os sistemas foram testados em pacientes, fisioterapeutas e desenvolvedores da área de jogos e sistemas de interação. O uso de movimentos biomecânicos e funcionais em sistema interativo apresentaram boa resposta e aceitabilidade pelos usuários. O valor terapêutico do sistema foi reconhecido pelos fisioterapeutas. O benefício da orientação do exercício foi demonstrado com maior número de execução correta de exercício com uso de sistema. Através do estudo realizado foi possível identificar a necessidade de melhoria em aspectos como diversão e interface do sistema. No futuro, o método de reconhecimento aqui proposto pode ser parte de sistemas desenvolvidos com maior foco na área de jogos de forma a tratar as limitações observadas.

Palavras chaves: Reabilitação motora. Realidade virtual. Realidade aumentada. Interação. Kinect; Análise de movimento. Biomecânica.

ABSTRACT

Traditionally, the rehabilitation process is a slow and repetitive process which leads to a high evasion rate. Due the growing of interactive technologies such as Virtual Reality (VR) and Augmented Reality (AR) diverse systems are being develop aiming to motivate patient in their exercise. Majority of them interacts using reaching, taking and putting movements for upper limbs in order to reach higher range of motion and equilibrium exercises for lower limbs and trunk. The aim of this work is to improve interactive system for motor rehabilitation applications making them more related to clinical practice.

A meeting with physiotherapists was performed to help on the requirements definitions. Among the listed requirements, one of the principal was the possibility to interact with system through movements which are traditionally performed on clinical routine with the flexibility to allow therapist to choose between of them. This thesis proposes a new method of movement recognition which is capable to analyze movement according with biomechanical conventions. The checkpoints method was also developed in order to contemplate the functional movements, which are also used in clinical practice. At this method the movements can be registered by the therapist or patient and then used to control applications.

The methods proposed were then integrated in a movement analysis library to allow their uses on different applications. This library provides information such as range of motion and movement quality. It was integrated to a motor rehabilitation system, which we named Ikapp, where the others requirements listed were included. This system made use of the movement recognition in an interactive application to motivate patient during exercise. It was also improved with a configuration file to provide therapist flexibility on choosing movement characteristics such as maximum range of motion and accuracy required during exercise in the application, and also provides a report for further evaluation by therapist. The possibility to guide and correct movement performance is another important requisite. It was allowed by using the movement analysis library which provides information about movement quality and its execution errors. These information could then be used to provide visual feedback.

Integrating the movement recognition library with the Ikapp system it was developed two applications, one VR and one AR based system. The reAIRbilitation is a game where the biomechanical or functional movement can control an airplane. Visual and auditory warnings suggesting how to correct the movement are provided. The mirrARbilitation was the AR based application where objects are positioned on the screen to induce movement. They are positioned according to user position and the aimed range of motion. Images and messages demonstrating how to correct the movement are provided.

Both systems were tested by patients, physiotherapists and developers from games and interaction area. The use of biomechanical and functional movements as interactive tool presented good response and acceptability by the users. Physiotherapists recognized the therapeutic values of these systems. Guidance benefits was demonstrated by the higher number of correct exercise performance while using the system. It was detected the necessity of improvements on fun aspects and system interface. It is proposed the use of the movement recognition here proposed for developments focusing on game aspects to work on the observed limitations.

Key words: Motor rehabilitation. Virtual reality. Augmented reality. Interaction. Kinect. Movement analysis. Biomechanics.

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1. INTRODUCTION

Figure 1: A patient performing motor rehabilitation using an interactive system.

Whoever participated in a rehabilitation program knows how boring and tiresome it is. In order to recovery a motor function, it is necessary to repeat a specific movement many times (Borghese *et al.*, 2013; Roy *et al.*, 2013). This is crucial to achieve gains in therapy. In order to make these repetitive movements less tedious the use of an interactive system, like a virtual and augmented reality (VR and AR) based one is being considered (**Figure 1**).

Motor rehabilitation is the therapy performed in order to recovery movements and lost motor functions. These can be originated by different causes such as a pathology, accident or pain. Since the cause is diverse, the population profile needing rehabilitation is global, including children with congenital pathologies, adults after accidents or elderly with motor changes provoked by aging. Between all of them, the public which spends more time on rehabilitation are the ones with chronic diseases or sequels, such as neurological patients. An example is stroke patients after suffering a Cerebral Vascular Accident.

The rehabilitation normally occurs by regular meetings between patient and physiotherapist at a clinical environment. These can occur every day or a few days in a week, depending on therapist and patient availability. The section duration normally is 40 minutes to one hour. It is possible to notice that the time that a patient spends in therapy is very short. As presented before, a motor gain requires repetitive performance of the movement, and it should be done preferably many times a day.

In order to improve therapy, patients are normally asked to perform the exercises at home. However, there are two main problems in this: patients are usually not motivated to do the home exercises and they can do it wrongly. These limitations are also benefited by the use of interactive systems (Danny Rado *et al.*, 2009; Da Gama, A. *et al.*, 2012a; Brokaw *et al.*, 2013). When these systems are developed enabling, besides the motivation, the control of patient during exercise and report or remote contact with therapist, they can help on these home exercise limitations.

Other important application for systems which enable therapy control at home is for the patients who live far from rehabilitation centers, or have transport limitations to reach these places. They need therapy but the drawback to reach a place to receive the treatment is limiting (Ustinova *et al.*, 2013). For these, the use of home based interactive systems is very useful, enabling them to perform their exercises in a controlled environment.

Home based interactive systems are also beneficial for chronic patients. They need a larger time to recover and require continuous exercise to maintain their gains. The clinical environment, normally due the high demand, treats these patients in the initial stages and after sends them home to continue their therapy by themselves (Crocher *et al.*, 2013; Simmons *et al.*, 2013). Due to that, a home system which can control the exercises performance is very useful for this population.

The start of the development of rehabilitative interactive systems started aiming to motivate patients to perform their exercises during the rehabilitation process. The use of interactive systems with the ludic aspect to divert patients from tedious repetitive movements making them more engaged has been studied by some works (Barresi *et al.*, 2013; Dukes *et al.*, 2013). This ludic aspect also distracts them from the pain that can be caused during the exercise, what helps them to perform the motion correctly (De Bruin *et al.*, 2010; De Carvalho Souza e Rodrigues Dos Santos, 2012).

Furthermore, the benefits of these systems can be explored besides the motivation. The benefits provided by these systems include movement stimulation, guidance and control, what is especially useful for home based systems (Brokaw *et al.*, 2013; Khademi *et al.*, 2013). With detailed movement recognition, capable of detect wrong performances, it is possible to alert the patient and avoid it (Danny Rado *et al.*, 2009; Da Gama, A. *et al.*, 2012a; Brokaw *et al.*, 2013). This can improve security of these systems preventing the emergence of new lesions caused by exercises compensations.

These new possibilities arose with the appearance of new technologies, which enable human skeleton detection based on only one small sensor, such as accelerometers and RGB-D sensors. For rehabilitation it is also important the less number of accessories as possible to enable the system (Lee e Sheng-Chung, 2012; Seung-Kook *et al.*, 2013). Preferable none artifacts is indicated. The portability associated with the low cost of the sensors increases widely the interactive systems applicability (Clark e Kraemer, 2009; Stone e Skubic, 2011; Borghese *et al.*, 2013; Metcalf *et al.*, 2013).

Although the number of works trying to develop rehabilitative systems for rehabilitation purposes, few attention is given to the way in which the movement is interpreted by these systems. It is a very important matter that movement be validated by the system according to biomechanical characteristics (Wu e Cavanagh, 1995;

Cappozzo *et al.*, 2005; Mundermann *et al.*, 2006). It is important that the movement normally done during therapy be used as reference movement by these systems. The more similar to the clinical reality these systems are, higher will be their applicability (Merians *et al.*, 2006; J W Buker *et al.*, 2010; Da Gama, A. *et al.*, 2012a). When planning a rehabilitation exercise routine the therapist chooses between a set of therapeutic exercises, which are described according to biomechanical descriptions. Each movement has specific aims in the recovery procedure in order to optimize it. So, the use of the specific therapeutic movements instead of the generic ones leads to better results.

In the rehabilitation science, movements are described based on the International Society of Biomechanics (ISB) statements (Wu e Cavanagh, 1995; Wu *et al.*, 2002; Wu *et al.*, 2005). They define how each movement should be described and analyzed. They take in consideration anatomic factors, which influence movement. The standardization of terms to perform movement recognition is very important in order to unify the language in biomechanics, sports and rehabilitation fields. The same advantage can be provided by using the ISB recommendations to perform movement recognition for interactive applications. Additionally, using the ISB recommendations makes the movement recognition more related to the clinical practice using terms and movements which therapists have familiarity.

The movement description standardized by the ISB is first composed by general concepts containing a definition of global reference frame, segmental local of mass center and global and local displacement and references. These descriptions are found in the first standard [1] that works as framework for further joints statements. After the first statement the main joints were standardized by each specific committee and their Joint Coordinate System (JCS) and movements were then described [2, 3]. The JCS defines the references for the three-dimensional axes centralized at each joint. Based on the JCS each segment can have its movements described. All JCS should follow the coordinate system described in the global reference system.

All descriptions in the ISB standard are performed starting in the anatomic position with proximal and distal segments aligned. From the start position, rotations are described using Euler angles at each coordinate. The rotations of the distal coordinate system should be described with respect to the proximal coordinate system.

Based on this perspective, this work intends to improve interactive rehabilitation systems based on VR and AR by trying to bring the clinical context and biomechanical movement recognition to the development of such systems.

1.1. HYPOTHESIS

This research is based on the hypothesis that recognizing movements according to biomechanical standardization can improve the possibilities of interaction and additional information for interactive system developed for rehabilitation applications.

It postulates that recognizing a movement based on the biomechanical descriptions will enable therapist to configure system to be controlled by the therapeutic movements that are already used on clinical routine, being not necessary the adaptation of the routine in order to be able to use such system. Besides that, recognizing movement based on de biomechanical standard will provide information about the movement that can be used for both guide and warning wrong performances suggesting corrections. It can also enable therapists to have an evaluation of the movements performed by patients according to standards that they already use.

1.2. OBJECTIVE

The aim of this research is recognize patient movements according to the biomechanical standards and develop a system that is similar to clinical routine capable to guide and correct the therapeutic exercises.

In order to recognize according with the ISB standard, since it is based on markers references, we need to map it to a markerless technique. Based on this mapping we aim to develop a movement recognition technique capable to classify the biomechanical movements. The development of an additional method for the functional movements is targeted to complement the system for recognizing the second category of exercises performed on therapy.

At the end, this study aims to evaluate the benefits of the movement recognition proposed by using them as input for an interactive system based on VR and AR. The goal is to evaluate recognition techniques benefits in providing information to guide and correct exercises through these systems.

1.3. THESIS STRUCTURE

This thesis is organized as follows.

First, in order to contextualize and direct the development of the methods and system here proposed, Chapter 2 will present the rehabilitation routine description and biomechanical fundamentals. Based on that their relation with interactive systems and possible improvements on this area will be highlighted.

Following a literature review about interactive systems, including VR and AR based ones, will be presented in Chapter 3. Yet on this chapter the areas of application of these systems for rehabilitation will be presented, followed by the evaluative systems.

After reviewing the systems a round about the Kinect sensor including technology, pose estimation software and others similar sensors will be presented (Chapter 4). In the same chapter a systematic review about the use of the Kinect for rehabilitation will be presented and discussed.

Just after presenting the state of the art, our proposed solution will be summarized (Chapter 5). The description will include the systems requirements regarding the clinical context and the respective proposed solutions will be introduced.

After introducing the reader to the general proposals, Chapter 6 will present the mapping of the biomechanical standard and its coordinate system for each joint to the markerless motion capture techniques. This mapping will be further used on the development of the two movement recognition techniques developed. These methods will be presented at Chapter 7. It will describe the recognition of biomechanical movements and the recognition of functional ones. The results obtained testing these movement recognitions will be presented in Chapter 9.

After presenting the methods developed, their application will follow. Chapter 8 will start with the presentation of the Movement Analysis Library developed, followed by describing the two case studies performed: reAIRbilitation and mirrARbilitation. The results obtained with them will be presented and discussed in Chapter 10.

To finish this work the conclusions and future works will be approached in Chapter 11.

2. ADAPTING SYSTEMS TO CLINICAL ROUTINE

Figure 2: Motor rehabilitation routine.

An overview on the clinical routine and biomechanical fundamentals will be presented in this chapter. First, a brief description about how the clinical routine occurs is described. Following, the role of interactive systems in helping this process is discussed showing what has been done and where it can be improved.

In sequence, the biomechanical concepts are presented. The biomechanics fundamentals are important to understand how movements are described in the therapy. Knowing how they are interpreted by this area will help on the knowledge about how to recognize the movements using the same terms and references used by the therapists.

2.1. CLINICAL ROUTINE DESCRIPTION

The first contact between therapist and patient is the moment where the therapist has to know patient limitations, mainly concerning movement performance and function. Due to that the first step in the rehabilitation routine is the Kinetic-functional evaluation.

At this step the therapist investigates which movements were damaged by the pathology or accident. It is also important to understand why the movement is limited. The restriction can be originated from different causes including pain, local inflammation, muscles weakness, ligament or tendon rupture or elasticity changes and neurologic modifications.

Knowing the limitations is an important step, but associated to it, it is also necessary to have objective evaluations which can be used as reference to evaluate status of limitations and also improvements during rehabilitation process. Kinetic-functional evaluation includes other tests which are used according to each case. For example, Range of Motion (ROM), strength, equilibrium and functional tests. Concerning movement amplitude the main ROM measure used in a clinical routine is the goniometry, where the movement's angles are measured through a goniometer (Clarkson, 2005). Goniometry standardizations measure angles according to biomechanical classifications, where movements are classified according to the plane where it is being performed. The biomechanical movement classification will be detailed forward in this work (chapter 7). Strength tests done in a clinical environment normally are performed manually and when it is possible specific equipment like dynamometer or electromyography is used. For functional and equilibrium tests, some protocols with different evaluations are provided in the literature.

Based on the results of the kinetic-functional evaluation the therapist is now able to decide which exercises are better indicated to recover the limited or lost movement. The biomechanics of each exercise is specific; when different movements are being performed they recruit different muscles and stretch specific ligaments and tendons. This way it is easy to conclude that each lesion and limited movement requires specific exercises in order to achieve better and more directed recovery.

So, the second step of the rehabilitation routine is the treatment planning including the exercises definitions and when required additional therapies, such as thermo and electrical therapy (**Figure 22**). The exercises include two main categories: biomechanical movements and functional exercises. The biomechanical movements, as described before, are specific to gain amplitude for a limited movement. The biomechanical movements are very important to the rehabilitation process, since they are more precise for joint anatomy. The lesion of a specific movement normally results in a change on some function, which can be essential for patient independence. Due to that it is very important in parallel or in a further step of the rehabilitation process to perform exercises to train this function, which are named functional exercises. The functional exercises are movements which are essential for patient independence. So, depending on the movement limitations the functional exercises can be performed in the same phase of recovery than the biomechanical movements or in a step forward as an evolution of the rehabilitation process.

During all exercise performance the therapist is continuously checking patient execution to avoid compensations. The compensations are wrong postures adopted by a person doing exercise trying to make it easier. However it looks easier, it can result in wrong muscle activities and can promote other lesions.

The process of evaluation and treatment planning is an iterative and continuous process. Based on patient performance and improvements new aims should be planned.

In order to recover a lost movement repetition is very important. Due to that the therapist has to ask and motivate the patient to perform the exercise a lot of times, not only during the clinical appointment but also at home. The time that the patient expends at the clinical environment is very short compared with the time expended at home. Therefore it is very important to clarify the patient about the importance to continue the exercises and stimulate him to perform them at home. The home exercises are commonly prescribed by oral instructions for the patient perform them latter, or via an instructional chart.

2.2. REHABILITATION ROUTINE AND THE INTERACTIVE SYSTEMS

Interactive systems are being widely developed aiming to help rehabilitation process mainly in the exercise motivation. However, when performing motor rehabilitation the motivational aspect is just one of the important characteristics. As described before the exercise is planed specifically to achieve a gain and joint motion recovery. The majority of systems developed focus on generic reaching movements for upper limbs, or are developed for very specific training such as hand grasping or balance exercises (Da Gama, Fallavollita, Teichrieb*, et al.*, 2015). These movements used by the systems cause the situation where the therapists have to adapt their therapy in order to be able to use the systems as a motivation tool, but restrict the use of the traditional movements performed.

As described before, when performing motor rehabilitation besides the movement specification it is also necessary the correct performance. The wrong exercises can delay the gains and also lead to new injuries. The importance of correcting the wrong exercises when using an interactive system was addressed by some works. However their correction is informing only the right and wrong situation (Anton *et al.*, 2013; Roy *et al.*, 2013), not detailing and not informing how to correct it.

Another important characteristic to be considered when using interactive rehabilitation systems is the capability to adapt to patient limitations. The first goal of such system is to motivate patient during exercise, but if it is not able to adapt according to the patient limitation it can produce the opposite effect frustrating the patient (Borghese *et al.*, 2013). This adaptation is normally performed by calibrating the reaching area that the patient can achieve (Dukes *et al.*, 2013; Sadihov *et al.*, 2013). Yet related to this adaptation, the use of a markerless technique to recognize movements is more adequate to patients. Besides providing the benefits of a natural interaction (Valli, 2005), for some patients it is impossible to hold a joystick and the marker based techniques are high cost and unpractical for daily use.

When analyzing the rehabilitation process in a clinical routine it is possible to detect an additional important characteristic for these systems which can help on this process. The process starts with the movement evaluation, so systems which provide evaluation are very useful, mainly if the outcomes are the ones related to the clinical ones. The evaluation performed by the systems are mainly related to games aspects such as interaction time and game scores (Roy *et al.*, 2013). The work developed by Anton and partners added subjective evaluation where the patient answers some questions asked after using the system (Anton *et al.*, 2013).

The exercise planning is an important step of the rehabilitation process. So the possibility to configure the system according to the therapeutic needs, including movement and range of motion which will be used is very important for rehabilitation interactive systems. As presented before the majority of systems interact with specific pre determinate movements. Some allow interaction using different movements, however they require the therapist to record the movement enabling patient to mimic it (Anton *et al.*, 2013; Fraiwan *et al.*, 2013). Lastly, to enable these systems to be used at home it is also necessary to remotely control the system which allows the therapist to continuously accompany the patient (Borghese *et al.*, 2013; Roy *et al.*, 2013).

Based on the exposed, it is possible to notice the importance of taking the clinical routine in consideration when developing a motor rehabilitation system. This can lead to an improvement of the application of such systems providing a more adequate help to the rehabilitation process. When developing a system for motor rehabilitation it is important to consider the evaluation, the movements which are used on therapy and the configuration of both movements used and interface aspects according to therapeutic needs.

2.3. BIOMECHANICAL FUNDAMENTALS

One of the main fundamentals necessary to understand the rehabilitation, mainly related to exercise are the biomechanics concepts. They are the base knowledge to adequate movement prescription on therapy.

Movement description seems to be a simple task, however when considering the joint mechanics it is not as trivial as it looks like. The confusion can start already in the name of body parts: the name arm, for example, easily gets misunderstood with the forearm term. However the nomenclature problem goes further than only the body parts names, leading to the achievement of different movements if they are not well and consensually described. These problems can be simply exemplified: if the movement description aims the user to lift the arm up, how would he/she position the arm? Frontally, laterally or posterior? And at which height? In a daily action description this is already confusing, and when it comes in a rehabilitation situation or during a research this confusion is really limiting. In a rehabilitation process the different position, in the case of the example of lift the arm up, promotes different gains in joint and muscle performance, which can take rehabilitation in a non-desirable way. In the research field the confusion resulted from the absence of standard and clear description makes difficult, or even impossible, to compare results and make conclusions.

In order to solve these problems when a movement description is required and also to perform a uniform movement description, according to joints anatomy and biomechanics, efforts have been done since 1990 by the International Society of Biomechanics (ISB). Their intention was to standardize the report of joint motion and description for kinematic reporting. With the standardization they hoped to achieve uniformity on data presentation making easy to read and compare scientific data from different investigators (Grood e Suntay, 1983; Wu e Cavanagh, 1995).

The first step towards this direction was the statements of adoption of the Joint Coordinate System (JCS), first proposed by Grood and Suntay (1983) for the knee (Grood e Suntay, 1983). Then a group from the ISB was established, named the Standardization and Terminology Committee (STC), with the aim to define the JCS and movements description for each big joint. One first general statement was composed with concepts and bases for descriptions that should be followed by the specific joint statements, working as a framework for the following standards (Wu e Cavanagh, 1995). The main joints defined had their standard descriptions published in two parts, part I for lower limbs and spine (Wu *et al.*, 2002) and part II for upper limbs (Wu *et al.*, 2005), and should be used as reference in all biomechanical research. The knee, since it was first described and worked as basis for the others is publish separately (Grood e Suntay, 1983).

Although the existence of the biomechanical standardization, when using movement recognition on interactive systems developed for rehabilitation none of the studies or systems makes relation to these standards. However, it is common to find the description of how to get and compare points to interact with the system (Borghese *et al.*, 2013; Dukes *et al.*, 2013). Based on the same motivational aspects that make the standard description important in general measurements, in computational interactive systems developed for clinical purposes a standard recognition method according to the ISB parameters is also important to unify languages enabling communication and comparison between researches and also to enable correlation with therapists clinical practices.

Due that, in order to fill in this lack of reporting joint motion on interactive systems developed for rehabilitation applications giving them the capability to use clinical movement and terms to interact, configure and produce report this research propose a movement recognition method and description for this interactive systems following ISB standards. This development will make system features more useful and welcoming to clinicians, and will also enable comparison among various studies on this area.

2.4. BIOMECHANICAL CONCEPTS

Before going forward with biomechanical standards, some basic concepts and terms will be presented to facilitate the comprehension of this area. In biomechanics an intersection between anatomic and mathematical concepts is performed in order to enable the study and description of body kinematics. Therefore this chapter will describe some anatomic references and positions used for biomechanical movement description and its intersection with mathematical concepts of axes, planes and directions.

Before describing the references it is important to clarify about the body segments names. It may look simple, and it is, however due to popularization of colloquial language the anatomic terms sometimes get confusing. The main names ambiguity happens regarding the use of arm and leg that are commonly used to refer to the complete limb. However the arm term is representative of the portion of the upper limb between the shoulder and the elbow. The leg is the region located connecting knee to ankle. When describing the complete member the terms upper limbs and lower limbs are used.

The first step to describe any movement is defining one starting position. In biomechanics this start is the body anatomic position (**Figure 3**). In this position, the body is erect and facing forward with the arms hanging at the sides of the body and the palms facing outward (Enderle *et al.*, 2011). At this position we can describe the median line (or midline) which crosses the body from the head to the feet, passing through the gravitational center dividing it into right and left sides (Clarkson, 2005).

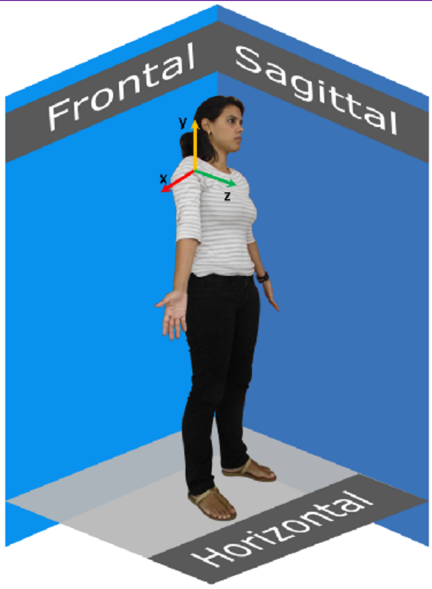


Figure 3: Anatomic position overlapped with the biomechanical planes.

Based on this posture body parts relative position and directions are described. The segments located closer to the trunk are named proximal and the far ones are called distal (Enderle *et al.*, 2011). It is important to notice that it is a relative position which is dependent of a second reference to be described. An example is the forearm, which can be a distal or proximal segment depending on the second reference; in relation to the arm it is a distal segment and in relation to the hand it is a proximal one. The proximal and distal reference is not used only to describe position but also movement direction, since the movement can be going to proximal, close to the trunk, or distal, far from it. In the description relative to the head and feet the segments can be superior, for the ones close to the head, and inferior for the ones close to the feet. When this reference is used to describe direction it receives special names: cranially for direction towards the head, and caudal, the feet. When using the midline as reference the location and direction are named medial or laterally, when close to the midline or far from the midline, respectively (Enderle *et al.*, 2011).

In order to describe a movement a coordinate reference system is required. In biomechanics this system will be needed to describe the position and displacement of a segment in relation to a joint. The coordinate system and axes direction definition used nowadays in biomechanics is determined by the ISB standards. A description of ISB standard is presented in the appendix A. However independent of axes directions chosen by the reference the planes formed between two axes receive specific names in anatomy (**Figure 3**). These planes are overlapped on the body and each of them divides the body in two portions. The Sagittal plane crosses the body along the midline and splits it in two lateral sides. Perpendicular to the Sagittal plane and also crossing the midline, the Frontal plane divides the body in anterior and posterior regions. The last one, the Horizontal or Transverse plane, is the common perpendicular to the other two and divides the body in superior and inferior halves.

Based on all these references presented above it is now possible to describe the movements and name them. They are named by the plane where the segment is moving and its direction in relation to the body or other segments. The movements that occur in the Sagittal plane are named Flexion and Extension. The Flexion is performed when the distal and proximal segments are approaching the Sagittal plane and Extension refers to the opposite direction. When the Extension goes further in relation to the anatomic position it is then named Hyperextension. In the Frontal plane the movements are called Abduction and Adduction and use the midline as reference. When getting far from the midline in the Frontal plane it is the Abduction and if going towards the midline it is the Adduction. The midline is also a reference for the movements executed in the Horizontal plane. The rotations are the movements in the Horizontal plane, and when the rotation happens in the internal direction it is named Medial or Internal rotation and for outside of body Lateral or External rotation (Bartlett, 2007).

Some movements receive specific names, some due to the fact that they are a combination of movements, or the traditional reference does not work, and others only to make a specific description. For the trunk movements, when the trunk is moving the midline is going together, this way it cannot be describe in relation to the traditional reference. In order to solve that in the Horizontal plane the right and left name are used: Right and Left rotation. For the Frontal plane the movement for the trunk is named Lateral Flexion and is described also according to the side where the movement is performed: Lateral Flexion for the right or for the left (Bartlett, 2007). For shoulder movements a specific name is given for rotation when it is performed with the arm lifted in plane of elevation (90 degrees of Abduction or Flexion). These movements use the midline as reference and are called Horizontal Adduction (the arm is approaching the midline) and Abduction (the arm is going away from the center). Forearm rotation, since it occurs in two joints at the same time, the radio-ulnar proximal and distal joint, it is not called rotation but pronation and supination, when hand faces are rotated back and to the anterior position, respectively. For the wrist movements performed in the Frontal plane special names are given in relation to the bones attached to the joint: the Adduction is named Ulnar deviation and the Abduction is called Radial Deviation. The movements performed by the ankle are specific in the Sagittal plane where the Flexion and Extension are named Dorsiflexion and Plantar Flexion, respectively. The other special name for this joint is the Inversion and Eversion; these movements are a combination of movements in the Frontal and Horizontal plane. Inversion is a combination of Adduction and Internal or Medial rotation, so during its performance the foot directs inside and a little down due to the rotation. The opposite movement is the Eversion combining Abduction with External or Lateral rotation with the foot directing outside and a little up (Bartlett, 2007).

2.5. SUMMARY

This chapter presented the main aspects related to the clinical routine and its limitation. It was also highlighted how the interactive system can help on the process and what has been done in these aspects. The main lacuna until now is in the movements used for interaction which are limited and related to the ones that are performed on clinical routine. The second main limitation found is in the exercise guidance with instructions about how to correct the movement when the therapist is not present.

To solve these two main lacunas we propose a movement recognition technique based on biomechanical concepts. This development will enable the therapist to use the traditional therapeutic movements in the interactive systems. With the information provided by the biomechanical analysis, it will also be possible to guide movements and inform user how to correct them.

The understanding about the biomechanical fundamentals and concepts was also given. They were base at this work in guiding the method development. The movement recognition proposed is based on the references and descriptions presented.

3. INTERACTIVE SYSTEMS FOR REHABILITATION

Figure 4: Interactive systems being used for motor rehabilitation purposes.

Interactive systems, which include VR and AR based ones, enable the user to interact in some way with the machine, this means that the system will answer according to user actions. These systems present diverse advantages for rehabilitation in terms of fun, multisensory stimulation and environment which can be defined to induce and help therapy. The application of these systems for rehabilitation started mainly using the environment control benefit for psychological treatments, like phobias (Glantz *et al.*, 1996; North *et al.*, 1998). The use of VR for rehabilitation purposes is not old. The first idea of using the virtual environment for physiological recovery started in 1992 with the Human-Computer interaction group at Clark Atlanta University (Hale e Stanney, 2002).

With the development of new technologies, mainly concerning the interaction capability, the applications of VR systems for rehabilitation started to expand achieving the cognitive and motor rehabilitation (Weiss *et al.*, 2004; Rose *et al.*, 2005). This was possible with the advent of interactive tools which enable users to interact with systems through movement which includes markers (fiducial or infrared reflexive markers), haptic sensors, gloves, objects or body parts recognition by cameras or sensors. The continuous technologies advances achieved the development of portable and low cost motion sensors, like inertial sensors and RGB-D sensors, with the popular versions represented by the Nintendo Wiimote and Microsoft Kinect. These characteristics enabled the quick grow of application of the VR and AR systems for motor rehabilitation (**Figure 4**) (Tsekleves *et al.*, 2014; Webster e Celik, 2014; Da Gama, Fallavollita, Navab*, et al.*, 2015).

The application of VR and AR based systems showed to be, over time, a successful tool for the optimization of the most varied treatment procedures. The use of interactive systems for rehabilitation purposes increased therapy time what probably results in quicker and more effective results (Merians *et al.*, 2006; Aung e Al-Jumaily, 2012; Chemuturi *et al.*, 2013). The portable systems also enable the use at home, improving therapy results by increasing the patients' opportunity to perform their exercise (Aung e Al-Jumaily, 2012; Khademi *et al.*, 2013).

These systems provide multisensory and multidimensional real time interaction (Sveistrup, 2004) and the individualization (and standardization) of the treatment or environment (Sveistrup, 2004; R Kizony *et al.*, 2005), which can be graduated and adapted accordingly to the rehabilitation program necessities (R Kizony *et al.*, 2005; E D De Bruin, 2010). Furthermore, they also provide patient safety and entertainment through interactivity as an option to distract them from their pain (E D De Bruin, 2010). In addition, AR allows the interaction with real objects, improving social communication, enabling uses on specific deficiencies, and promoting users motivation (E Richard, 2007; Bai *et al.*, 2013). Although, major interactions tools used with these systems are restricted to some body parts, which limits treatments diversity and control and also patient freedom during therapy execution.

Some of the VR and AR systems developed for rehabilitation and their characteristics will be presented here. In sequence, different applications for rehabilitation purposes will be described and evaluative systems will be shown.

3.1. VIRTUAL REALITY

The use of virtual environments and their possibilities to help in motor rehabilitation started in the end of the 90´s. The VR systems are commonly used to motion stimulation by tasks directed through obstacles or catching, reaching and avoiding objects. The VR systems are categorized in two types according to their immersion level: immersive and non-immersive systems. This categorization is mainly related with their visualization proprieties; when the visualization involves a large part of the user view it is considered immersive, including large screen projections, CAVES and Head Mounted Displays (HMD). Games played on a computer screen, television or small projections are considered non-immersive systems (Abdel Rahman e Shaheen, 2011).

For upper limbs the reaching or pick and place objects tasks are the more popular activities on these systems due to their relation with daily life activities (Abdel Rahman e Shaheen, 2011; Turolla *et al.*, 2013). It is normally done by a virtual environment where the patient sees an avatar or a virtual segment of his body interacting with the virtual world and objects (Holden *et al.*, 1999; Broeren *et al.*, 2004).

For upper limbs interaction it is very common the use of haptic sensors (Broeren *et* *al.*, 2004; Li *et al.*, 2011). A study with VR haptic system for hand rehabilitation showed improvement on grip strength, manual dexterity and upper limb control (Broeren *et al.*, 2004). These sensors have the advantage of enabling force information. To interact with the arms and hands, sensors which can be grasped by the hand are also used, such as magnetic (Tanaka *et al.*, 2013) or inertial sensors (Zhibin *et al.*, 2011; Kim *et al.*, 2013). One example of inertial sensor used for interaction can be seen in **Figure 5**.

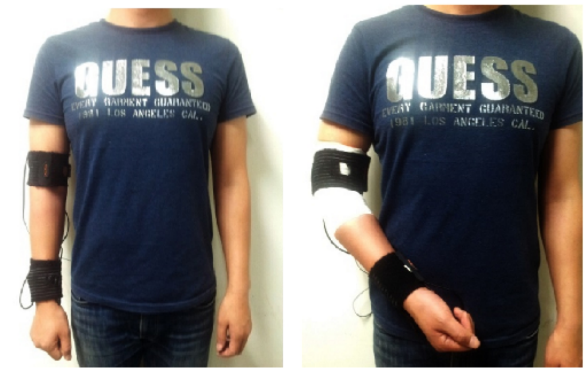


Figure 5: Inertial sensor for interaction with virtual system (Kim *et al.*, 2013).

Lower limbs training is normally focused on steps, walking and center of mass control, being more directed for gait and balance rehabilitation. One study compared the effect of virtual objects stepping while user was walking in a treadmill with stepping real objects in a 10m walk way and found improvement on gait velocity (Jaffe *et al.*, 2004). **Figure 6** shows a VR system using a treadmill (Cho e Lee, 2013). Studies working with treadmill in VR systems show improvements not only in walking speed (Yang *et al.*, 2011; Cho e Lee, 2013) but also in balance (Jung *et al.*, 2012; Cho e Lee, 2013), walking cadence (Cho e Lee, 2013) and medio-lateral control of center of pressure during gait (Yang *et al.*, 2011).

Figure 6: Treadmill interaction with virtual system (Cho e Lee, 2013).

Other tools can be used for lower limbs gait and balance training. In order to perform balance training, Kim and partners applied VR technology during cycling in a stationary bike (Kim *et al.*, 1999). Other possibility is the use of haptic and force robotic technologies for interaction with rehabilitation systems, like the Rutgers Ankle robot, a six-degrees of freedom Stewart platform force-feedback system (Mirelman *et al.*, 2010). Studies developed with a VR system using the Rutgers Ankle robot found improvement on gait velocity and distance (**Figure 7**) (Mirelman *et al.*, 2009) and also on ankle and knee range of motion and ankle power generation (Mirelman *et al.*, 2010).

It has been shown that due the stimulus provided by the virtual environment important changes and reorganization in cortical activity occurs, neuroplasticity, what is especially important for neurologic patients (You, Jang, Kim, Hallett, *et al.*, 2005; You, Jang, Kim, Kwon, *et al.*, 2005). The motor learning provided by the training on a virtual environment has been shown to be effective extrapolated to real life (Merians *et al.*, 2006).

Figure 7: Rutgers Ankle robot for lower limbs interaction. (Mirelman *et al.*, 2009).

Some of the systems developed use a virtual environment, but also enable the insertion of real world content about the user in this environment, instead of using an avatar (Jang *et al.*, 2005). This made them categorized as mixed reality based systems. One study developed by You and partners tested the IREX system in stroke patients and showed through a randomized control study that the use of this kind of system can promote the cortical reorganization and positive changes on functional ambulation (You, Jang, Kim, Hallett, *et al.*, 2005). The same group when testing this kind of system with children with cerebral palsy found benefits in functional motor skills such as reaching, self-feeding, and dressing (You, Jang, Kim, Kwon, *et al.*, 2005). Another mixed reality system was created by the use of an interactive and projective table where the user can interact with virtual objects using his real hand and showed that its use can improve upper limb motor control (Wilson *et al.*, 2011).

The use of VR for rehabilitation is a growing area. Its popularization for the application in clinical practice started with the emergence of the commercial games with motion interaction. These include the Nintendo Wii, PlayStation eye toy, PlayStation Move, and Xbox Kinect. These games brought an easy tool to therapists to motivate patients to perform their exercises. **Figure 4** shows examples of the use of these games in the clinical environment. With this widely use a lot of studies were developed testing the effectiveness of these games as a rehabilitation tool (Rosa *et al.*, 2013; Sin e Lee, 2013; Thomson *et al.*, 2014; Tsekleves *et al.*, 2014). The use of Xbox Kinect games, such as Kinect sports and Kinect adventures, showed to improve balance, posture (Rosa *et al.*, 2013) and upper limbs range of motion and motor and functional abilities (Sin e Lee, 2013). Improvements on upper limbs motor skill was also found with the use of Nintendo Wii (Saposnik *et al.*, 2010) and PlayStation eye toy (Yavuzer *et al.*, 2008). The Nintendo Wii fit board enables additional use of this game for balance exercises, with its positive benefits in this training already demonstrated in elderly (Bieryla e Dold, 2013) and cerebellar dysfunction patients (Schiaviato *et al.*, 2010).

Despite the popularization and advantages, like easy access, the use of commercial games for rehabilitation purposes has its limitations. These games were designed for healthy subjects and due to that a lot of games require elevate motor skill to adequate interaction, which cannot be achieved by a large number of patients (Ustinova *et al.*, 2013). These games are also not directed to specific rehabilitation requirements. For example, the movements used for interaction are generic and the patient do not need to do the movements with the precision required for his recovery and treatments need (Da Gama, A. *et al.*, 2012a; Ustinova *et al.*, 2013). Other limitation is that they do not control any motor performance (Deutsch *et al.*, 2011). An additional limitation is given by the necessity of holding the joystick in some of them (Aung e Al-Jumaily, 2012), and no control of wrong exercises, what can injury the patient (Sparks *et al.*, 2009; Da Gama, A. *et al.*, 2012a).

3.2. AUGMENTED REALITY

While the VR systems create a total simulated environment, AR uses the real world scene and adds synthetic information on it. This technology makes possible users feel the reality and also interact with the real objects (Craig, 2013), while having access to virtual information that helps task execution. For rehabilitation application, the number of systems developed compared to VR systems is small. However there are characteristics of this kind of system that seem to be more benefic for rehabilitation purposes.

The use of AR systems for rehabilitation retains the advantages enabled by the VR systems, such as motivation, while adding some additional ones (Klein e De Assis, 2013). It has been shown that the use of AR systems for this purpose improves spatial perception of patients and realism (Dionisio Correa *et al.*, 2013; Khademi *et al.*, 2013). These systems also provide better realism (Bell Boucher *et al.*, 2013; Klein e De Assis, 2013) and make patients more conscientious of the exercise performance, what can improve the therapy effects (Stanton *et al.*, 2011; Thikey *et al.*, 2012). The patient auto-visualization during rehabilitation is already widely used in clinical environments by the usage of mirrors. These are used to increase patient postural and motion conscience (Thikey *et al.*, 2012; Caudron *et al.*, 2014). It is also shown that the movement learning that you have when training in a situation closer to real environment, like a real scene in AR, it is better transferred for the real activity (Bell Boucher *et al.*, 2013). The auto-visualization improving learning is also shown in education area, where AR is used to improve anatomy perception in students (Ma *et al.*, 2013; Stefan *et al.*, 2014).

A study developed by Khademi et al. in 2013 (Khademi *et al.*, 2013) compared the effects of non-immersive VR with AR in the patients performance. They found a more accurate exercise performance with the use of an AR system resulting also in higher scores levels. Figure 8 shows the X and Y positions of the target and hand during task performance in a VR and AR system compared with the respected targets center position. It is possible to notice that with AR the user precision is higher.

The cortical region that is activated during interaction is important to define the training effect on motor learning. A study developed by Perani and partners in 2001 evaluated the area of the cortical system which is activated with the visualization of a virtual hand during the task performance, compared with the real hand view. They found that only real actions performed in a natural environment activate the right posterior parietal cortex, crucial for the visuospatial network and full motor knowledge (Perani *et al.*, 2001). As occurs with VR systems, most of AR technologies developed for rehabilitation are focused on upper limb exercises. They are predominant reaching and pick and place exercises in order to simulate functional tasks (Aung e Al-Jumaily, 2012; Bell Boucher *et al.*, 2013; Dionisio Correa *et al.*, 2013; Khademi *et al.*, 2013). All these studies described potential use of AR to help, motivate and induce exercise.

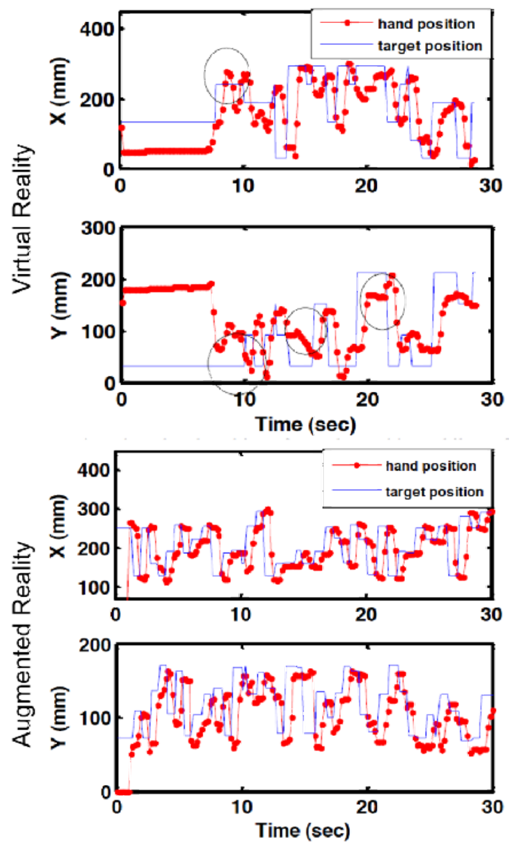


Figure 8: Comparison of hand accuracy in target position between a VR (above) and AR (bellow) system performing the same task. (Khademi *et al.*, 2013).

The digital information added on a real scene using AR can be only ludic or task related. They are used to orientate the treatment, simulating daily activities inducing a movement that the user should do during the rehabilitation program (J W Buker *et al.*, 2010; Aung e Al-Jumaily, 2012; Dionisio Correa *et al.*, 2013). The use of simulation of a home task activity (**Figure 9**) is very useful since the aim is to recover these functions to achieve patient independence (J W Buker *et al.*, 2010).

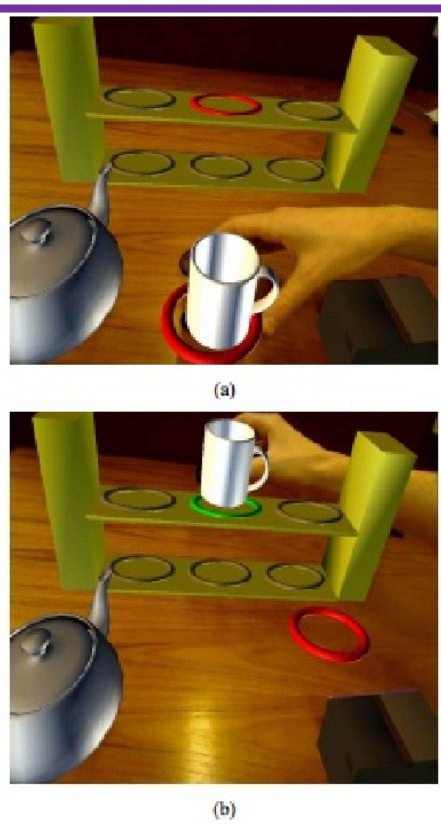


Figure 9: Augmented reality adding a home task related digital data to induce daily life activities training (J W Buker *et al.*, 2010).

The benefits of AR systems have already been experimented on different populations including children (E Richard, 2007) and stroke survivors (X Luo *et al.*, 2005; J W Buker *et al.*, 2010; Loh Yong Joo, 2010). Development of systems for children is also very important. This population needs an extra ludic factor in order to attract them to participate in the therapy. An AR based system was developed for cognitive rehabilitation of children. This study compared the interaction of healthy and disabled children with the system, and observed that the last one were very enthusiastic during the use of it. In general, all subjects showed to be more motivated, but mainly the autistic and trisomy children (**Figure 10**) (E Richard, 2007).

Figure 10: Augmented reality system associated with the use of real objects for autistic children. (Bai *et al.*, 2013).

Association of music as a ludic factor is also used for children, showing efficacy on the rehabilitation process (Correa *et al.*, 2009). Interacting with real objects is one interesting possibility provided by AR systems which was used to improve interaction and the ludic aspect for autistic children (Bai *et al.*, 2013).

Augmenting the real world can also be used to induce patient illusion. It has been show that for the patients who lost their movement, due neurologic causes, the visualization of the paralyzed segment moving can confuse the neurologic system and induce new connections, the neuroplasticity. An AR system was developed where the patient can see a virtual arm or hand moving in the place of their paralyzed one (**Figure 11**) (Klein e De Assis, 2013; Regenbrecht *et al.*, 2014). These systems showed AR utility presenting important advantage provided by their capability to induce illusion.

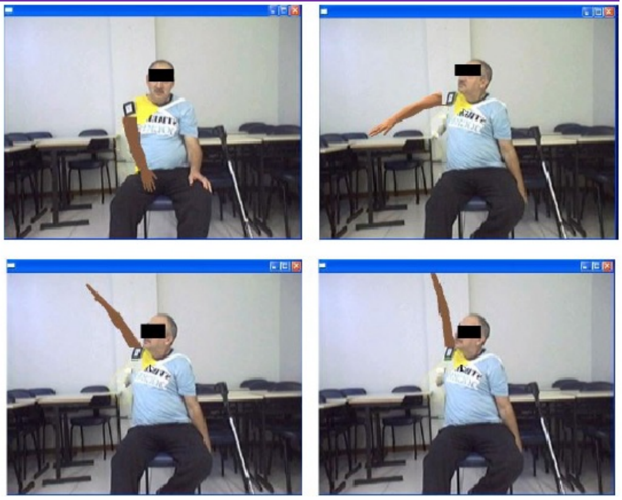


Figure 11: Augmented reality system for patient illusion to induce neuroplasticity (Klein e De Assis, 2013).

A study performed by Bell Boucher (Bell Boucher *et al.*, 2013) detected that for Parkinson patients the number of information provided should be controlled. These patients have difficulty with excess of information. Interface difficulties are also present in stroke patients which have difficulty with 3D scenes (Khademi *et al.*, 2013). All these limitations may occur also when the system is used by other neurologic and older patients. Due to that the type of interface, feedback and the number of information should be chosen carefully during the development of interactive systems.

In general, the interaction methods applied to devices used with AR systems for rehabilitation are predominantly marker based (J W Buker *et al.*, 2010; Bell Boucher *et al.*, 2013; Dionisio Correa *et al.*, 2013) or relies on the tracking of the color of an object (Aung e

Al-Jumaily, 2012; Khademi *et al.*, 2013). These markers are used as reference to gather information about the scene and the positioning of the virtual object, through which the treatment is directed to the patient.

It is common during the development of AR systems the integration of technologies trying to provide more information and senses to patients (Khademi *et al.*, 2012; Lu *et al.*, 2012; Bell Boucher *et al.*, 2013; Klein e De Assis, 2013). One example is the use of head mounted displays (X Luo *et al.*, 2005; Lee e Sheng-Chung, 2012; Bell Boucher *et al.*, 2013). The problem is that these attached equipment's are a drawback to natural interaction systems, contrariwise, the user should feel free when experiencing an interface, being not tied to additional objects (Valli, 2005). Although their immersion advantages, for daily use they may not be so practical. There is no indication that the use of large number of accessories and high level of immersion is beneficial for patients during rehabilitation.

It is common in AR systems to apply these techniques associated to haptic sensors to improve interaction (X Luo *et al.*, 2005). However, it is important to notice that for this kind of system it is very important that the scene is tracked in order to perform the overlapping of the augmented content. Due to that the isolate use of haptic or inertial sensors for interaction is not possible. These sensors provide motion information but no scene characteristic is given. For this reason, the AR developed systems which make use of these kind of interactive tools commonly integrate camera information (Khademi *et al.*, 2012; Lu *et al.*, 2012).

The limitation on using markers is that it restricts therapy and user mobility. This happens mainly due the limit of vision angle of the marker to the camera and tracking failures. Additionally, the use of markers makes interaction less natural, due to the need of attached equipment, and promotes reduction of tracking efficiency due the high incidence of motion blurs.

Interactions using marker tracking, color objects or haptic sensors have are limited for motor rehabilitation application due the fact that such technologies do not provide direct body references. This absence of anatomic information turns it difficult to analyze movement carefully. Movement information is a powerful tool not only for the patient current status evaluation but also for the storage and future analysis of his progress on the rehabilitation treatment (Chien-Yen *et al.*, 2012; Da Gama, A. *et al.*, 2012a). The advent of new technologies will certainly improve and allow low cost markerless tracking enabling development of more potential, directional and high quality rehabilitation systems (J W Buker *et al.*, 2010). The Kinect sensor is a new technology which goes in this direction and will be discussed in the next chapter (chapter 4).

3.3. Areas of Application

Interactive systems are more widely developed focusing on neurologic patients (Abdel Rahman e Shaheen, 2011), such as Stroke (Henderson *et al.*, 2007; Webster e Celik, 2014), Parkinson (A J Espay *et al.*, 2010; Bell Boucher *et al.*, 2013), traumatic brain injury (Ustinova *et al.*, 2013; Venugopalan *et al.*, 2013) patients, among others. They focus commonly upper (Henderson *et al.*, 2007) and lower limbs exercises (Cho e Lee, 2013), and also balance training (Cho *et al.*, 2012).

The predominance of systems for this public is probably because of the high incidence of these pathologies. Additionally, their chronic characteristics require rehabilitation for long periods of life. For these patients, therapy in a clinical environment is normally provided only in the first stages of therapy and then continued at home. If not, patients may pass the rest of their life going to clinics. Due to that, the development of rehabilitation systems which enable the patient to continue his therapy at home is crucial for the chronic neurologic patients.

However, this kind of system does not diminish the importance and applicability of system development for others contexts. In orthopedic and rheumatic rehabilitation, for example, the pain is a very limiting factor during exercise performance. With the help of interactive systems patients can be distracted from pain and perform better movements (Schonauer *et al.*, 2011; Li *et al.*, 2012). This way they will achieve better results and recovery. Children normally have difficulty to adapt to pain but they are easily distracted by VR systems. So it is beneficial to them using VR as a non-pharmacologic during physiotherapy sections (Steele *et al.*, 2003). The distraction factor proved by VR systems is also suggested as an anxiety reduction tool for hospitalized young patients (Kato, 2010).

The distraction from pain was also explored for burn-injured patients (**Figure 12**) (Hoffman *et al.*, 2001; Sharar *et al.*, 2008). The use of immersive VR to distract the patient while the therapist performed passive motion on the burned segment showed to be benefic (Sharar *et al.*, 2008). The VR psychological effects for pain distraction are also observed in cancer patients but in this case no studies involving exercise were performed (Baños *et al.*, 2013).

Figure 12: Immersive VR to distract burn-injured patient from pain while doing movement (Sharar *et al.*, 2008).

The use of virtual environments by amputees' subjects has also been proposed. It is done by the use of muscles sensors which detect residual activity of the limbs and convert this movement intention to movement of the virtual limb. The use of this simulation works in the motivational aspects for the amputees to perform the exercises to maintain their residual motor ability (Kuttuva *et al.*, 2005). The same principle can be used as an evaluation tool to check where the activation occurs during movement and help on prosthesis development (Hauschild *et al.*, 2007). In this field is also suggested the use of virtual environments for prosthesis trainee to quicker user adaptation (Pons *et al.*, 2005; Soares *et al.*, 2012).

Cardiac rehabilitation also can make use of interactive systems. The cardiologic program includes different stages of exercise according with rehabilitation phase. These exercises can be performed associated with a VR or AR systems in order to motivate patients in continue them. One study developed by Chuang and partners checked out the engagement of patients after coronary artery bypass graft in treadmill training associated with VR. They found improvement on patient exercise tolerance resulting in better oxygen utilization, cardiac supply and peak VO2 (Chuang *et al.*, 2005). In a transversal study analyzing effects of VR on cycling activity performing a cardiopulmonary test it was found an improvement on cycling duration, distance and user energy consumption, showing the engagement promoted by the VR during the aerobic activity (Chuang *et al.*, 2003).

Interaction with a machine can be done also with bio signals. Any biological signal can be used for interaction since it can be voluntary controlled by the user. These signals have to be acquired by some sensor, and the data information digitalized before being received by the computer which will interpret it and provide adequate response by the system.

The use of respiratory flow is an example which can be used for development of spirometer games (Figure 13) (Bingham *et al.*, 2010; Bingham *et al.*, 2012). Bingham and partners (Bingham *et al.*, 2012) developed spirometer games in order to provide pediatric patients with cystic fibrosis pulmonary exercise. The forced expiration controls some activity in the game. After application of the system they found improvement on pulmonary function tests (Bingham *et al.*, 2012).

Figure 13: Spirometer game with interaction performed according with flow data (Bingham et al., 2010).

It is possible also to use mioeletrical (Lyons *et al.*, 2003; Klein e De Assis, 2013) or cerebral signals (Qiang *et al.*, 2010) acquired by Electromyography and Electroencephalogram, respectively. The mioeletrical signal can be used to promote muscle control training. The cerebral system can train the cognitive system and also induce plasticity in patients without motor activity.

Sport training is another area which can benefit from interactive systems advantages. However due to their high level exercise performance required it is very useful to develop a system with high accuracy and vast motion information. So the use of multimodal systems with motion capture, muscle activity and other types of input is indicated (Tripicchio, 2012).

3.4. Evaluative systems

Evaluation is an important feature in rehabilitation systems, since it provides patients performance information and also their changes and improvements during rehabilitation. This can lead to information about rehabilitation effects and prognostics. Evaluative systems can also be used to plan and replan therapy. They can be integrated with an interactive system, providing extra functions (Danny Rado, 2009; Anton *et al.*, 2013; Brokaw *et al.*, 2013). But in this section we will focus on the researches developed directly for evaluative purposes.

The studies and development of methods for human motion capture started based on the need to understand normal and pathological locomotion. Movement´s changes are strongly related to human performance and treatment and prevention of a lot of diseases. The movement evaluation and understanding is very important for biomechanics and the rehabilitation area (Cappozzo *et al.*, 2005; Mundermann *et al.*, 2006).

Body capture and motion analysis for biomechanics and rehabilitation applications have some requirements. Therefore, methods are necessary to accurately measure locomotion patterns. It is also very important that the number of artificial stimulus be maximally reduced due the fact that they can be altered and mask the natural motion pattern (Mundermann *et al.*, 2006).

The study of motion capture started with the use of sequences of images and visual analysis of body part changes during the movement. All these information extracted from images is then used to motion description. The process started manually and nowadays it can be done automatically by motion capture systems (Mundermann *et al.*, 2006). The main technologies used for motion capture are markers attached to the body or body pose tracking based on multi camera views or depth cameras, such as the Kinect.

Marker based motion capture, also known as stereophotogrammetry, is the oldest and more accurate technique for movement analysis until now. This technology uses an infrared optical tracker which is a passive marker based motion tracking. It works by the user wearing markers or suits with retroreflective markers attached to them (Cappozzo *et al.*, 2005; Christian Schönauer *et al.*, 2011). The infrared retroflective markers are positioned in a way that they cover the user body and special cameras detect them (**Figure 14**). The computer reconstructs the movement based on the markers extracted. The problems of this method are in the applicability, cost and time required for data collection, processing and interpretation (Mundermann *et al.*, 2006). The stereophotogrammetry requires a laboratory environment and the attachment of markers or fixtures to the body's segments (Christian Schönauer *et al.*, 2011; Chien-Yen *et al.*, 2012). This laboratory condition besides making the process complicate, can also cause unknown experimental artifacts (Chiari *et al.*, 2005; Christian Schönauer *et al.*, 2011).

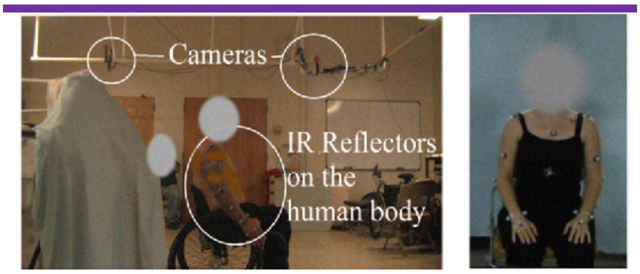


Figure 14: Stereophotogrammetry setup (Chien-Yen et al., 2012).

The problems crossed by the use of marker based motion capture systems stimulated researches trying to perform motion capture without any marker or artefact attached to the user's body (Mundermann *et al.*, 2006). Therefore, the use of cameras to detect human body pose has been studied (**Figure 15**) (Moeslund *et al.*, 2006; Mundermann *et al.*, 2006). However the accuracy of this method is dependent on the number of cameras. It has been shown that using less than 8 cameras is not indicated, prone to high error on estimation (Mundermann *et al.*, 2006). With this large number of cameras required this approach falls in the same setup and space requirement limitation of the marker based motion capture (Moeslund *et al.*, 2006; Mundermann *et al.*, 2006).

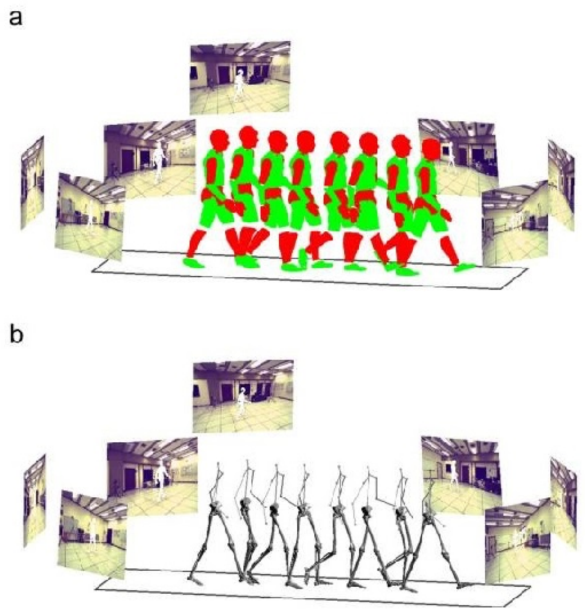


Figure 15: Markerless motion capture system based on multiple camera views (Mundermann et al., 2006).

A review about markerless movement analysis for biomechanical systems presented that besides the camera there are other several approaches which can be used to skeletal movement measure. These apparatus include stereoradiography, bone pins, external fixation devices, real-time magnetic resonance imaging (MRI) or single plane fluoroscopic techniques. Notwithstanding, these methods provide direct measurement of skeletal movement, they are invasive or expose the test subject to radiation (Mundermann *et al.*, 2006). So, it is easy to conclude that they are not practical and have no indication for clinical use.

The more recent technology developed for markerless motion capture is the RGB-D cameras, which include the Microsoft Kinect and Asus Xtion. These sensors provide depth information based on infrared light emission and capture. The emitter projects the infrared light in a determinate pattern which is recognized by the camera (**Figure 16**). The depth is then estimated by triangulation between camera and emitter information (Smisek *et al.*, 2013). Based on the depth information body pose can then be detected and used further for motion analysis. Since the Microsoft Kinect was the sensor chosen as the main tool in the development of this work, it will be discussed in more detailed in the next chapter.

Based on the exposed characteristics it is possible to conclude that for advancement in human motion capture it is useful the development of a non-invasive and markerless evaluative system (Mundermann *et al.*, 2006; Da Gama, A. *et al.*, 2012a). In human movement analysis, for biomechanical and rehabilitation applications the quantities that describe joint kinematics must be repeatable. For evaluation in the rehabilitation field it is desirable that the methods lend themselves to be interpreted consistently with the language in use in functional anatomy and related disciplines (Cappozzo *et al.*, 2005).

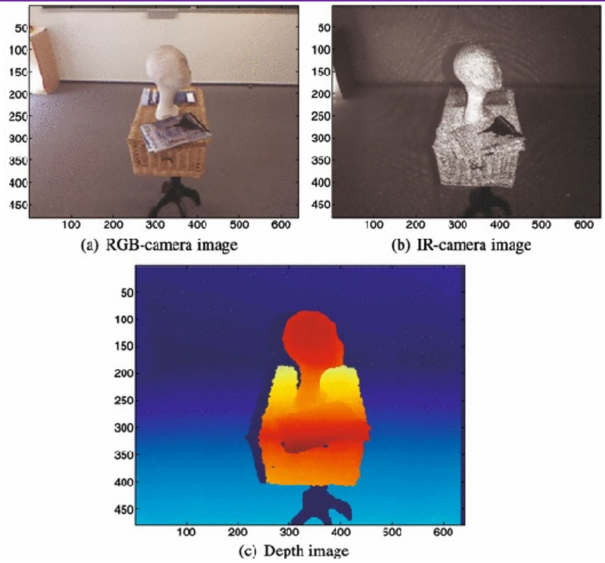


Figure 16: Kinect sensor RGB-camera image, infrared pattern image and depth image computed (Smisek et al., 2013).

3.5. SUMMARY

This chapter presented a brief literature review about the interactive systems for rehabilitation applications. It showed the motivations which lead development in this area, the technologies that are being used and how they are being applied. This text showed the systems based on VR and AR technologies. It also demonstrated the different areas in rehabilitation where such tools are being applied. The systems developed aiming to evaluate movement for rehabilitation purposes were also shown.

This literature review introduces the base aspects considered in the development of this work. The next chapter will also present conceptual studies but being more directed to the technology chosen to lead this work, the Kinect sensor.

4. THE MICROSOFT KINECT DEPTH SENSOR

Figure 17: Microsoft Kinect sensor.

With the intention of improving interaction systems without the necessity of any markers attached to the user's body, Microsoft launched the Kinect sensor (Microsoft, 2011). This sensor works with RGB-D technology which makes use of depth information to track skeletal data. A 3-D human motion capturing algorithm makes it possible to create interactions between users and an application, such as a game, without the need to touch/hold a controller.

Kinect and the other RGB-D devices available in the market are receiving a lot of attention thanks to their portability associated with a fast human skeleton recognition system developed on top of 3D measurement (Gonzalez-Jorge *et al.*, 2013).

With the appearance of this technology, several studies were developed trying to apply it in different fields, for example, games, human body tracking (Lu *et al.*, 2011), 3D reconstruction (Cui e Stricker, 2011; Izadi *et al.*, 2011) and rehabilitation (Lange *et al.*, 2011; Schonauer *et al.*, 2011; Chien-Yen *et al.*, 2012) and also studies to evaluate this technology, such as depth information precision (Gonzalez-Jorge *et al.*, 2013).

4.1. RGB-D SENSORS

Similar technologies to the Microsoft Kinect sensor were also produced. The first generation of RGB-D sensors includes besides the Microsoft Kinect, the Asus Xtion PRO LIVE and PrimeSense Carmine. These are based on a depth map generated using a projected pattern, according to a patent developed by PrimeSense (Freedman *et al.*, 2010).

The technology of these sensors combines structured light with computer vision techniques. The principle is simple; the emitter projects a known infrared light pattern into the scene and an infrared camera captures the result of this projection. The distortion of this light pattern allows the 3D depth map computation (Freedman *et al.*, 2010; Jungong *et al.*, 2013). The pattern is pseudo random, what reduces the interference effects of using multiple sensors since it is not the same pattern emitted. **Figure 18** shows the technique setup of depth mapping using structured light pattern with a light emitter and camera, and a depth scene represented by a hand.

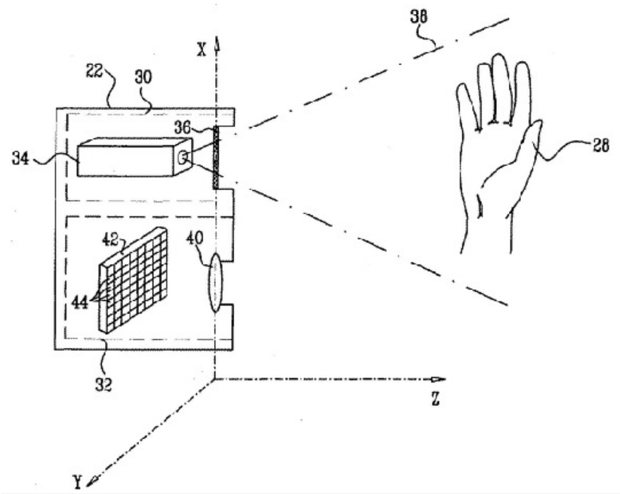


Figure 18: Technique of depth mapping using projected patterns (Freedman *et al.*, 2010).

The second generation of RGB-D sensors combines the RGB camera with a time-of-flight (ToF) sensor that provides a depth image of the scene. The ToF camera computes depth information by measuring the time that a light pulse takes to travel from the camera to an object and back (Payne *et al.*, 2014; Sell e O'connor, 2014). Examples of this generation include the Microsoft Kinect second version (Kinect v2), SoftKinetic DepthSense and Intel Creative Senz3D. This technology was developed trying to provide high-resolution, low-latency, lighting-independent 3D image sensing (Sell e O'connor, 2014).

4.2. SKELETON ESTIMATION SOFTWARE

The Kinect skeleton estimation software is an auxiliary library which receives information captured by the Kinect in order to perform skeleton estimation and provide skeleton tracking and joint positions. Actually there are two main tools to aid developers with Kinect sensor based implementation: OpenNI associated with Primesense´s NITE software (Primesense, 2011) and Microsoft Kinect SDK (Microsoft, 2011).

The main difference between the two principal software is the platform in which they can be used. Microsoft Kinect SDK (MSSDK) is available only for Windows (Microsoft, 2011) whereas OpenNI is a multiplatform and open-source tool (Primesense, 2011). The number of joints tracked is also different: 15 joints with OpenNI (Primesense, 2011) and 20 joints with MSSDK (the five additional points are the two wrists, two ankles and the hip center) (Microsoft, 2011). Additionally MSSDK is able to track user´s upper limbs when lower body is not visible, allowing its use for scenarios where the user is sitting in a wheelchair (Microsoft, 2011).

Despite these advantages, the MSSDK is more prone to false positives than the OpenNI, especially when the initial pose of a human body is too complicated, like squat. The calibration time varies greatly depending on environment conditions and processing power. Furthermore, OpenNI focuses on hand detection and hand-skeletal tracking whereas Microsoft SDK realizes simple gesture recognition, such as "grip" and "push" gestures (Jungong *et al.*, 2013).

4.3. KINECT V1 VERSUS KINECT V2

This thesis started in 2011 just after the release of Microsoft Kinect v1, which was November 2010. In July of 2014 Microsoft launched the second generation, Kinect v2. During the period of development some limitations using Kinect v1 were detected, mainly related to biomechanical applications. Due that, when the new generation of sensor arrived, we performed a preliminary test comparing Kinect versions analyzing these critical points in order to check the sensor improvements.

A brief description of the findings based on simple interaction tests performed using the SDKs demos will be presented here focusing on the improvements of Kinect v2 in relation to Kinect v1. The differences here presented are related to the skeleton tracking of Kinect v1 performed by the SDK 1.8 and Kinect v2 using the public preview 2.0 SKD.

The first difference between the two Kinect versions is the number of joints. The new Kinect provides five extra skeletal points estimations: Neck, Fingers tip (right and left hand) and Thumb (right and left). The skeleton points tracked by both Kinect versions are presented in **Figure 19**.

When using Kinect v1, one of the first problems detected was the location and behavior of shoulders joints during movement of the arm. This problem happens when the user moves his arm upper than 90 degrees, the location is lower than the real shoulder position, as can be seen in **Figure 19**. The Kinect v2 shows a more accurate position and stable behavior of joint estimation during movement.

By analyzing the upper limb region, another difference observed is that the scapular girdle movements can be detected using the new Kinect, what was not possible with the previous one. Figure 20 shows the skeleton tracking of Kinect v2 during scapular elevation. It is possible to notice that there is a change on joint's position during movement, which did not occur with the Kinect v1.

Observing the midline joints there was some changes also. The head position for the Kinect v2 is located a little further than the other joints of the line; this can be visualized in the diagonal view in Figure 19. This makes the normal position recognized as the head to be tilted frontally. Only when the head is tilted back the position stays aligned. This is very important to be considered when performing motion analysis. This also happens with the Kinect v1; however, due the higher distance for the next point the inclination is smoothed.

The spine center is also differently positioned. In the Kinect v1, it is positioned very low, at the lumbar spine. The new version presents a higher location for this point what seems to be a more adequate location. The first version provides a very distal reference resulting in a big gap of reference in all trunk.

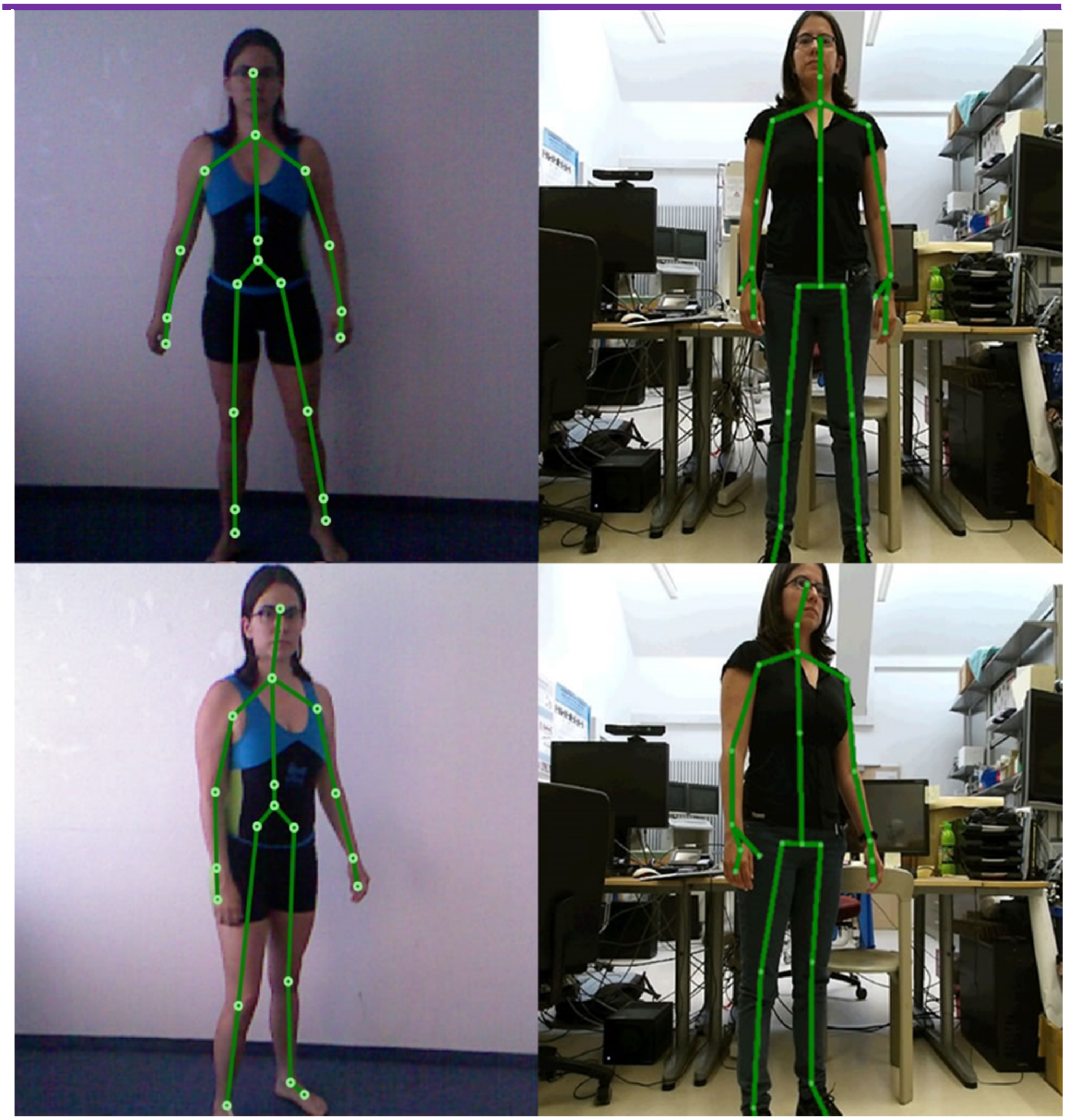


Figure 19: Kinect v1 (left) and Kinect v2 (right) skeletons tracking. Frontal (above) and diagonal view.

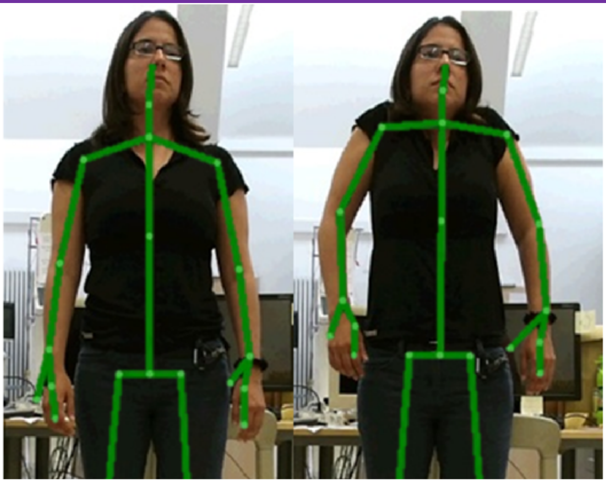


Figure 20: Skeleton tracking of Kinect v2 during scapular girdle elevation.

The same head position alignment problem that occurs in the new Kinect used to occur with the hip center estimation in the Kinect v1. The hip center in the old version is positioned a little frontally than the neighbor points. In the Kinect v2 this point is aligned with the others midline estimations. Figure 19 illustrates this difference.

For the other joints' estimations there are no big visual change compared to the old version. These tests show better skeleton recognition provided by the new Kinect generation, which solves some limitations of the first version. However, anatomic accuracy is yet a limitation.

4.4. Kinect based rehabilitation systems – Systematic Review

As presented before, interactive systems for motor rehabilitation purposes have been studied and developed. However, these systems present as main limitations the necessity of holding or attaching to the user's body some sensor or marker which can limit movement freedom, disturbing patient performance (Chien-Yen *et al.*, 2012). This limitation can be overcome with the use of sensors such as the Kinect. Additionally the Kinect technology allows the use of these systems at home due to its simplicity and low cost (Nixon *et al.*, 2013).

Taking into consideration these advantages, the Microsoft Kinect sensor was chosen to develop this work. Therefore, the review of Kinect for rehabilitation application was performed more rigorously. For that, a systematic review following was performed. This review was accepted for publication in the Games for Health Journal, and will be presented next.

Evidence Acquisition

The literature review was performed following the PRISMA protocol (Moher *et al.*, 2009). The first step of the review was to establish the search guideline for the paper selection. Based on the following question: What is the actual research status of Kinect, as a skeleton and movement recognition tool, for motor rehabilitation? We performed a systematic research in the IEEE Xplore and PubMed databases using the keyword combination 'Kinect AND rehabilitation'. These two databases were selected to screen papers in the technological and clinical fields respectively. To be included in the review, articles should follow the following criteria: (i) English language; (ii) page number > 4; (iii) Kinect system for assistive interaction or clinical evaluation, or (iv) Kinect system for improvement or evaluation of the sensor tracking or movement recognition.

The resulting papers were divided according to their main focus in the following categories: (a) Assistive: including development papers of rehabilitation assistive systems; (b) Evaluation: articles focusing on development of clinical measurement, movement analysis or classification techniques; (c) Applicability: papers presenting an application of a system in clinical routine; (d) Validation: includes validation or evaluation studies of Kinect skeleton tracking or measures for rehabilitation purposes; and (e) Improvement: papers describing improvements to the Kinect tracking or recognition directed to rehabilitation applications.

With the articles organized by category it was possible to evaluate their content. A list of minimal tenor required for paper acceptance follows below. Each category has unique criteria due the different methodologies used:

i. Assistive: should present a clear description on how to interact with the system and how to recognize the movement which is used during interaction.
ii. Evaluation: should perform an evaluation of a measure which is used in clinical daily routine in the evaluation step of rehabilitation, or a movement evaluation or classification. It should also present a detailed description on how it recognizes this measure and perform an evaluation of the validity of the measure.
iii. Applicability: should present the effect of the system comparing the results with a control group of patients that are not making use of the system (i.e. with clinical outcomes and statistics).
iv. Validation: should perform validation of the skeleton tracking or clinical measures used on rehabilitation comparing the Kinect results with gold standard methods.

The research within the databases performed in May 2014 detected a total of 109 papers (68 from IEEE Xplore and 41 from PubMed). After the evaluation of the first inclusion criteria described above 46 papers were included in the review. After checking the content criteria for each category 20 articles were excluded (Chang *et al.*, 2011; Dutta, 2012; Ilg *et al.*, 2012; Lloréns *et al.*, 2012; Strbac *et al.*, 2012; Chang *et al.*, 2013; Crocher *et al.*, 2013; Exell *et al.*, 2013; Luna-Oliva *et al.*, 2013; Metcalf *et al.*, 2013; Mortensen *et al.*, 2013; Paolini *et al.*, 2013; Penelle e Debeir, 2013; Rantz M. *et al.*, 2013; Shires *et al.*, 2013; Ustinova *et al.*, 2013; Dutta *et al.*, 2014; Galna *et al.*, 2014; Pompeu *et al.*, 2014; Ulaşlı *et al.*, 2014) leaving 26 eligible articles. Naturally in this review paper we only considered articles disseminated since 2010 since this coincided with the launch of Microsoft Kinect.

Lastly, to better present the review articles they were tabulated according to their specific characteristics. For each paper the information below (if available) were discussed:

- Skeleton tracking software used
- Movements analyzed and movement recognition procedures
- Visualization and feedback
- Features of system
- Evaluated measure

- Improvement technique
- System or user evaluation
- Results and opinion about system or technology

QUALITY OF REPORTING

A quality assessment of papers included in the review was performed. Since this review is focused on technology development and improvement for rehabilitation, the QualSyst standards (Kmet *et al.*, 2004), developed by the Healthy Technology Assessment (HTA) research group, was selected for quality control. The QualSyst guideline (Kmet *et al.*, 2004) is composed of 14 items evaluating study questions: design methodology, sample, outcomes, results outcomes, description, and conclusions. Four items were not included due the non-applicability in our study's methodology: random allocation, evaluator binding, user blinding, and confounding. To compute the final score, each item is classified as total, partial and none with assigned values of 2, 1 or 0 points respectively. The total sum should be divided by the maximal possible points (e.g. 10 items x 2 points = 20 points). The final score of each included review paper will be presented as a percentage.

EVIDENCE SYNTHESIS

Thirteen of 26 papers were focused on the development of assistive systems for rehabilitation (Cordella *et al.*, 2012; Da Gama, A. *et al.*, 2012a; Anton *et al.*, 2013; Barresi *et al.*, 2013; Borghese *et al.*, 2013; Brokaw *et al.*, 2013; Dukes *et al.*, 2013; Fraiwan *et al.*, 2013; Ibarra Zannatha *et al.*, 2013; Robertson *et al.*, 2013; Roy *et al.*, 2013; Sadihov *et al.*, 2013; Ting-Yang *et al.*, 2013). From the 15 excluded papers in the content inclusion criteria one was of this category and was excluded since it did not present a clear description of skeleton tracking and movement recognition procedures (Crocher *et al.*, 2013). The description of the main characteristics of these papers is presented in **Table 1**. In the Assistive category, the predominance of developed systems involved patients controlling an avatar or a game to perform a predetermined task to stimulate one or more movements required during rehabilitation (Cordella *et al.*, 2012; Anton *et al.*, 2013; Barresi *et al.*, 2013; Borghese *et al.*, 2013; Dukes *et al.*, 2013; Fraiwan *et al.*, 2013; Ibarra Zannatha *et al.*, 2013; Robertson *et al.*, 2013; Roy *et al.*, 2013; Sadihov *et al.*, 2013). The other two system interactions were performed by an image generated for patients to mimic, one via a reference video (Ting-Yang *et al.*, 2013) and the other via a task guiding exercise (Da Gama, A. *et al.*, 2012a). Finally, Brokaw et al. (Brokaw *et al.*, 2013) developed a system with real targets and feedback enabled by a haptic glove. To interact with these systems the main movement recognition was the tracking of hand position (Cordella *et al.*, 2012; Barresi *et al.*, 2013; Ibarra Zannatha *et al.*, 2013; Robertson *et al.*, 2013; Roy *et al.*, 2013; Sadihov *et al.*, 2013), and the mimic recognition with direct comparison of the 3D points in relation to a pre-recorded movement (Anton *et al.*, 2013; Borghese *et al.*, 2013; Brokaw *et al.*, 2013; Fraiwan *et al.*, 2013; Ibarra Zannatha *et al.*, 2013; Ting-Yang *et al.*, 2013). The last two recognitions were the maximum and minimum position of upper limb joints during reaching activities (Dukes *et al.*, 2013) and angle computed on the plane where the movement is being performed (Da Gama, A. *et al.*, 2012a). Regarding tracking, we note a predominant use of upper limb movements to interact with systems, in which tracked the 3D joint positions (Anton *et al.*, 2013; Borghese *et al.*, 2013; Brokaw *et al.*, 2013; Fraiwan *et al.*, 2013; Ibarra Zannatha *et al.*, 2013; Ting-Yang *et al.*, 2013). The key movement performed was general upper limbs movements (Anton *et al.*, 2013; Barresi *et al.*, 2013; Borghese *et al.*, 2013; Brokaw *et al.*, 2013; Fraiwan *et al.*, 2013; Ibarra Zannatha *et al.*, 2013; Roy *et al.*, 2013) as well as the 'reaching' movement in three papers, where the patient has to simulate a functional activity and achieve some object to complete the task (Dukes *et al.*, 2013; Robertson *et al.*, 2013; Sadihov *et al.*, 2013). The other papers had patients interact with hand grasping (Cordella *et al.*, 2012), Tai Chi movements (Ting-Yang *et al.*, 2013), and therapeutic movements (Da Gama, A. *et al.*, 2012a). Different features to help patient and therapist in the system were also discussed. Enabling the therapist to configure the technology was presented in (Anton *et al.*, 2013; Borghese *et al.*, 2013; Fraiwan *et al.*, 2013). Warnings to inform when the exercise is being performed in a wrong way (Da Gama, A. *et al.*, 2012a; Anton *et al.*, 2013; Roy *et al.*, 2013; Ting-Yang *et al.*, 2013), as well as guidance to orientate how to perform the proper movements through visual (Da Gama, A. *et al.*, 2012a), haptic(Brokaw *et al.*, 2013) or robotic (Ibarra Zannatha *et al.*, 2013) feedback are also presented. Three of the studies presented a performance evaluation which enables therapists to have information about how a patient executed an exercise during specific tasks (Cordella *et al.*, 2012; Brokaw *et al.*, 2013; Roy *et al.*, 2013). One additional study performed a patient auto-report evaluation (Anton *et al.*, 2013). For rehabilitation an important feature is the capability of a system to adapt to patient limitation (Borghese *et al.*, 2013; Dukes *et al.*, 2013; Sadihov *et al.*, 2013). Tele-rehabilitation to enable patient-therapist communication was presented in one of the systems (Roy *et al.*, 2013). An additional feature was the illusion characteristic which was developed with the intention to give a patient the sensation of a complete movement in the injured limb in order to induce them to perform better movements (Dukes *et al.*, 2013; Robertson *et al.*, 2013). These systems were developed targeting the general rehabilitation population (Cordella *et al.*, 2012; Da Gama, A. *et al.*, 2012a; Anton *et al.*, 2013; Barresi *et al.*, 2013; Borghese *et al.*, 2013; Fraiwan *et al.*, 2013) or specific for neurologic patients (Roy *et al.*, 2013; Ting-Yang *et al.*, 2013), mainly strokes (Brokaw *et al.*, 2013; Dukes *et al.*, 2013; Ibarra Zannatha *et al.*, 2013; Robertson *et al.*, 2013; Sadihov *et al.*, 2013).

The Evaluation category was the subject in six reviewed papers (Exell *et al.*, 2013; Kitsunezaki *et al.*, 2013; Leightley *et al.*, 2013; Rantz M. *et al.*, 2013; Seung-Kook *et al.*, 2013; Dutta *et al.*, 2014). From the six, one was excluded due to the absence of evaluation of the measure (Exell *et al.*, 2013) and two which did not evaluate clinical measures (Rantz M. *et al.*, 2013; Dutta *et al.*, 2014). **Table 2** presents the characteristics of the three included papers in this category. The evaluation through classification was the subject of two of the papers. One paper focused on the individual classification using Principal Component Analysis (PCA) and K-Nearest Neighbors (Seung-Kook *et al.*, 2013) and the second paper used Support Vector Machines and Random Forests, trained on the PCA feature space, and showed results were proportional to the classification of the exercise performed (Leightley *et al.*, 2013). The third paper (Kitsunezaki *et al.*, 2013) assessed the capability of Kinect when performing some kinetic functional tests: Up & Go test – the patient has to get up and walk 3 meters, get back and sit; 10 meters walk test – the patient has to walk 10 meters; and Range of Motion test – angle of movement of each joint in a specific plane.

For the Applicability category thirteen papers were found. However, most of them presented only a simple application of systems with no comparison to a control group of users not using the system (Chang *et al.*, 2011; Ilg *et al.*, 2012; Lloréns *et al.*, 2012; Chang *et al.*, 2013; Luna-Oliva *et al.*, 2013; Mortensen *et al.*, 2013; Ustinova *et al.*, 2013; Galna *et al.*, 2014; Pompeu *et al.*, 2014; Ulaşlı *et al.*, 2014). Hence, only three papers were included in this category (Rosa *et al.*, 2013; Sin e Lee, 2013; Hsieh *et al.*, 2014) and their main characteristics are described in

Table 3. From the three papers only one tested a system develop specifically for rehabilitation (Hsieh *et al.*, 2014), the other two evaluated the efficacy using the commercial video-game Xbox 360 with the Kinect games (Rosa *et al.*, 2013; Sin e Lee, 2013). Each study focused on different pathologies with no prevalence of participants. All games focused on upper limb movement activities (Rosa *et al.*, 2013; Sin e Lee, 2013; Hsieh *et al.*, 2014), however the benefits and outcomes were related to global effects in balance and posture in all papers, with only one of them evaluating Range of Motion (Sin e Lee, 2013).

The Validation category included seven papers (Mobini *et al.*; Schonauer *et al.*, 2011; Fern'ndez-Baena *et al.*, 2012; Obdrzalek *et al.*, 2012; Kurillo *et al.*, 2013; Nixon *et al.*, 2013; Bonnechère *et al.*, 2014). These works are presented in

Table 4. Almost all studies used as gold standard a marker infrared motion capture, except for one paper which used a plywood model as reference (Mobini *et al.*). Validation of angle measures was performed in 4 papers, two evaluating main limb joints angles (Fern'ndez-Baena *et al.*, 2012; Bonnechère *et al.*, 2014) and the other focusing only on upper limbs (Kurillo *et al.*, 2013) and shoulder angles (Nixon *et al.*, 2013). Two of them evaluated also direct 3D measures of joints positions (Kurillo *et al.*, 2013; Bonnechère *et al.*, 2014). For the last three papers, 3D point comparison was performed for hand and feet positions (Schonauer *et al.*, 2011), the entire human skeleton (Obdrzalek *et al.*, 2012), and also joint center displacements for the main upper limbs joints (Mobini *et al.*).

QUALITY OF THE STUDIES

In the Assistive category, the mean QualSyst score was 47.7%. All of the presented systems were technically well-built, however the methodology descriptions and evaluations of the system were limited thus lowering the total quality score. This category featured issues when defining the research objectives, since most papers simply described a system instead of answering a research question. Furthermore, the main problem occurred with the evaluation of the system as (i) the sample size of participants in the user study was small (53.8%) (Da Gama, A. *et al.*, 2012a; Anton *et al.*, 2013; Brokaw *et al.*, 2013; Dukes *et al.*, 2013; Roy *et al.*, 2013; Sadihov *et al.*, 2013; Ting-Yang *et al.*, 2013), or (ii) there was no user study and full system results (38.5%) (Cordella *et al.*, 2012; Borghese *et al.*, 2013; Fraiwan *et al.*, 2013; Ibarra Zannatha *et al.*, 2013; Robertson *et al.*, 2013). For those that showed results the quality was low (Anton *et al.*, 2013; Brokaw *et al.*, 2013; Roy *et al.*, 2013; Sadihov *et al.*, 2013). In conclusion, these studies indicate the need to perform proper evaluations of the systems to assess both the feasibility and applicability of the technology when transferred to rehabilitation scenarios.

The Evaluation category presented better QualSyst scores with a mean value of 81.6%. Similar to the Assistive category, a major issue of this category is the lack of a proper sample size in the user studies. Only one article featured a statistically significant population size (Leightley *et al.*, 2013), measured by the difference between the mean and standard errors (Kmet *et al.*, 2004). The other two studies had scores ≥ 70% points but still had a limited sample size (Kitsunezaki *et al.*, 2013; Seung-Kook *et al.*, 2013).

QualSyst scores for Applicability category presented a mean of 85% with two papers presenting 95% score. Only one paper presented a lower score (65%) due to the choice of control group with no specific therapy. This makes it difficult to compare the effect of the proposed system in relation to traditional therapy, raising the question if the benefits were related to the system or only to the physical activity performed.

With a mean score of 79.3% in QualSyst, the Validation category also presented low scores on sample size, but also in description. A description of the sample containing some characteristics of the users was performed in only two papers (Kurillo *et al.*, 2013; Bonnechère *et al.*, 2014), with 57.1% of studies only outlining the numbers of tested subjects (Obdrzalek *et al.*, 2012; Nixon *et al.*, 2013), or complete absence of sample information (Schonauer *et al.*, 2011; Fern'ndez-Baena *et al.*, 2012). One of the papers validated with the plywood model did not require sample size (Mobini *et al.*). For this category, this is a serious limitation since a proper validation relies on statistical reliability from a large participation pool. Only one study presented enough sample size which included 48 subjects (Bonnechère *et al.*, 2014), however only four main movements were evaluated. The other two largest sample size in the included studies was respectively 19 (Nixon *et al.*, 2013) and 10 subjects (Kurillo *et al.*, 2013), but the results showed high standard deviations (Kmet *et al.*, 2004). The study that achieved the lowest score for this category was (Schonauer *et al.*, 2011) as no detailed result description in the Kinect validation was performed.

DISCUSSION

At the end of 2010, Microsoft launched the Kinect sensor (Microsoft, 2011) for the video game Xbox 360. Kinect has subsequently gained popularity in the areas of gaming (Soltani *et al.*, 2012; Borghese *et al.*, 2013), robotics (Boyraz *et al.*, 2013), gestures (Chaves *et al.*, 2012; Soltani *et al.*, 2012), medical (Gallo *et al.*, 2011) and rehabilitation applications.

Kinect has found a niche in rehabilitation primarily because of its portability, low-cost, and its markerless feature (Bo *et al.*, 2011; Fern'ndez-Baena *et al.*, 2012; Dukes *et al.*, 2013; Metcalf *et al.*, 2013; Penelle e Debeir, 2013; Seung-Kook *et al.*, 2013). As a result of its compactness, it is now foreseeable to develop a complete system which enables patients to perform their exercise at home in a supervised, interactive and motivated manner (Da Gama, A. *et al.*, 2012a; Barresi *et al.*, 2013; Borghese *et al.*, 2013; Metcalf *et al.*, 2013; Roy *et al.*, 2013; Ustinova *et al.*, 2013). Besides these aspects, it also enables patients to go home with all advantages of a virtual/augmented reality system which includes configuration of therapy (Anton *et al.*, 2013; Borghese *et al.*, 2013; Fraiwan *et al.*, 2013), evaluation for therapeutic accompaniment (Cordella *et al.*, 2012; Anton *et al.*, 2013; Roy *et al.*, 2013), adaptable to patient limitations (Borghese *et al.*, 2013; Dukes *et al.*, 2013; Sadihov *et al.*, 2013), and increased exercise guidance and control (Da Gama, A. *et al.*, 2012a; Roy *et al.*, 2013; Ting-Yang *et al.*, 2013). Additionally, the markerless feature of Kinect enables a natural user interaction for rehabilitation applications, which alleviates existing issues for patients having pathologies that make it impossible for them to hold any sensor or marker (Da Gama, A. *et al.*, 2012a; Ave *et al.*, 2013; Garrido *et al.*, 2013).

Stimulated by these favorable features of Kinect, various research works are being performed for the development of assistive systems that help to interact with patients during their therapeutic exercises. These systems are developed for general rehabilitation (Cordella *et al.*, 2012; Da Gama, A. *et al.*, 2012a; Anton *et al.*, 2013; Barresi *et al.*, 2013; Borghese *et al.*, 2013; Fraiwan *et al.*, 2013) or mainly for neurologic patients (Brokaw *et al.*, 2013; Dukes *et al.*, 2013; Ibarra Zannatha *et al.*, 2013; Robertson *et al.*, 2013; Roy *et al.*, 2013; Sadihov *et al.*, 2013; Ting-Yang *et al.*, 2013). This predominance probably occurs due the higher chronicity of these pathologies which requires long rehabilitation. However, most of these studies were performed with samples smaller than 10 subjects (Cordella *et al.*, 2012; Obdrzalek *et al.*, 2012; Anton *et al.*, 2013; Borghese *et al.*, 2013; Brokaw *et al.*, 2013; Dukes *et al.*, 2013; Fraiwan *et al.*, 2013; Ibarra Zannatha *et al.*, 2013; Kitsunezaki *et al.*, 2013; Robertson *et al.*, 2013; Seung-Kook *et al.*, 2013; Ting-Yang *et al.*, 2013; Hsieh *et al.*, 2014).

As described previously, the predominant interaction in the existing rehabilitation systems were through an avatar or game, probably due to the interest on increasing patient motivation to perform the exercises. Through the use of these games the system tries to induce the patient to perform a predetermined task to stimulate one or more movements required during rehabilitation (Cordella *et al.*, 2012; Anton *et al.*, 2013; Barresi *et al.*, 2013; Borghese *et al.*, 2013;

Dukes *et al.*, 2013; Fraiwan *et al.*, 2013; Ibarra Zannatha *et al.*, 2013; Robertson *et al.*, 2013; Roy *et al.*, 2013; Sadihov *et al.*, 2013). A large selection of papers focused on patient 'reaching' movements as these are frequent in everyday life. 'Reaching' movements enabled physiotherapists to adapt the maximum and minimum ranges of a task according to the patient range limitation (Borghese *et al.*, 2013; Dukes *et al.*, 2013; Sadihov *et al.*, 2013), in hope of not demotivating the patient during the rehabilitation exercises.

Movement recognition is an important characteristic during system development since it is related to user interactivity, adaptability and performance during rehabilitation. Movement recognition is primarily performed through hand tracking (Cordella *et al.*, 2012; Barresi *et al.*, 2013; Robertson *et al.*, 2013; Roy *et al.*, 2013), however this limits patients to 'reaching' exercises, which ends the possibility to control and track shoulder and elbow movements simultaneously. The mimic recognition has the advantage to enable a system configuration with any prerecorded movements since it can be recognized by Kinect (Anton *et al.*, 2013; Borghese *et al.*, 2013; Brokaw *et al.*, 2013; Fraiwan *et al.*, 2013; Ting-Yang *et al.*, 2013). Nevertheless this method can only label the outcome of the exercise as 'right' or 'wrong' with no added clinical information. On the other hand, movement recognition by angles in a predetermined plane was proposed (Da Gama, A. *et al.*, 2012a), with the advantage of enabling different exercises according to a therapeutic configuration. However this study was limited to upper limb exercises (Da Gama, A. *et al.*, 2012a).

For home interactive systems, it is important that they include the capability to evaluate patient performance in activities, as well as evaluate clinical measures which can be used to analyze kinetic functional movements. The works in (Cordella *et al.*, 2012; Brokaw *et al.*, 2013; Roy *et al.*, 2013) only evaluated interactivity performance and not clinical outcome measurements. The consideration of patient information was considered by Anton et al. (Anton *et al.*, 2013) who allowed patients to fill in an auto-report questionnaire including pain level. This information provides therapists on how exercises were performed and how the patient feels subsequently.

Regarding the assessment of patient rehabilitation at home, Kitsunezaki et al. (Kitsunezaki *et al.*, 2013) evaluated the applicability of some functional tasks performed using Kinect by comparing the system measure with the clinical evaluation of the therapist. They found good correlation with similar results between the clinical procedure and the Kinect evaluation concluding that the system has practical utility. However for angle measures there is a limitation when the movement range is small (Kitsunezaki *et al.*, 2013). The classification studies also demonstrated good applicability of Kinect for movement analysis, resulting in good accuracy (95%) (Seung-Kook *et al.*, 2013) and enough classification rates with a reasonable number of subjects (8-10) during the training process (Leightley *et al.*, 2013).

The real effects in the practice of Kinect systems were shown in the papers within the Applicability category. The included studies found improvements in clinical outcomes including balance (Rosa *et al.*, 2013; Hsieh *et al.*, 2014), posture, sensory information (Rosa *et al.*, 2013; Sin e Lee, 2013) and range of motion (Sin e Lee, 2013). In the study performed with patients having Multiple Sclerosis (Rosa *et al.*, 2013), the effects on posture and sensory information with the use of a Kinect game was better than traditional therapy. One hypothesis for that is the opportunity of patients to play more times a week than in traditional therapy groups. The same conclusion was found in the study with Stroke patients where the experimental group performing traditional therapy resulted in a larger rehabilitation time (Sin e Lee, 2013).

Although there are numerous benefits when using the Kinect sensor, it also has its limitations. The main issues of Kinect related to rehabilitation are the non-anthropometric reference for skeleton tracking and the occlusion problems during movement performance (Obdrzalek *et al.*, 2012). Other limitations concerning Kinect tracking is the space requirements and lighting conditions. The ideal space to work with the Kinect is 1-2 meters distance from the sensor and with no direct sunlight (Gonzalez-Jorge *et al.*, 2013). In order to evaluate the capability of Kinect and the influence of these limitations for rehabilitation, studies have been performed comparing the Kinect measurement precision to infrared marker motion capture as the gold standard (Schonauer *et al.*, 2011; Fern'ndez-Baena *et al.*, 2012; Obdrzalek *et al.*, 2012; Kurillo *et al.*, 2013; Nixon *et al.*, 2013; Bonnechère *et al.*, 2014). According to some Validation studies, Kinect worked well when measuring the patient activities which included 'reachable' workspaces for upper limbs (Schonauer *et al.*, 2011; Kurillo *et al.*, 2013) and stride length (Schonauer *et al.*, 2011). Since some of the developed assistive systems in this review paper used hand reaching positions as the interactive tool (Cordella *et al.*, 2012; Barresi *et al.*, 2013; Robertson *et al.*, 2013; Roy *et al.*, 2013), the studies described above (Schonauer *et al.*, 2011; Kurillo *et al.*, 2013) indirectly validated those papers.

Joint angle is an important measure that can be computed from the Kinect data. The angle is an important measure performed in clinical practice to define therapy aims and also to accompany patient progression during therapy. The use of the skeleton extracted from Kinect to measure angles was evaluated (Fern'ndez-Baena *et al.*, 2012; Nixon *et al.*, 2013; Bonnechère *et al.*, 2014) and these papers concluded that this technology is a useful and potential tool for measuring angles in rehabilitation applications, with a maximum error of 10% (Nixon *et al.*, 2013), +10° (Fern'ndez-Baena *et al.*, 2012) and -11° (Bonnechère *et al.*, 2014). This accuracy is acceptable compared to the routine therapeutic manual measure. Furthermore, it is important to note that these are the maximum errors for the movements that are more difficult to track and more influenced by occlusion. But movements which present good visualization for the Kinect camera offer very good accuracy levels (e.g. shoulder abduction presented only 0.9° degree difference in relation to marker tracking (Bonnechère *et al.*, 2014)).

To evaluate the general accuracy of Kinect, a comparison of direct 3D joint positions with traditional marker techniques was performed (Obdrzalek *et al.*, 2012; Kurillo *et al.*, 2013; Nixon *et al.*, 2013; Bonnechère *et al.*, 2014). The result of these studies demonstrates that Kinect accuracy is dependent on movement and user position. Reliable and reproducible accuracy is found in planar motions (Bonnechère *et al.*, 2014) and standing position (Obdrzalek *et al.*, 2012). However this becomes problematic in situations of occlusion, or when objects are close to each other (e.g. Kinect will not disambiguate patient body limbs accurately when sitting in a chair – **Figure 21**) (Obdrzalek *et al.*, 2012). The accuracy on joint positions is not a Kinect limitation, but a limitation on anatomic position of joints, which is found even in traditional marker techniques. This is highlighted in (Kurillo *et al.*, 2013) which evaluated the accuracy with a plywood model and found sufficient accuracy for rehabilitation for upper limbs.

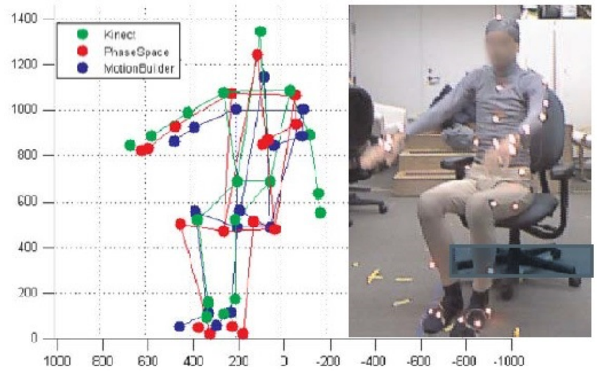


Figure 21: Example of a failed skeletonization performed by Kinect (green skeleton) compared with two marker motion capture systems: online - PhaseSpace’s Recap (red skeleton) and offline - Autodesk Motionbuilder (blue skeleton). The chair was mistaken for the left arm (Obdrzalek et al., 2012)

Another limitation of Kinect is the precision of its hand tracking (Strbac *et al.*, 2012; Exell *et al.*, 2013; Metcalf *et al.*, 2013; Shires *et al.*, 2013). Depending on the software used for skeleton tracking, the user hand may not be visible. When it is present it is depicted as a point in space which makes it difficult to disassociate the finger joints. When treating several pathologies with rehabilitation, hand and finger movements are required to perform functional movements and fine motor skills. For this, it is essential that a complete hand tracking including thumb and finger movements are performed. Several studies (Strbac *et al.*, 2012; Metcalf *et al.*, 2013; Shires *et al.*, 2013) achieved good accuracy and applicability of the Kinect for hand and finger detection. In these studies the Kinect is positioned focusing on the hand, normally a superior view from a table, not requiring the view of all body and any skeleton positions. Metcalf et al. (Metcalf *et al.*, 2013) compared the hand tracking results with the marker motion capture and demonstrated that Kinect accuracy levels increase with a specific range of motion (i.e. 97% accuracy at 10° motion). Lastly, the study by Paolini et al. (Paolini *et al.*, 2013) tried to improve foot tracking via visible markers, for the evaluation of walking exercises, and found it to be an effective solution.

As presented in this review the possibilities of research and development with the Kinect for rehabilitation applications are extensive. A system which allows the physiotherapist to configure patient interaction with different movements and exercises, according to their physical limitation and stage of recovery, is yet to be conceived. Additionally an interactive system using Kinect for augmented reality was not found in this review. Hence, a complete system must be developed which consists of all the features required for an effective rehabilitation assisted technology: therapeutic configuration, different exercise possibilities, guidance, and feedback (warnings).

It is important that systems are capable of evaluating the clinical measures that are traditionally used during therapy. This will aid physiotherapists in making diagnostic and prognostic assessments. This is an open area of research yet to be explored.

4.5. SUMARRY

This chapter presented the Kinect sensor characteristics and how this technology work. The Kinect sensor is a RGB-D camera capable to detect 3D scene and body. This chapter also described the skeleton estimation software and brings a brief description of the two Kinect versions, the first one released at the beginning of this work, December 2011, and the new version launched during the last months of this work, August 2014. The comparison is focused in skeleton recognition characteristics which have influences on the rehabilitation applications. The chapter finishes presenting a systematic review about Kinect based rehabilitation systems, showing the status of researchers on this field and the lacunas. This review showed that diverse interactive systems for patient motivation during rehabilitation using this technology are being developed, however they focus on generic movements without recognizing them according with the therapeutic language. It also showed the low methodology quality of studies which develop these systems with few system tests and no or small user test. These results helped on guiding this work.

Table 1: Characteristics of papers of the Assistive category.

Study	QualSyst score	Type	Target population	Visualization / Feedback	Skeleton tracking	Movements	Recognition procedure	Features of system	User / System evaluation	Results / Opinion
Anton et al. 2013 (Anton *et al.*, 2013)	50%	Virtual system	General Rehabilitation	Screen video / Reference and patient avatar; Target and warning	MSSDK	Any movement recorded	Initial and final position + trajectory of main 3D joints	Configuration by therapist; Warnings; Evaluation – patient auto report and system	5 users – compared with therapeutic supervision	91% posture warning; 88% correct detection of correct exercises and 94% of wrong ones
Barresi et al. 2013 (Barresi *et al.*, 2013)	95%	Virtual double system	General Rehabilitation	Screen trajectory and smartphone	OpenNI	Hand trajectory and touch	Hand 3D position	Dual task coordination	12 researcher questionnaire and time + collision numbers	Dual task fatigue distraction; ↑time to tolerate exercise ↓precision ↑collision
Borghese et al. 2013 (Borghese *et al.*, 2013)	20%	Virtual game	General Rehabilitation	Screen game	MSSDK	Upper limb movements	Normalized joint position comparison	Configuration by therapist; Adaptable to patient; Tele-communication	-	Personalized health system
Brokaw et al. 2013 (Brokaw *et al.*, 2013)	45%	Guidance system	Stroke	Haptic feedback	MSSDK	Upper limb movements	Direct joint position trajectory	Evaluation and guidance through haptic effector robot	One health subject tested	Coordination training
Dukes et al. 2013 (Dukes *et al.*, 2013)	75%	Virtual game	Stroke	Screen game / Avatar with complete amplitude of movement	MSSDK	Upper limb reach movements	Minimum and maximum position of shoulder elbow and wrist were memorized by keyboard pressing	Adaptation to patient limit; Illusion motivation	6 participants in 5 sections; Pre and Post	↑patients movements
Fraiwan et al. 2013 (Fraiwan	15%	Virtual game	General Rehabilitation	Screen game / Reference and patient	OpenNI	Any recorded movement	Direct joint position comparison	Configuration by therapist	-	Stimulate therapy

***et al.*, 2013)**				avatar						
Ibarra Zannatha et al 2013 (Ibarra Zannatha *et al.*, 2013)	20%	Interactive Virtual Environment + NAO robot	Stroke	Screen targets	MSSDK	Shoulder and elbow plane movements	Joint angles – projection on the plane	Robotic therapist	-	Robot therapist to improve time-cost therapist relation
Robertson et al. 2013 (Robertson *et al.*, 2013)	45%	Virtual game and illusion	Stroke	Screen duplicated virtual hand and game	Frantracer	Hand visualization and reach movements	Hand tracking	Illusion visualizing the paretic hand as the healthy one	-	Illusion accessive and interesting; Not good results in hand tracking
Roy et al. 2013 (Roy *et al.*, 2013)	50%	Virtual game	Neurologic patients	Screen game / Avatar plus visual and audio warning	MSSDK	Shoulder abduction and hand stability	Hand trajectory tracker	Warnings; Performance evaluation; Tele-communication	6 patients and 5 specialists – subjective questionnaire	Fun; Easy; Homecare
Sadihov et al. 2013 (Sadihov *et al.*, 2013)	35%	Virtual haptic system	Stroke	Screen game / Feedback through gloves	OpenNI	Reaching UL activities	Hand position	Adaptable to patient	Therapists and patients – Reaction time and others	↑Haptic sensor immersion
Ting-Yang et al. 2013 (Ting-Yang *et al.*, 2013)	70%	Virtual system	Parkinson	Screen video / Reference video and auto-image plus warning	MSSDK	Tai chi movements	Direct joint position comparison	Warnings	2 patients: baseline x intervention	↑Exercise performance
Cordella et al. 2012 (Cordella *et al.*, 2012)	25%	Virtual system	General Rehabilitation	Screen reference hand and target	OpenKinect	Hand grasp	Direct hand joint position trajectory	Performance evaluation	-	Enable patient performance evaluation
Da Gama	75%	Virtual	General	Screen auto-	OpenNI	Shoulder and	Shoulder angle	Warnings;	3 therapists,	↑Efficacy detecting

et al. 2012 (Da Gama, A. *et al.*, 2012a)		system	Rehabilitation	image, target and warning		elbow therapeutic movements	and angle in relation to the plane of movement	Guidance	4 adults and 3 elderly - Angle compared with goniometry; Correction evaluated by a therapist; Usability test	correct therapeutic exercises, avoiding wrong ones; ↑exercise performance

Table 2: Characteristics of papers of the Evaluation category.

Study	QualSyst score	What was evaluated?	Target population	Skeleton tracking	Recognition procedure	Reference for evaluation	System evaluation	Results / Opinion
Seung-Kook et al. 2013 (Seung-Kook *et al.*, 2013)	70%	Individual classification during a squat exercise	Knee Osteoarthritis	MSSDK	Principal Component Analysis (PCA) and K-Nearest Neighbors Method to relate exercise with individual	Euclidian distance	Compare the Euclidian distance between records and individual	95% classification accuracy; markerless and simplified interface for homecare
Kitsunezaki et al. 2013 (Kitsunezaki *et al.*, 2013)	80%	Up & Go test; 10 meters walk test; Range of Motion	General Rehabilitation	MSSDK	Up & Go test: height of head or other reference to count up and sit; 10 meters walk test: two Kinects to detect when cross in front of each one; Range of Motion: Angle between bones	Physiotherapist evaluation	Up & Go test: compared different references for height measure and compared system counter with therapist (Podsiadlo e Richardson, 1991); 10 meters walk test: compare therapist and system time (Timed 10-Meter Walk Test); Range of Motion: compare system angle with therapist measured with protractor (Cdcp, 2010)	Good similarity and practical utility; For angle measure is useful when high range of motion is performed. Not good results for crotch and knee. Good applicability in medical fields
Leightley et al. 2013 (Leightley *et al.*, 2013)	95%	Classification of kinematic activities	General Rehabilitation	MSSDK	Support Vector Machines and Random Forests trained on the	User performing activity	Accuracy: correct classification versus number of frames recorded	8 to 10 participants are enough to set classification stable. Setting Kinect to a lower

	Principal Component Analysis (PCA) feature space	dimensional space enables simple and reliable classification

Table 3: Characteristics of papers of the Applicability category.

Study	**QualSyst score**	**System**	**Population**	**N of subjects**	**Movements / game**	**Protocol**	**Outcomes**	**Results and Conclusion**
Hsieh et al 2014 (Hsieh *et al.*, 2014)	65%	Virtual Reality	Health Elderly – fall prevention	N = 8 (4 Control Group (CG) and 4 Experimental Group (EG))	Arm reaching	EG: Virtual system during 30 min 5x / week during 6 weeks. CG: no training.	Berg Balance Scale and Timed Up and Go	Improved balance ability; Helps balance in promotion of fall prevention.
Rosa et al 2013 (Rosa *et al.*, 2013)	95%	Xbox Kinect game	Multiple Sclerosis	N = 47 (23 CG and 24 EG)	Throwing and hitting objects (Kinect sports, Kinect Adventures and Joy Ride)	EG: Telerehabilataion with game during 20min 4x / week during 10 weeks. CG: Traditional therapy 40 min 2x / week during 10 weeks	Computerized Dynamic Posturography and Sensory Organization Test	Experimental group presented better balance and postural automatic response. Virtual system optimized sensory information.
Sin et al 2013 (Sin e Lee, 2013)	95%	Xbox Kinect game	Stroke	N = 40 (20 CG and 20 EG)	Boxing and Bowling (Kinect Adventures)	EG: 30min game + 30min of traditional therapy 3x / week during 6 weeks. CG: 30 min of traditional therapy 3x / week during 6 weeks.	Range of Motion, Fugl-Meyer Assessment and Box and Bock test	Experimental groups greater improvement on shoulder elbow and wrist range of motion and higher scores in Fugl-Meyer Assessment and Box and Bock test

Table 4: Characteristics of papers of the Validation category.

Study	**QualSyst score**	**What was evaluated?**	**Skeleton tracking**	**Gold standard**	**Comparison test**	**Results / Opinion**
Bonnechère et al 2014 (Bonnechère *et al.*, 2014)	**95%**	Joint angles: shoulder abduction, elbow flexion, hip abduction, knee flexion	MSSDK	Vicon Marker motion capture	Angle average, Interclass correlation coefficient, Coefficient of variation and Root Mean Square	Higher differences average in degrees: Shoulder abduction 0.9; Elbow flexion 8; Hip abduction -5; Knee Flexion -11. Comparison not satisfactory for most of motions. Reliability in joint center estimation and reproducible for planar motion.

Kurrilo et al 2013 (Kurillo *et al.*, 2013)	**85%**	Upper limb joints position, reachable workspace and angles:	MSSDK	PhaseSpace Motion Capture	Euclidian distance, Angle difference and Relative surface area.	Accurate and reliable results for reachable workspace. Kinect high variability in angle and joint location due occlusion. Accuracy 66.3mm.
Mobini et al 2013 (Mobini *et al.*)	**75%**	Joints center displacement	Flexible Action and Articulated Skeleton Toolkit (FAAST)	Polywood model in shape of upper body	Joints center displacement in the three axis comparison between model and Kinect displacement	Joint displacements at a smaller than 24mm in X, 23mm in Y and 24mm in Z; Sufficient accuracy in joint position estimation for upper limbs rehabilitation applications.
Nixon et al. 2013 (Nixon *et al.*, 2013)	90%	Joint angles for upper limb: shoulder abduction, flexion and 3D angle	MSSDK plus Butterworth 6 order filter 3hz cutoff	Vicon Marker motion capture	Difference error and absolute error (% of difference / theoretical maximal angle, i.e. 180 degrees)	Maximum error of 10% for shoulder abduction. Potential measure for home access
Fernandez-Baena et al. 2012 (Fern'ndez-Baena *et al.*, 2012)	70%	Joint angles of the mains limbs: knee flexion, hip flexion and abduction, shoulder flexion, abduction and horizontal abduction	OpenNI plus smooth low pass filter (5 frames of time window)	Vicon MX3 Marker motion capture	Mean error and mean error relative to the motion	All error < 10º ranging from 6.78º to 8.98º. Useful technology for rehabilitation treatment. Error found is acceptable compared to therapeutic visual measure where error of 10º is acceptable
Obdrzalek et al. 2012 (Obdrzalek *et al.*, 2012)	80%	Pose estimation (skeletonization)	MSSDK	Online (PhaseSpace's Recap) and offline (Autodesk Motion builder) Marker motion capture	Compared distance of knee point to floor and 3D position of joints. Visual analysis of tracking failure and confusing of body with background objects. Tested Kinect in different angulations	Significant potential for low cost real-time motion capture in health applications. In controlled posture as standing up: accuracy comparable with motion capture; others postures variation of 100mm
Schönauer et al. 2011 (Schonauer *et al.*, 2011)	60%	Hand position during reaching activities and stride length and velocity during walking on a treadmill	Flexible Action and Articulated Skeleton Toolkit (FAAST)	Marker motion capture	Compared Kinect with motion capture output of hand 3D position, hand reaching height from torso and stride length	Kinect worked surprisingly well as an alternative motion capture. Difference of 50 to 70mm may be caused by different reference systems

5. SOLUTION OVERVIEW

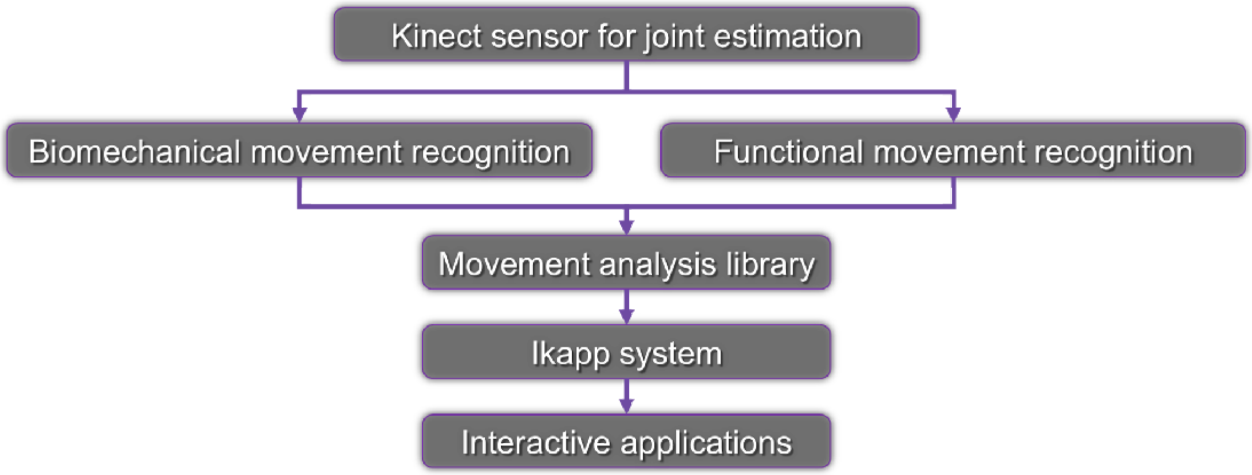


Figure 22: Solution overview.

This study aims to improve the motor rehabilitation interactive systems by bring to them the biomechanical concepts and making them more clinical related. In this context we propose solutions which will be presented in this chapter.

Aiming to better understand the rehabilitation process and this way develop improvements which are more related and useful to clinical practice a study about the routine and continuous interaction with specialized physiotherapists and doctors was performed. The therapist group was composed of five physiotherapists, four specialized on neurologic patients and one in biomechanics. Two doctors also helped on this process, one general practitioner and one specialized on shoulder surgery. Regular meetings with the physiotherapists group were performed in order to develop a requirements list and receive continuous opinion about the system under development in this research and how to improve it. A study with them using commercial games and checking their limitations to patient use was also performed. As a result of these studies and meetings the requirements were defined and are presented in section 5.1.

After presenting the requirements in order to develop a system more clinical related the proposed solution is presented in the section 5.2. After that, an overview of the system resulted from this work will be described (**Figure 22**).

5.1. REQUIREMENTS

As presented in the clinical routine description (section 2.1), the first step of the rehabilitation process is the evaluation. In order to define how the Ikapp system could help in this step, therapists were asked the main clinical reference in the aspect of movement gain, which is the focus of our Ikapp system. According to them the main reference is the goniometer and therefore the goniometry measure for ROM was chosen as a requisite for our system. So as a requirement a virtual goniometry should be developed and performed by our system as a report of patient performance.

After evaluation the therapist can then plan and choose the exercise which can be biomechanical or functional movements. So the system to be more appropriated to clinical routine should enable the therapist to configure the movement which will be used to interact with the application according to the rehabilitation interests. Beyond, the system needs to be able to recognize biomechanical and functional exercises. So, three more requirements were listed: configuration of the movement which will be used to interact with the system according to the therapist rehabilitation plan; recognition of movements based on biomechanical classification; recognition of functional exercises.

During exercise the therapist has to be continuously checking the patient to avoid wrong execution. So it is important that the system also be able to detect when the movements are not being performed correctly and inform the patient on how to do them right. This way the next requirement is the warning and correction of wrong exercises.

An additional requirement established was the patient body movement interaction. Since some patients are not able to hold any device, like a joystick, the interaction with system must be markerless, enabling the patient to use it only with his body movement which is performed according to the rehabilitation plan configured by the therapist. Markerless patient tracking was also required to make usability simple, not wasting time to position markers and enabling easy use at home.

Summarizing, the following requirements were defined for the Ikapp system proposed in this thesis:

- Patient motivation through interactive systems, such as VR and AR;
- Evaluation of ROM (virtual goniometry);
- Patient movement performance report, including ROM and percentage of wrong exercises;
- Interaction with the system through exercises traditionally performed in a clinical routine;
- Configuration of movements to be performed during exercises based on the clinical routine;
- Recognition of movements based on biomechanical classification;
- Recognition of movements related to functional exercises;
- Correction of wrong performed exercises;
- Markerless body interaction with the system.

5.2. PROPOSED SOLUTIONS

Based on that the specific goals to be achieved in this work are:

- Based on literature review and on meetings with physiotherapists, to list requirements to improve the similarity with the clinical practice of a rehabilitation system to be developed in this work;

- To develop movement recognitions techniques which enable system interaction through exercises traditionally performed in a clinical routine: a biomechanical movement recognition and functional movements recognition;
- To map the Joint Coordinate System (JCS) from the International Society of Biomechanics (ISB) to a markerless body movements recognition method;
- To define a tool to allow tracking be used for future developers in different applications;
- To evaluate the movement recognition method;
- To develop a VR and a AR application for rehabilitation support to check the movement recognitions proposed benefits;
- To evaluate the efficacy of guiding biomechanical and functional exercises through VR and AR rehabilitation application for rehabilitation support.

The requirements listed above will be attended using the following approaches.

MOTIVATIONAL ASPECTS

The motivational aspect will be addressed by developing interactive systems, such as VR and AR. The interaction with the system will be performed by therapeutics movements and will help patient to perform them. Virtual scene or elements, for the AR case, will be used to induce movement and to provide instructions for patients (Da Gama, A. *et al.*, 2012a; Da Gama, A. E. F., Carneiro, M.*, et al.*, 2012; Freitas *et al.*, 2012). We aim to divert patient from the tedious nature of repetition engaging them on exercise. These system will be presented at chapter 8.

RANGE OF MOTION EVALUATION AND REPORT

For the evaluation of ROM it is proposed a virtual goniometry where angles of each biomechanical movement will be computed. This ROM can be used to define the target the patient should aim when playing the interactive game application provided by Ikapp or to perform patient evaluation being saved as a report for further use by the therapist (Da Gama, A. E. F., Carneiro, M.*, et al.*, 2012; Freitas *et al.*, 2012; Oliveira *et al.*, 2013). The ROM computation and how it will be specific for the biomechanical movement will be presented in the chapter related to movement recognition (chapter 7).

CLINICAL ROUTINE BASED EXERCISES CONFIGURATION AND RECOGNITION

In order to enable an interactive system for motor rehabilitation application working with the proper exercises already used in the clinical routine, human body movement recognition techniques are proposed. Two methods are included in our Ikapp system: 1) a biomechanical movement classification method, where the movements are recognized considering the plane where the body segment is being moved, and this way classified according to the biomechanical standards (Da Gama, A. E. F., Chaves, T. M.*, et al.*, 2012; Da Gama *et al.*, 2014); and 2) a checkpoints based method, where any movement can be recorded and compared with original reference movements previously configured (Chaves *et al.*, 2012). The checkpoints method was developed to contemplate functional exercises and other exercises which were not classified as biomechanical. These methods will be described in detail in the movement recognition section (chapter 7).

Another important feature to attend this requisite is the system flexibility. It should enable the therapist to choose the movement which will be used to interact with the system and also the motion amplitude, in order to follow the therapy plan for that patient. Due to that a configuration feature where the therapist can choose, among other characteristics, the movement and maximal ROM required for interacting with the system is proposed and it will be presented in chapter 8.

CORRECTION OF WRONG PERFORMED EXERCISES

The correction of wrongly executed exercises by the patient will be performed using a movement tolerance margin (MTM) which defines how far from the right movement the movement can go to continue being considered as right (presents no harm to the patient). Additional characteristics are also evaluated when required, for example trunk inclination while lifting the arm (Da Gama, A. *et al.*, 2012a). These restrictions and tolerances will also be configurable by the therapist in the configuration feature of Ikapp (Da Gama, A. E. F., Carneiro, M., *et al.*, 2012; Oliveira *et al.*, 2013). All kinds of corrections regarding wrong exercises will be presented in the section about system features (chapter 8).

MARKERLESS BODY INTERACTION

For the markerless characteristic of the system the choice of the movement capture sensor was crucial. As explained in the previous chapter, the Microsoft Kinect sensor was chosen due to its capability of tracking in 3D a human skeleton without needing markers, beyond being of low cost and portable (Da Gama, A. *et al.*, 2012b). Our research started using the Kinect v1 sensor and was updated for the Kinect v2 version launched in 2014. The sensor details have been described in the previous chapter.

5.3. SOLUTION OVERVIEW

The overview of the solution developed can be seen in **Figure 22**. The method starts by tracking the body using a markerless technique. For that the Kinect sensor was chosen due its practical, portable and low cost characteristics. This thesis started just after the Microsoft launched the first Kinect, at the end of 2010. So all the work was developed based on this sensor. During the last semester, the new version of the sensor with improvements was launched (July 2014). The system was developed with the first version, however in the end upgraded to be possible to use it with the two sensor versions.

Based on the body tracking used two movement recognition techniques were developed. The first one is based on the biomechanical standards. This method is able to classify the movements according to biomechanical concepts. These movements are performed on therapy aiming to achieve specific gains. They are very precise to joint anatomy being specific to ligament, muscles and this way motion recovery. The ISB standard was used as reference to develop the movement recognition. However this statement is performed based on marker based references. So in order to enable the standard to be used in a markerless technique a mapping of the JCS to this technology was performed. After mapping the technique to recognize the movements could be developed. To complement the movements used on therapy the method to recognize the functional ones was developed.

The two movement recognition techniques developed were then integrated in a movement analysis library. This library enables access to the recognition information from both techniques using the same functions, for example 'getCurrentStatus()' returns the angle or the percentage of movement when using the biomechanical or the functional technique, respectively. This library can then be used by any application.

This work integrated the movement analysis library with the Ikapp system. The Ikapp is an interactive system that we also developed where the features are integrated and the applications can be implemented. The Ikapp system is composed of three modules: game, report, and configuration. In this system the additional features listed on the requirements list were developed, such as configuration file and report. Since they are connected with the movement analysis library they can based on these data configure the movement recognition characteristics or extract information for the report.

With the movement analysis library integrated to the Ikapp system the applications could be developed. This work developed two preliminary solutions, based on VR and AR. They were implemented in order to test the movement recognitions developed as interactive tool and their capability to provide information to guide and correct exercises. These information were used by the applications to provide feedback.

5.4. Summary

This section presented the steps performed to develop the major solution of this work. The requirement list was defined based on the literature review lacunas and the therapists suggestions. Then the proposed solutions according with the needs were proposed and the resultant system overview presented.

The next chapter details the development steps. It will begin with the mapping proposed from the ISB standard to the markerless technique. The chapter following will present the movement recognition techniques and the applications.

6. PROPOSED ISB STANDARDS MAPPING TO MARKERLESS MOTION CAPTURE

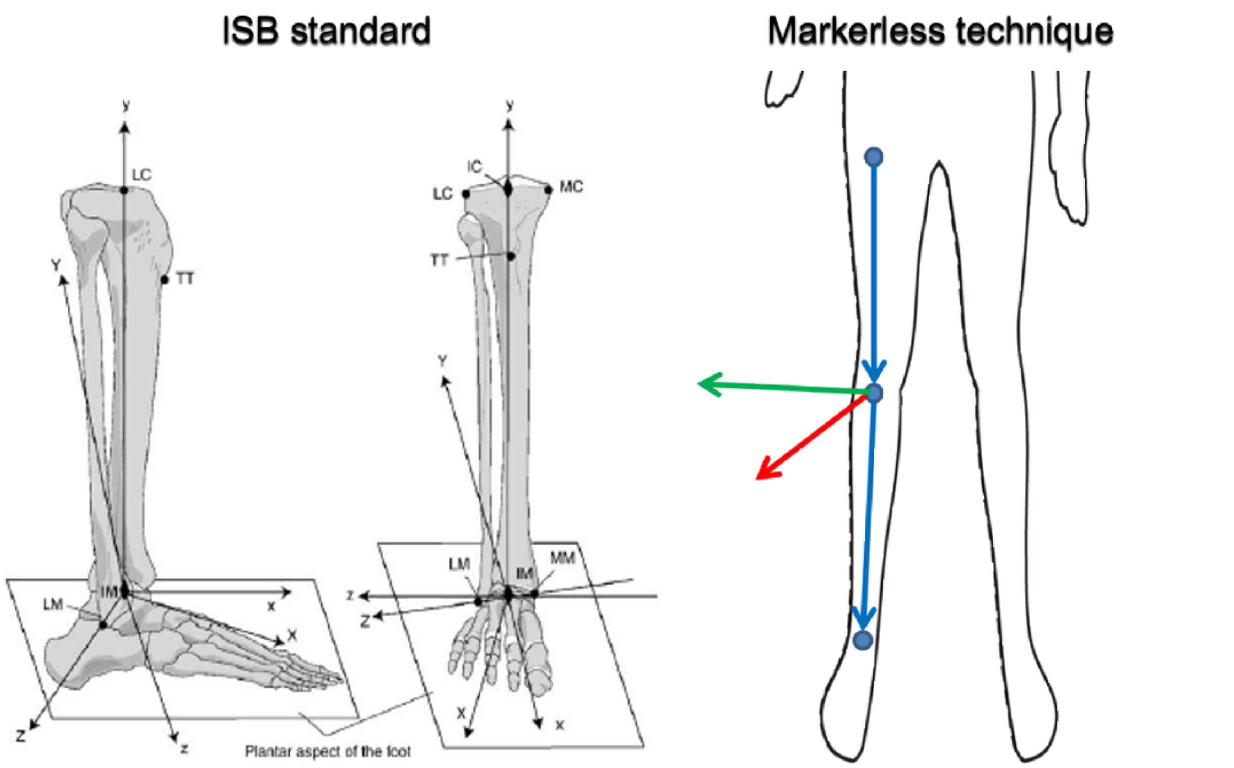


Figure 23: One example of ISB standard mapping to the markerless technique. In the left ISB references using markerless technique. Right picture shows the equivalence performed using the markerless joint estimation.

Based on the ISB standard (Wu e Cavanagh, 1995; Wu et al., 2002; Wu et al., 2005), this work translated the reference and axis information, adapting them to enable the markerless recognition of biomechanical movements by a computational technique. The ISB standard was developed using a marker tracking as reference to compute the joint axes. Figure 23 shows the ankle mapping as one example of the process. It was done by searching the nearest equivalence between the two techniques providing the same resultants axes directions.

The standardization of terms and their description for markerless motion capture to perform movement recognition is very important in order to unify the language in biomechanics, sports and rehabilitation fields.

So, this section will present the mapping of the ISB standard in order to correlate it with the markerless motion capture characteristics.

The main difference concerning the marker and markerless motion recognition techniques is the access to anatomic landmarks. This is possible when using the marker procedures, but impossible in the markerless technique. When accessing anatomic points to perform localization and positioning of the markers it is possible to find a more accurate joint location. Additionally the possibility to use more markers to define also the surroundings of the joint enables more than joint location but also the information of rotational direction.

Therefore the main difference of this mapping will be the form used to find the references used to calculate the JCS. For the markerless body tracking, instead of using physical landmarks to locate joints positions, the system will estimate them based on body pose. For the plane definition the marker based techniques use the surrounding markers as reference; since markers are not available in markerless tracking techniques our proposed method will make use of the central joint position and the two adjacent joints to help in the axis, plane and movement definition, for example for the knee joint the hip and ankle will be used as reference as well.

One limitation caused by the anatomic accuracy of the Kinect sensor (used in this work) is the impossibility of the system to detect displacement movements, since they are small and internal joint movements. Due to that the displacement movements are not present in this statement translation. However this do not interfere on applications for motor rehabilitations exercises. The displacements movements are not executed as exercise; they are treated using manual therapy which has to be performed by the physiotherapists.

The mapping of the ISB standard for each joint is described in sequence. The axis equivalence will also be presented. Since the planes reference for movements are composed by each pair of two axes, as described before, the planes description for all joints will follow these references: Frontal plane will be composed by the Y and Z axes and the normal vector of the plane will be the X axis; Sagittal plane is the plane containing Y and X axes with the Z axis as its normal vector; Horizontal or Transverse plane is the one composed by X and Z axes with the normal vector being represented by the Y axis.

For all joints, additionally to joints references, it will also be presented the moving vector together with references. However in some joints the axis proposed by the ISB will be equivalent to the moving vectors. For the method proposed in this work to be used adequately it is not functional to make use of the moving vector as an axis. This overlap between axis and moving vector would result in loss of movement reference; the axis will be moving during the movement being not possible to detect the relative movement between the moving vector and the JCS. When this case occurs we will present the adaptation proposal to enable its uses for interactivity purposes.

In this work the skeleton markerless tracking will be performed by the Microsoft

Kinect RGB-D camera. However the mapping and movement recognition method proposed here can be extended to any technology that enables the same joints estimations provided by the Kinect sensor.

6.1. MAIN JOINTS MAPPING

In sequence the mapping of movements' description in order to be recognized by a markerless technique is explained.

SCAPULAR GIRDLE – CLAVICLE AND SCAPULA

With the use of a markerless movement recognition technique it is not possible to differentiate scapular and clavicle movements. The accuracy of scapular movements is a delicate process even for marker based techniques where change on the Euler angle sequence can influence the error which can achieve 50 degrees (Karduna et al., 2000). However it is possible to perform an evaluation of the scapular girdle motion which is correspondent to the movement of the clavicle and scapula together.

➢ **References**

- Central joint: Neck;
- Proximal joint: Spine center;
- Distal joint: Shoulder;
- Moving vector: Neck-Shoulder.

➢ **JCS**

- Y axis: Since the Y axis represents line pointing cranially the correspondence will be performed by a vector connecting spine center to neck, pointing upwards;
- Z axis: To make the correspondent line which crosses the Clavicle from the sternoclavicular joint to the acromioclavicular joint the most proximal correspondence possible with the skeleton markerless tracking technique is performed by a vector connecting neck to shoulder points, resulting in a vector point right;
- X axis: Since the X axis is the common axis perpendicular to Z and Y it was computed by the cross product between these two axes.

➢ **Movements**

- X axis: The rotations through the X axis are normally named adduction and abduction. However due to Clavicle position they received special names: Elevation and Depression. Their descriptions are performed in relation to the Clavicle and Thorax midline (Y axis) angle when occurring in the Frontal plane.
  - Depression: Occurs when clavicle moves in the positive direction, with the Clavicle line going down, so the angle between these two vectors increases;
  - Elevation: Negative movement of the Clavicle going up and reducing the angle between Clavicle bone and Y axis.
- Z axis: For this joint the axial rotation occurs in the Z axis. This axial rotation is not visible externally being difficult, or even impossible to track it with the Kinect skeleton tracking. Since it is a limitation

of the sensor used in this work, this estimation is not included in this method.

- Y axis: Same way that in the X axis, the clavicle movements for this axis receive special names: Protraction and Retraction.
  - Protraction: The positive movement of the clavicle going forward;
  - Retraction: The negative movement of the clavicle in backward direction.

SHOULDER

➢ **References**

- Central joint: Shoulder;
- Proximal joint: Spine;
- Distal joint: Elbow;
- Moving vector: Shoulder-Elbow.

➢ **JCS**

For this joint adaptation is proposal for movement reference preservation. Since the shoulder is a joint directly connected to the trunk, the same coordinates of the trunk can be displaced for the glenoumeral center and used as shoulder JCS. The advantage of this method is that it can be used independent of shoulder position enabling better description of humerus movement in relation to anatomic position.

- Y axis: Since the Y axis is a vertical line pointing cranially this axis is represented by the Spine vertical axis which is a vector from spine center to neck, pointing cranially. The long axis of femur was not used due the fact that its change during movement which would perform a change on Y axis direction;
- X axis: The X axis direction which is composed of a vector pointing frontally was computed by the cross product between Y axis and the shoulder girdle, represented by a vector from shoulder to shoulder;
- Z axis: Once the Z axis is the common axis perpendicular to Y and X it was computed by the cross product between these two axes.

➢ **Movements**

- Z axis:
  - Flexion: Positive direction with bones approximation, so angle between the arm and Y axis decrease during movement;
  - Extension: Negative direction, with bones departing each other, increase on angle between arm and y axis.
- X axis:
  - Adduction: Positive movement on this axis with arm approaching from trunk;
  - Abduction: The negative movement of arm going far away from trunk.
- Y axis: The rotation detection in this axis is a limitation of the Kinect skeleton tracking due its joint position estimation based on the body pose. However it is yet possible to detect this movement based on the forearm movement if the user is in a predetermined position.

In order to perform shoulder rotation measurements the position of the shoulder at 0 degrees in the sagittal plane is required with the elbow also at 90 degrees in the same plane. This position was chosen due its accessibility to be tracked and due the fact that this is the position used on traditional goniometry measurements (Clarkson, 2005).

Based on that position we have:

- Internal rotation: positive rotation of forearm;
- External rotation: negative rotation of forearm.

ELBOW

➢ **References**

- Central joint: Elbow;
- Proximal joint: Shoulder;
- Distal joint: Wrist;
- Moving vector: Elbow-Wrist.

➢ **JCS**

The ISB standard proposes the Y axis located at the forearm long axis. So, as presented before this is a limitation for interactive use. So it is necessary to change the reference maintaining the biomechanical characteristics. Nevertheless it is yet important that the JCS accompanies the movement to be reasonable independent of the forearm position in relation to body. Due that it is not possible to use body system as used for the shoulder. So the proposed method is:

- Z axis: This axis is described as the perpendicular axis to the longitudinal axis of arm and forearm, due that it was computed by the cross product between shoulder-elbow and elbow-wrist vectors;
- Y axis: To follow the vertical direction from elbow position the correspondence for Y axis is made by arm longitudinal axis, being represented by elbow-shoulder vector;
- X axis: Once the X axis is the common axis perpendicular to Z and Y it was computed by the cross product between these two axes.

➢ **Movements**

- Z axis:
  - Flexion: Positive rotation. Bones of arm and forearm approaching each other;
  - Extension: Movement in the negative direction with arm and forearm getting far from each other.
- Y Scapular axis: The forearm movement at this axis is not an elbow movement. This movement occurs on the radio-ulnar joint. Due the skeleton tracking limitation in markerless technique using Kinect it is not possible to detect radio-ulnar movement. Due that this movement is not described here.
- X axis: No active movement can be found at this axis. However there is the carrying angle which during elbow movements passively disappears. The aim of this study is movement analysis, and

not postural, due to that this measure was not included.

  - Carrying angle: Postural angle on the anatomic position. External angle between arm and forearm.

WRIST

- **References**
  - Central joint: Wrist;
  - Proximal joint: Elbow;
  - Distal joint: Hand;
  - Moving vector: Wrist-Hand.

- **JCS**:

The same that occur for the elbow happens here for wrist. The ISB standard proposes the Y axis located at hand long axis. However, as described before, it is not very useful for interactive applications. So we propose the adaptation above needing change only at Y axis.

- Y axis: To maintain the correspondence and at the same time do not move the axis reference during movement, the correspondence is done by a line equivalent to forearm long axis, being represented by elbow-wrist vector;
- Z axis: Once the Z axis is a vector point laterally it will be composed by the cross product between forearm and arm vector and origin of this vector displaced for wrist center;
- X axis: The X axis as proposed by ISB reacquires more than one reference point at metacarpal position. Since in the skeleton tracking only one hand point is possible the equivalence for this axis will be performed by the cross product between Y and Z axes.

- **Movements**
  - Z axis:
    - Flexion: Positive rotation. Bones of hand and forearm approaching each other;
    - Extension: Movement in the negative direction with hand and forearm getting far from each other.
  - Y Scapular axis: As described before, no wrist movement is found in this axis.
  - X axis:
    - Abduction or radial deviation: Positive movement through this axis with hand longitudinal axis going far away from anatomic midline;
    - Adduction or ulnar deviation: Negative movement of hand approaching from body midline.

ANKLE

- **References**
  - Central joint: Ankle;
  - Proximal joint: knee;
  - Distal joint: Foot;
  - Moving vector: Ankle-Foot.

- **JCS (Figure 23)**
  - Y axis: Since the Y axis represents the line of tibia and fibula long pointing cranially the correspondence will be performed by a vector

connecting ankle joint center to knee joint center, resulting in a vector pointing cranially;

- Z axis: To make the correspondent line which cross both malleolus the Z axis was computed by performing the cross product between the Y axis and the thigh longitudinal axis resulting in a vector pointing laterally which is displaced for the ankle center;
- X axis: Once the x axis is the common axis perpendicular to Z and Y it was computed by the cross product between this two axes.

➢ **Movements**

- Z axis: These rotations will be described based on the angle between the leg and feet, Y and X axis respectively, since they occur around the Z axis when it is being performed at sagittal plane.
    - o Dorsiflexion: the positive rotation circling this axis occurs when the anterior angle between the leg and the foot decrease;
    - o Plantar flexion: the negative rotation when the leg and foot angle is increasing anteriorly.
- X axis: The rotations through the X axis are normally named adduction and abduction. However due the oblique angle of this movement as a result of joint anatomy this angle received special names: inversion and eversion. Their descriptions are performed in relation to leg and foot angle when occurring in the frontal plane.
    - o Inversion: Occurs when foot moves in the positive direction, approaching body midline;
    - o Eversion: Negative movement of foot going far away from midline.

- Y axis – Rotation through this axis:

The ankle anatomy does not allow rotation through the Y axis. So no movement is described here.

KNEE

➢ **References**

- Central Joint: Knee;
- Proximal Joint: Hip;
- Distal Joint: Ankle;
- Moving vector: Knee-Hip.

➢ **JCS**

Since the Y axis is equivalent to the moving vector it is necessary to change the reference maintaining the biomechanical characteristics. Additionally it is important that the JCS system here described be able to accompany the movement to be reasonable independent of leg position in relation to body. Due that it is not possible to use body system as used for the knee. So the proposed method is:

- Y axis: To maintain the direction but not moving with movement the correspondence will be done with the thigh (femoral) long axis so is represented by the hip-knee vector;
- Z axis: Since this axis is a vector pointing laterally (or medially for the left side) it is described as the

perpendicular axis to the longitudinal axis of thigh (femur) and leg (tibia and fibula). Due that it was computed by the cross product between hip-knee and knee-ankle vectors;

- X axis: Once the X axis is the common axis perpendicular to Z and Y it was computed by the cross product between these two axes.

➢ **Movements**

- Z axis: Differently for the others joints, by observing the movement at knee it is possible to notice that at the negative direction the bones are getting approached and the positive direction they are getting away from each other. Due that, in order to maintain biomechanics movements rules the mathematical difference will be performed where the positive rotation at this axis will be named flexion and negative extension.
  - Flexion: Positive rotation. Bones of arm and forearm approaching each other;
  - Extension: Movement in the negative direction with arm and forearm getting far from each other.
- Y axis:
  - Internal rotation: Positive rotation of the leg;
  - External rotation: Negative rotation of the leg.
- X axis: Due knee anatomy none movement is found at this axis. The abduction and adduction that normally occurs in X axis is not presented on knee.

HIP

➢ **References**

- Central joint: Hip;
- Proximal joint: Hip center;
- Distal joint: Knee;
- Moving vector: Knee-Hip.

➢ **JCS**

Since the hip is a joint connected to the trunk, the same coordinates of trunk can be used but displaced for the joint center. But a small change on the Y and X vectors to a more near reference will be made.

- Y axis: Since the Y axis is a vertical line pointing cranially this axis is represented by the spine vertical axis which will be composed by a vector from hip center to spine center, pointing cranially. The long axis of femur was not used due the fact that its change during movement which would perform a change on Y axis direction;
- X axis: The X axis direction which is composed of a vector pointing frontally was computed by the cross product between Y axis and the pelvic girdle, represented by a vector from shoulder to shoulder;
- Z axis: Once the Z axis is the common axis perpendicular to Y and X it was computed by the cross product between these two axes.

➢ **Movements**

- Z axis: For movements in the Z axis the reference for movement description will be the angle between the thigh and the Y axis when occurring in the sagittal plane.

- Flexion: Positive direction with bones approximation, so angle between the thigh and Y axis decrease during movement;
- Extension: Negative direction, with bones departing each other, increase on angle between thigh and y axis.

- Y axis: The rotation detection at this axis is a limitation of the Kinect skeleton tracking due its joint position estimation based on the body pose. However it is yet possible to detect this movement based on the leg movement if the user is in a predetermined position, as done for goniometry (Clarkson, 2005).

In order to perform hip rotation measurements hip position at 90 degrees in the sagittal plane is required with the knee also at 90 degrees at same plane. This position was chose due its accessibility to be tracked and due the fact that this is the position used on goniometry measurements, with patient sited. However to be used with the system the user can be sited or not, inasmuch as the hip and knee position in sagittal plane be maintained.

From this position the reference axis turns to be the X axis and the leg, represented by the vector from ankle to knee. Based on that we have:

- Internal rotation: positive rotation of leg in X axis;
- External rotation: negative rotation of leg in X axis.

- X axis: Movements are described by the angle between the thigh and the Y axis when occurring in the frontal plane.
  - Adduction: Positive direction when thigh is approaching body midline;
  - Abduction: Negative direction with thigh going far from body midline.

THORAX

Thorax translation will performed together with spine, being represented by thoracic spine, since with markerless technique it is not possible to differentiate this two yet.

SPINE

Making use of the markerless technique it is not possible to use a reference based on each vertebra. Due this fact, in order to perform the recognition of each portion of spine the translation here presented will describe the movements for each portion separately based on the spine center and surrounding joints.

Cervical Spine

References

- Proximal joint: Head;
- Central joint: Neck;
- Distal point: Spine center.

JCS

- Y axis: Since the Y axis represents the line in the middle of spine pointing cranially the correspondence will be performed by a vector connecting spine center to neck;
- Z axis: To make the correspondent line which cross both right and left pedicles the Z axis was represented by

the left shoulder to right shoulder vector;

- X axis: Once the x axis is the common axis perpendicular to Z and Y it was computed by the cross product between this two axes.

➢ **Movements**

- Z axis: These rotations will be described based on the angle between the cervical and thoracic spine, neck to head vector and Y axis respectively.
    - Extension: the positive rotation circling this axis occurs when the anterior angle between the cervical and the thoracic spine increase;
    - Flexion: the negative rotation when the cervical and thoracic angle is decreasing anteriorly.
- X axis: The rotations through the X axis are normally named adduction and abduction, according with their displacement in relation to spine midline. Since for spine the movements' starts at the midline movement the movement through this axis for these joints are named lateral flexion and differentiated by the side, right or left. Their descriptions are performed in relation to cervical spine (neck to head vector) and scapular girdle (Z axis) angle when in the frontal plane.
    - Right lateral flexion: Occurs when cervical spine moves in the positive direction going for the right;
    - Left lateral flexion: Negative movement of cervical spine going for the left side.
- Y axis: The rotation detection is a limitation of the Kinect skeleton tracking due its joint position estimation based on the body pose. So this estimation is not included in this method.

❁ **Thoracic Spine**

➢ **References**

- Proximal joint: Neck;
- Central joint: Spine center;
- Distal point: Hip center.

➢ **JCS**

- Y axis: Since the Y axis represents the line in the middle of spine pointing cranially the correspondence will be performed by a vector connecting hip to hip midpoint to spine center;
- Z axis: To make the correspondent line which cross both right and left pedicles the Z axis was represented by the left hip to right hip vector;
- X axis: Once the x axis is the common axis perpendicular to Z and Y it was computed by the cross product between this two axes.

➢ **Movements**

- Z axis: These rotations will be described based on the angle between the thoracic and lumbar spine, spine center to neck vector and Y axis respectively.
    - Extension: the positive rotation circling this axis occurs when the

- anterior angle between the cervical and the thoracic spine increase;
- Flexion: the negative rotation when the cervical and thoracic angle is decreasing anteriorly.

- X axis: As described for the cervical spine, the rotation through the X axis is specially named lateral flexion and differentiated by the side of performed movement, right or left. Their descriptions are performed in relation to thoracic spine and pelvic girdle angle when in the frontal plane, spine center to neck vector and Z axis, respectively.
  - Right lateral flexion: Occurs when thoracic spine moves in the positive direction going for the right;
  - Left lateral flexion: Negative movement of thoracic spine going for the left side.
- Y axis: The rotation detection is a limitation of the Kinect skeleton tracking due its joint position estimation based on the body pose. So this estimation is not included in this method.

Lumbar Spine

Reference

- Proximal joint: Spine center;
- Central joint: Hip center;
- Distal point: Knee to Knee midpoint.

JCS

- Y axis: Since the Y axis represents the line in the middle of spine pointing cranially the correspondence will be performed by a vector connecting knee to knee midpoint to hip to hip midpoint;
- Z axis: To make the correspondent line which cross both right and left pedicles the Z axis was represented by the left hip to right hip vector;
- X axis: Once the x axis is the common axis perpendicular to Z and Y it was computed by the cross product between this two axes.

Movements

- Z axis: These rotations will be described based on the angle between the lumbar spine and inferior limbs, hip to hip midpoint to spine center vector and Y axis respectively.
  - Extension: the positive rotation circling this axis occurs when the anterior angle between the cervical and the thoracic spine increase;
  - Flexion: the negative rotation when the cervical and thoracic angle is decreasing anteriorly.
- X axis: Due to the fact that spine movements are moving through the midline they receive the special name of lateral flexion being differentiated by the side, right or left flexion. Their descriptions are performed in relation to the lumbar spine and pelvic girdle angle when in the frontal plane, hip to hip midpoint to spine center vector and Z axis, respectively.
  - Right lateral flexion: Occurs when thoracic spine moves in the

positive direction going for the right;
- o Left lateral flexion: Negative movement of thoracic spine going for the left side.

- Y axis: The rotation detection is a limitation of the Kinect skeleton tracking due its joint position estimation based on the body pose. So this estimation is not included in this method.

6.2. SUMMARY

This section presented the mapping from the ISB standard, which is based on marker references, to a markerless technique. The mapping was made by looking the ISB axes direction and searching the nearest way to compute them using the markerless method. It will be the reference system for the movement recognition methods development. This translation was an important step of this work making possible to recognize movements according to the biomechanical descriptions. Additionally, since the coordinate system is referenced based on the body it will allow the recognitions to work independently of user position in relation to sensor..

7. BIOMECHANICAL AND FUNCTIONAL MOVEMENTS RECOGNITION

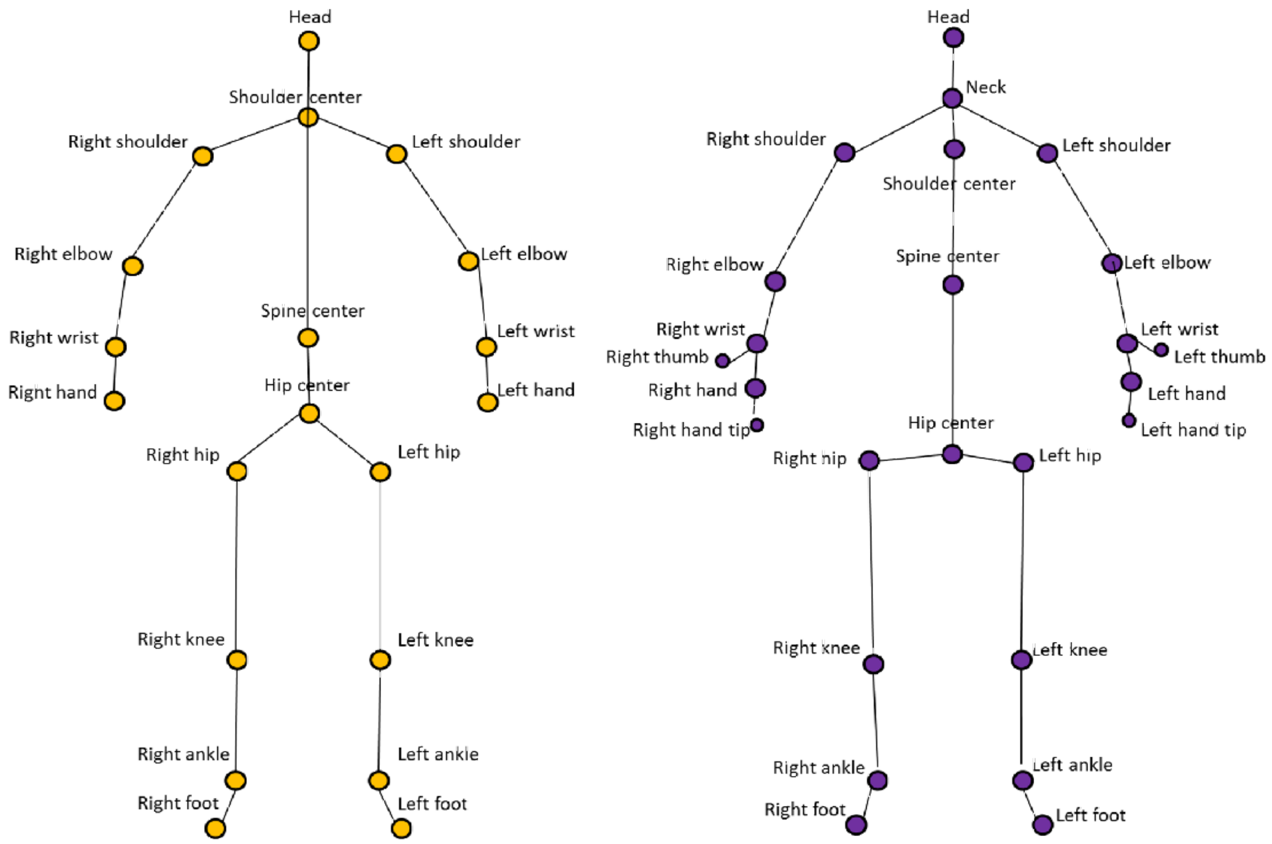


Figure 24: Skeleton position extracted from the Kinect v1 and Kinect v2 sensors (left and right, respectively).

After doing the possible correspondence and adaptations of the ISB standard for markerless tracking in this chapter we will present the movement recognition technique developed respecting the mapped ISB standard proposed in this work. With this method it is possible, with simple functions, to extract information of biomechanical movements and use them for controlling an interactive system, while also performing patient movement evaluation and performance report. Using the ISB recommendation makes the movement recognition more related to clinical practice and also allows extrapolating data information.

In order to recognize a movement it is necessary to have a moving segment and a

Cartesian system reference to understand and describe the movement. The moving segment which represents a body part will be composed by points as the body representation presented below (section 7.1). The Cartesian system will be centralized regarding each joint (section 1.1) and its directions will respect the ones proposed by the ISB standard, according with the mapping done above (chapter 6).

The body segments with their JCS mapped according with the standards will be then used as input to the two movements recognitions developed: the biomechanical movement recognition (section 7.3) and the functional movement recognition (section 7.4).

7.1. BODY REPRESENTATION

One important requirement for a rehabilitation application identified in this research is that the patient movement tracking and recognition needs to be performed with no need for the patient to wear any accessory, in other words, a markerless movement recognition method. In order to attend this requirement we chose to use the technology provided by the Kinect sensor, a RGB-D device from Microsoft. With this sensor and its SDK three-dimensional skeleton pose estimation can be done.

However some limitations are found using the directly extracted information from this sensor. The data given by the device is very sensitive to the user position and anatomy. If the user simply rotates his body (even maintaining the relative positions of hands, arms, legs, etc.) the sensor will generate a whole new set of points' positions. This problem also happens if two different users perform exactly the same movement. Since the proportions of the body are not the same, the position of the points will not be the same. This way, even if it is the same movement being performed, it would be a totally new set of information, thus, being a problem for recognition.

So, in order to provide the system with the segments required for biomechanical description and also solve these problems, a body representation using normalized vectors was defined.

All specific function calls from the Kinect SDK were abstracted in the movement analysis library developed (section 8.1). It also has a function to transform the user's skeleton data (the 3D points) into an adequate representation that is used in the recognition methods. This representation is done by converting the 3D points coming directly from the Kinect skeleton to normalized vectors. Each pair of points will be forming a vector which will be representing a segment. So, instead of using the 20 body points provided by the Kinect v1, or 25 by the Kinect v2 (**Figure 24**), each segment of the body is represented by a vector, giving a set of 19 and 24 vectors, respectively, as shown in **Figure 25**.

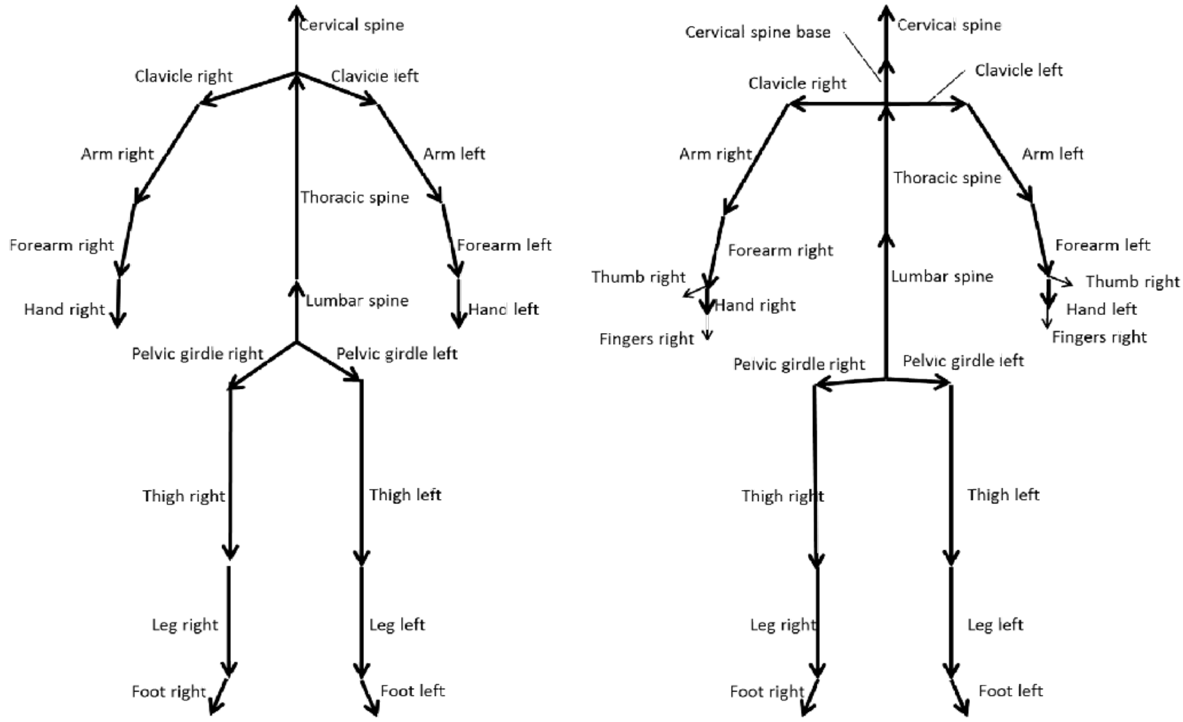


Figure 25: Segments representation based on vectors between two successive joints used in our proposed movement recognition method for the Kinect v1 and Kinect v2 sensors (left and right, respectively).

7.2. JCS

In order to analyze a movement a Cartesian system is required. The three-dimensional joint position tracked by the sensor has its own Cartesian system; however this system is centralized on the sensor point of view. There are two problems in this reference; the first is that since it is not centered on the user it will always point in the same direction even if the user turns around. Additionally, as presented before, for biomechanical analysis the Cartesian system does not only need to be centered in the user but it also has to be centered in each joint (**Figure 26**) and in a very specific way that respects each joint anatomy (Wu e Cavanagh, 1995).

The first interesting thing to notice is that some joints can use the same coordinate system due to their similarities, like position and orientation in relation to the body center. So, clustering similar joints, the JCS was categorized in the JCS for the upper proximal body, lower proximal body, central trunk, elbow, wrist, knee and ankle.

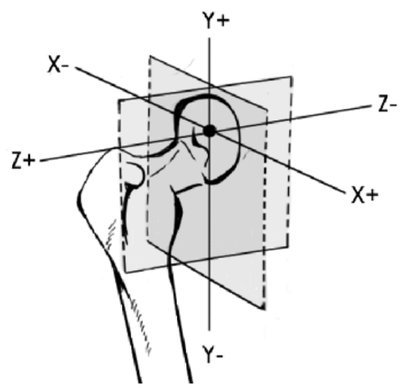


Figure 26: Cartesian system centralized in the hip joint center.

The upper proximal body includes the shoulder joints, sternoclavicular joints (shoulder center) and the cervical spine (neck). For these joints the same coordinate system can be used. The only change required is the translation of the origin of the Cartesian system to the joint center, maintaining the ISB standards' recommendations. So, the Cartesian system for the upper proximal body will be represented as follows.

Since the Y axis is a vector parallel to the gravity pointing upward it will be represented by a vector from the spine center to the shoulder center, for the Kinect v1, and the spine center to the base neck point, for the Kinect v2. The X axis in the ISB convention is pointing forward, away from the body. So in order to compute it, the cross product between the Y axis and the scapular girdle is performed. The girdle vector is composed by the shoulder to shoulder vector. Since the Z axis is the common perpendicular axis to Y and X it was computed by the cross product between the two other axes. Figure 27 shows this Cartesian system based on the Kinect v1 skeleton.

A similar process was used for the lower proximal body, which includes hips and pelvis. However their vector references used for axes computation were located more close to their region (Figure 28). The Y axis was represented by the hip-center to spine vector for both Kinect versions. For the X axis, the same cross product between the Y axis and the girdle was performed but using the pelvic girdle, composed by the hip to hip vector. The Z axis was computed by the cross product between the two other axes.

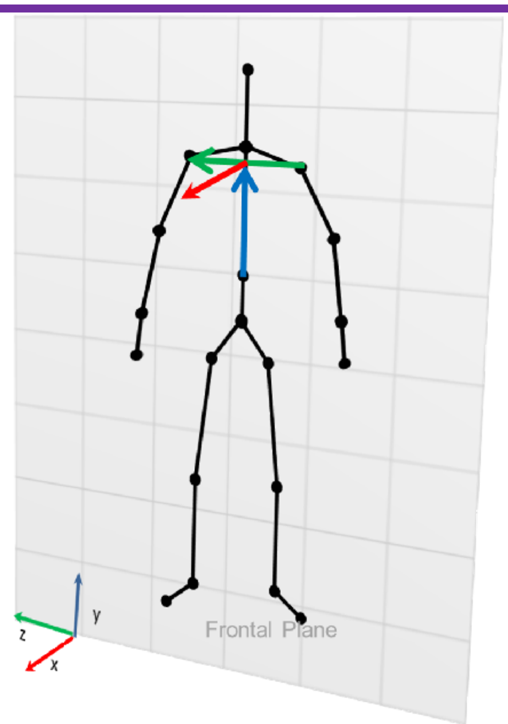


Figure 27: Upper proximal body Cartesian system references.

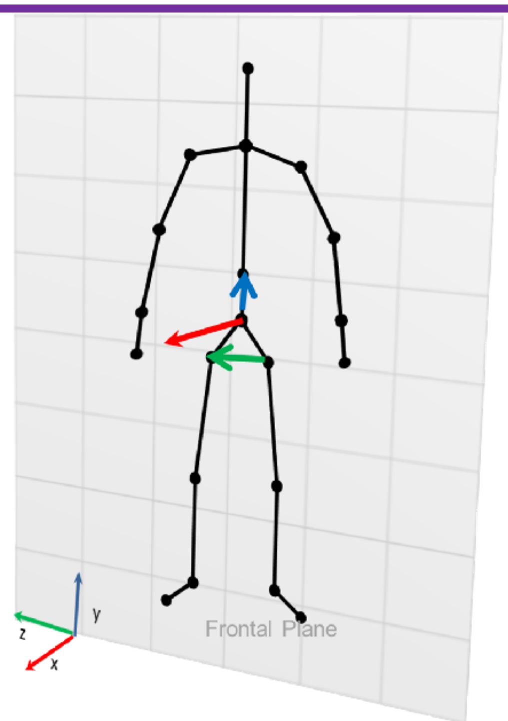


Figure 28: Lower proximal body Cartesian system references.

One important thing to notice is that when computing the body vectors to represent the JCS these vectors cannot be equivalent to the vector correspondent to the moving segment which will be analyzed during movement. If the body part that is being analyzed is used as one axis reference on the coordinate system the respective axis will be moving and changing during movement resulting in no movement recognition at all. So, due the fact that the spine is the Y axis in the above described bases, an additional JCS is needed. These body parts were categorized as central trunk and include the thoracic and lumbar spine.

Since the spine is the midline of the body, in order to recognize changes on its position it is necessary to use the Y axis of the sensor coordinate system. So the Y axis was referenced only by the device orientation (Figure 29). The X axis was computed in a similar way to the lower proximal body by the cross product between the Y axis and the pelvic girdle (hip to hip vector) and the Z axis applying the cross product between the two resultant axes.

Joints that are not directly attached to the trunk, such as elbow or ankle, cannot use trunk references to compute their JCS. This occurs due to the fact that their direction can be easily changed according to the limb position. So, to compute the axes of their JCS it is necessary to use as reference points present on the limb and as close as possible to the joint in question. This procedure is used in order to compute individually elbow, wrist, knee and ankle JCS.

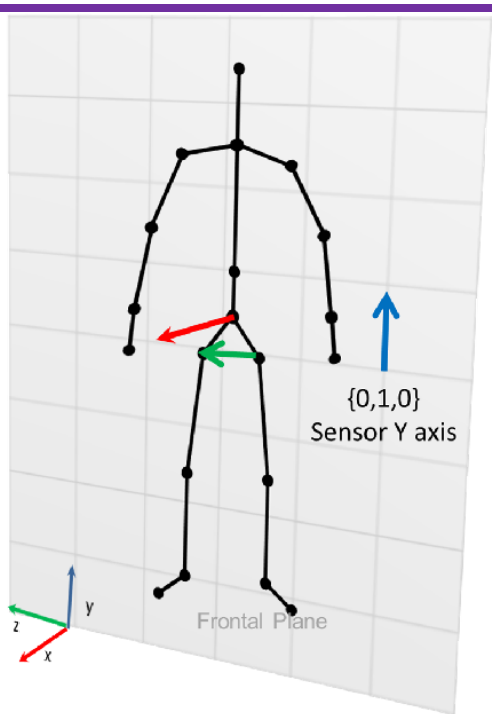


Figure 29: Central trunk Cartesian system references.

The distal joints Cartesian system is computed based on the surrounding bones and the cross product between them, as follows. The Y axis is composed by the longitudinal axis of the proximal bone of the joint. For the elbow, the Y axis is composed by the arm (shoulder to elbow vector); for the wrist it is represented by the forearm (elbow to wrist); for the knee it is presented as the thigh (hip to knee); and for the ankle it is composed by the leg (knee to ankle). The Z axis is computed by the cross product of the two big bones of the respective limb. For the elbow and wrist, the cross product between arm and forearm vectors is computed, and for the knee and ankle, the cross product of thigh and leg. This means arm and forearm for upper limb distal joints, and thigh and leg for lower limbs (the blue and orange vectors in Figure 30). These cross products will result in a vector pointing laterally from the joint (green vector in Figure

30), as described by the ISB standard. The most important thing is that they will follow the joint pointing out independent of the limb position. Since the X axis is a common perpendicular axis it is computed by the cross product between the Y and Z axes (red vector in Figure 30).

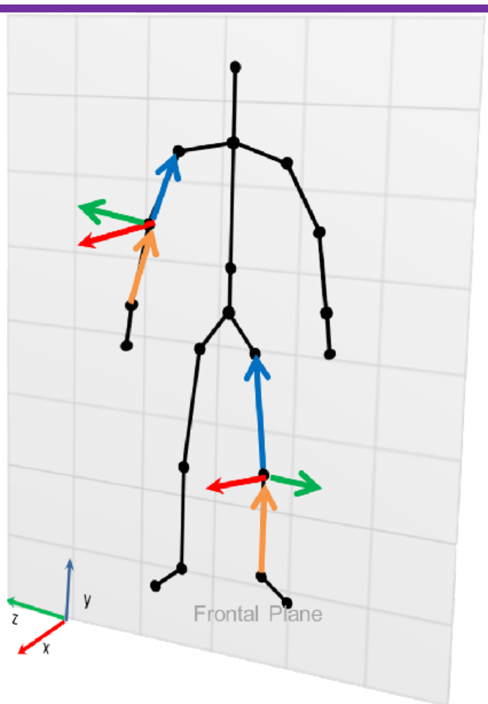


Figure 30: References used to compose the Cartesian system from joints not attached to the trunk, for upper and lower limbs.

7.3. BIOMECHANICAL MOVEMENT RECOGNITION

This method was developed aiming to recognize and classify the biomechanical movements. The recognition of these specific movements will enable use them for interaction, using the angle information as input to control a game. It will also provide movement evaluation and information about wrong performance, which can also be used as evaluative tool or for interactive information, for example providing corrective feedback.

The biomechanical movement recognition uses the body representation with the JCS described above (sections 7.1 and 1.1) following the biomechanics standards. Through them the method computes movement angle (section 0) and classify them according with segment position in relation to the plane where it is being moved (section 0). These steps for movement recognition are presented next.

After a method for axial movements recognition is presented (section 0), due the fact that these cannot be recognized directly by the method proposed. This occurs due the fact that the axial rotations do not promote changes on human pose, which is the reference used by the Kinect to estimate skeleton position.

Additional postural control were develop in order to avoid wrong exercises, which can be harmful for the patients. These analysis are presented at 0.

ANGLE MEASUREMENT

Now that the body is represented and the coordinate system is established, it is possible to compute the angles between two successive segments. Angles are obtained from the arc cosine of the dot product between the moving vector of the respective joint and the Y axis for movements at frontal and sagittal plane or X axis for horizontal plane. For example, the shoulder and knee angles formulas for angle measurement at sagittal plane are presented in Equation 1 and 2, respectively.

$$\text{shoulderAngle} = \arccos\left(\frac{\text{arm} \cdot \text{shoulderYaxis}}{\|\text{arm}\| \, \|\text{shoulderYaxis}\|}\right) \quad (1)$$

$$\text{kneeAngle} = \arccos\left(\frac{\text{leg} \cdot \text{kneeYaxis}}{\|\text{leg}\| \, \|\text{kneeYaxis}\|}\right) \quad (2)$$

It is important to notice that the angle resultant from this measurement is the same, independent of the segment movement direction. This is shown in **Figure 31**. For example, if the shoulder moved 90 degrees with the arm going to the front or laterally, there will be no difference in the angle measure; the same happens with the thigh at 60 degrees. It was presented in the biomechanics related chapter that, anatomically, the segment movements in different planes are not the same, resulting in different behavior of joint mechanics and muscles action. This is an important detail for rehabilitation, making crucial to differentiate movements according to the planes where they are happening.

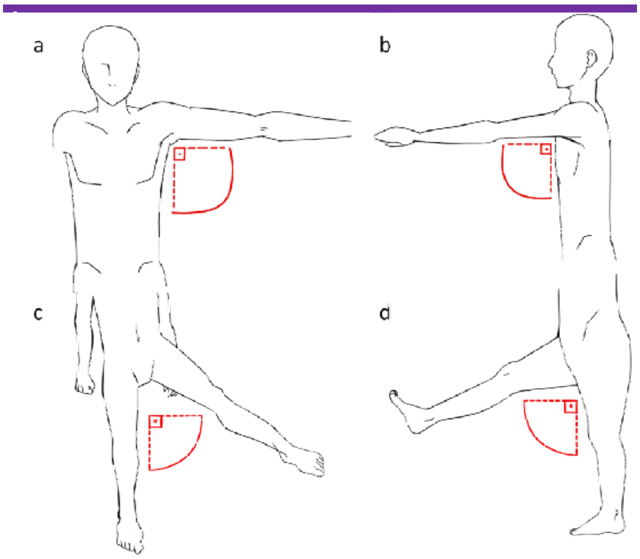


Figure 31: Shoulder (a and b) and Hip (c and d) movements in different planes (Abduction – a and c / Flexion – b and d): same angle but different biomechanical movements.

Based on the exposed information, in order to develop a recognition method which follows the biomechanical concepts it is necessary to classify the movements according to the plane where the moving segment is performing the exercise. In order to be able to differentiate these movements, it is necessary to have the plane reference. The planes are based on the Cartesian system composed by each pair of axes. The Frontal plane is composed by the Y and Z axis; Y and X axis compose the Sagittal plane; and the Horizontal or Transverse plane is composed by the X and Z axis.

BIOMECHANICAL MOVEMENT CLASSIFICATIONS

In order to ensure the angle output provided by the system is equivalent to the angle of the specific movement, the absolute angle is not enough and thus, an additional measure is necessary. The additional information to correctly compute the movement angle is obtained using the planes normal. In the three-dimensional Cartesian system the normal of a plane is the axis that is not used in the plane composition. This way the normal vector for the Frontal plane is the X axis, for the Sagittal plane the Z axis and the Y axis for the Horizontal plane.

Using the normal of the plane, it is possible to restrict the movement to a plane by requiring that the moving segment is positioned at 90 degrees to its normal. If the segment is not at this position it cannot be classified as the movement of that plane. However the perfect alignment of a moving vector with the plane is utopic. Due that, to allow recognition with some flexibility a Movement Tolerance Margin (MTM) is set. The MTM defines how far from the plane the segment can go in order to still be considered as a movement of that plane (**Figure 32**). The value of the MTM is settable by the physiotherapist according to therapy needs. At this point the movement can be classified. If the movement is not classified in any of the classification categories the performance evaluation of the patient or the interaction with the system will not occurs. This guarantees that if the therapists want the user to interact with the system using certain exercise it will not work with a wrong movement. Additionally, the report will be equivalent to the clinical measures traditionally performed by the therapists.

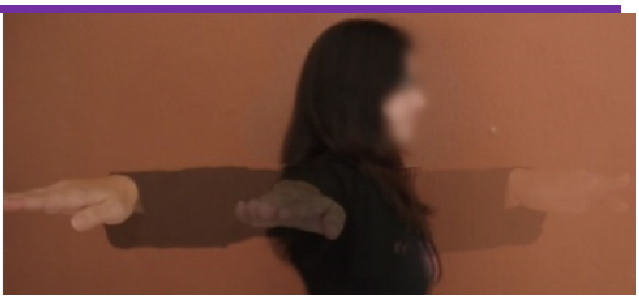
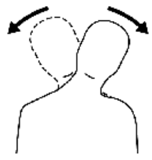
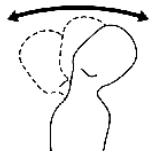
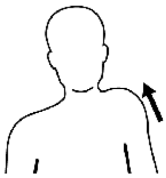
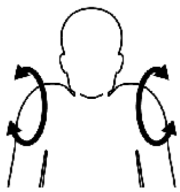
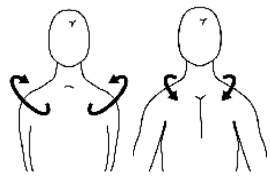
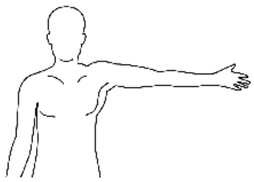
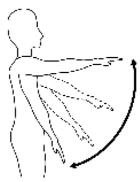
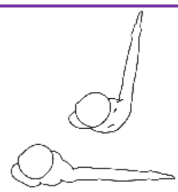
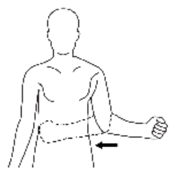
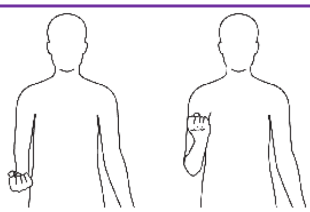
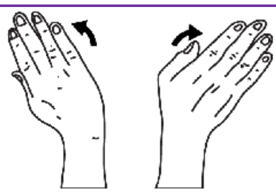
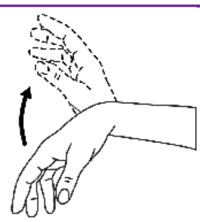


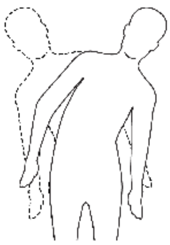
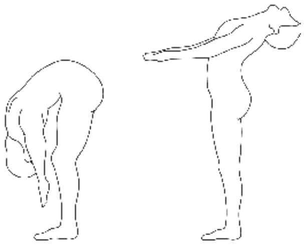
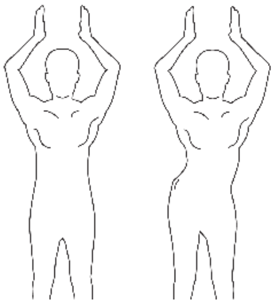
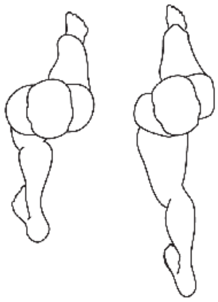
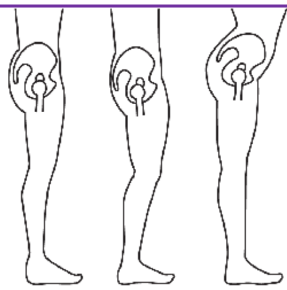
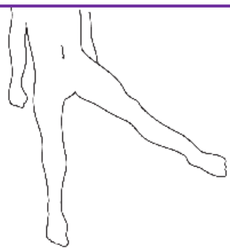
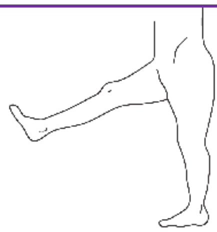
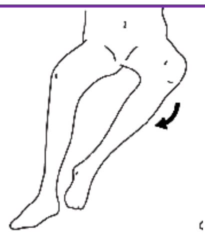
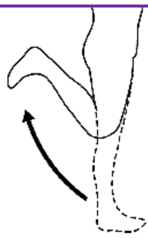
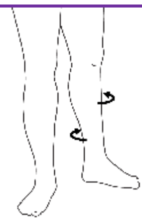
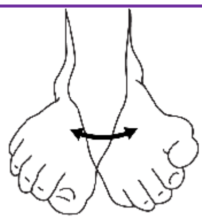
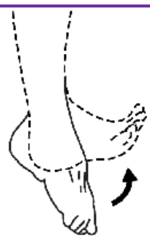
Figure 32: Movement Tolerance Margin (MTM): how far away from the plane the movement can go.

The MTM value represents how precise the physiotherapist needs the movement to be performed. Its definition is one important step on the treatment planning. The therapist can choose the MTM based on the movement accuracy that is required for that treatment or according to the patient limits, or even use the MTM to control the therapy progression, starting given more movement freedom with higher MTM and further reducing the tolerance to user improve the movement precision.

The Table 5 presents the classified movements for each segment. The movements that could not be recognized by the markerless technique are marked with asterisks (*). When segment does not perform any movement at some plane due to its joint anatomy and mechanics, it is described as “no movement” in the table. It is possible to notice that the main limitation on recognition is for the axial rotations. This occurs due to the fact that during the axial rotation no changes on body pose occur. Since the markerless technique makes use of body pose to estimate position, the joint estimation does not change being not possible to detect the movement. Improvements to better pose recognition are a challenge in the computer vision research area.

Table 5: Classified movements for each segment.

Segment	Movements on plane		
	Frontal plane	**Sagittal plane**	**Horizontal plane**
Cervical spine	 Lateral flexion	 Flexion and extension	 Axial rotation*
Clavicle	 Elevation and depression	 Axial rotation*	 Protrusion and retraction
Arm	 Abduction and adduction	 Flexion and extension	 Horizontal abduction and adduction  Axial rotation*
Forearm	∅ No movement	 Flexion and extension	∅ No movement
Hand	 Radial and ulnar deviation	 Flexion and extension	∅ No movement

	Frontal plane	**Sagittal plane**	**Horizontal plane**
Spine	 Lateral flexion	 Flexion and extension	 Axial rotation*
Pelvic girdle	 Elevation and depression	 Pelvic rotation*	 Protrusion and retraction
Thigh	 Abduction and adduction	 Flexion and extension	 Axial rotation*
Leg	∅ No movement	 Flexion and extension	 Axial rotation*
Foot	 Inversion and eversion	 Flexion and extension	∅ No movement

AXIAL ROTATION MOVEMENTS

As mentioned before, during axial rotations the pose of the joint does not change or changes very smoothly, being not possible for Kinect to detect it. Therefore, the technique developed in this thesis was not able to classify axial rotations movements.

However, the strategy used by clinicians to measure the ROM of these movements for the shoulder and hip joints during goniometry can be also applied here. In order to evaluate the axial rotation movement the user has to maintain a predetermined position during the procedure (Clarkson, 2005). So, in order to include shoulder and hip axial rotation recognition in our system, the procedures described below must be performed.

For the shoulder axial rotation the ROM can be measured by the forearm angle related to the trunk since the forearm is positioned at the horizontal plane with the arm close to the body (Figure 33).

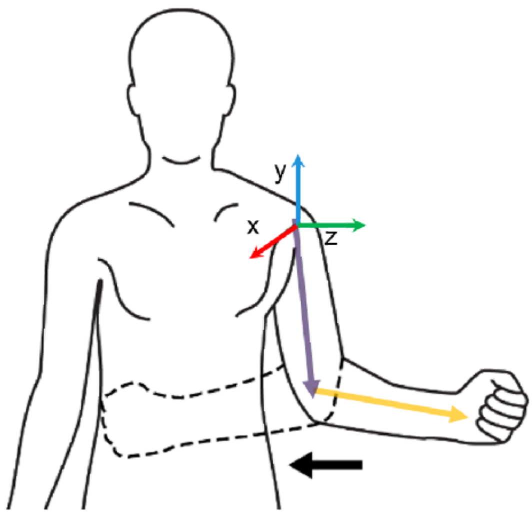


Figure 33: Required position to measure shoulder axial rotations and the vectors references.

In order to do that in our method, the measure will be performed by the angle between the forearm and, instead of using the elbow axis; it uses the upper proximal body Z axis as reference to compute the movement angle. Since this angle computation will be done using the proximal body Cartesian system it is necessary that the arm be positioned near the trunk. In order to guarantee this proximity the angle between the arm and the trunk is computed, and an arm opening tolerance is created to configure how far from the trunk the system can allow the arm to go. The second measure requirement is for the forearm to be stable on the horizontal plane, to assure that the angle between the forearm and the Y axis from the elbow is 90 degrees. Since it is a plane requisite, the tolerance about how far from the plane the forearm can go to movement classification is defined by configuring the MTM described before (section 0).

The same procedure can be performed for the hip axial rotation. However, in this case the required position is for the hip and knee flexion to be at 90 degrees (**Figure 34**). The hip position is measured by the flexion angle computed according to the method described above with the thigh height limited by the MTM. The flexion angle has to be 90 degrees plus or less the tolerance. The second restriction to the measure be valid is the thigh frontally to the trunk. This position is restricted by leg opening tolerance, similar to the arm open tolerance, which also can be configurable by therapist. If the thigh is opened more than the tolerance or flexed more or less than 90 degrees it is not classified as hip axial rotation. Similar to the shoulder, the hip axial rotation angle measure is computed by the angle between the leg and the Z axis from the lower proximal body Cartesian system.

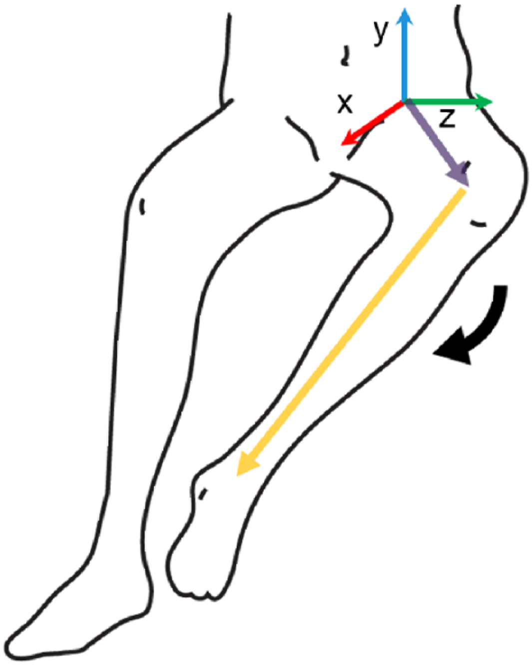


Figure 34: Required position to measure hip axial rotations (Clarkson, 2005).

POSTURAL ANALYSIS

During exercises performed at rehabilitation it is common patients to perform postural and others compensation in order to make the movement easier. For example it is common during upper limbs exercises to tilt the trunk to achieve higher height, or to flex the elbow. During motor rehabilitation, the wrong exercise can undermine the effectiveness of the therapy, or even be harmful for the patient. According to Rainville and partners (Rainville *et al.*, 1997) the use of postural compensations during therapy can promote pain and also reduce motor ability. Based on that, additional movement controls are also provided.

The main control provided is for the trunk position. During exercises it is normally required patient to be with the spine aligned, not doing any inclination. For that, the angle between the vector going from right to left shoulder and the one going from right to left hip are computed and then the variation of this angle is analyzed. This variation is accepted until a maximum tolerance value for trunk inclination is reached. This tolerance can be configured according to procedures to measure it or user limitations requirements. For example, scoliosis patients, whose trunk is naturally inclined, will need a larger range depending of scoliosis degree.

During development it was detected that for shoulders movements higher than 90 degrees the system detects automatically an inclination due the normal scapular movement, which is not a real compensation. In order to normalize the range in order to consider this scapular movement, a new range is computed whenever the arm angle is higher than 90 using the Equation 3.

$$newTolerance = tolerance + \frac{10 * (actualAngle - 10)}{100} \quad (3)$$

During limb exercises, elbow and knee position can be controlled by physiotherapist choosing its minimum angle required during the movement performance, for shoulder or hip for example. If the patient cannot perform the shoulder elevation with the elbow extended the therapist can configure 0 degrees as the minimum accepted as correct.

7.4. FUNCTIONAL MOVEMENT RECOGNITION

The clinical routine includes two main types of exercises, the biomechanical and the functional ones. The movement recognition method described before is capable of classifying the majority of biomechanical movements. However, it is not able to recognize functional exercises. In order to be capable of supporting this kind of movement in our Ikapp system, we developed a method called checkpoints.

The checkpoints technique is based on a vector state representation that is capable of recording and tracking motion. The method is composed of segment positions' registration over time through vector position recording. This record is then used for comparison between the current performed movement and the registered one. A tolerance range defines how far from the registered movement the user can perform the exercise and yet be considered the registered one. Different from the biomechanical movement recognition, where ROM and error type is informed, the checkpoints method only informs about whether the movement is correct or not and its relative position in relation to the complete movement (% of movement). This make this method useful for interactivity, where the movement can control the game according with its status and feedback can be provided using the right and wrong information. However, for evaluation this method is not capable to provide a lot of useful information, such patient ROM and the type of error which is being performed. To fulfill this lacuna it is possible to use the biomechanical movement recognition method to evaluate the movement while using the checkpoints for interaction as a control for the game.

MOVEMENT RECOGNITION BASED ON CHECKPOINTS

The movement recognition based on checkpoints was developed based on the same technology used for the biomechanical movements, i.e., the Kinect.

The checkpoint method process is composed of two phases, the recording and the analysis, summarized in **Figure 35**. At an initial step the method extracts joints positions from body representation described above (section 7.1). In sequence it is made a change of basis to coordinates centered on the user's body in order to achieve invariance to sensor position, the same used for biomechanical movement recognition (section 1.1). These vectors compounded are then used as a registry in a structure called checkpoint, which corresponds to a state of the movement in time, a pose. Thus, the sequence of checkpoints denotes several poses over time which describes one movement. The collection of checkpoints can then be exported for further use, guaranteeing persistence of the data. The second phase, the analysis, makes use of this saved data. Here, the current performance can be compared in the match process with the checkpoints saved on the recording phase.

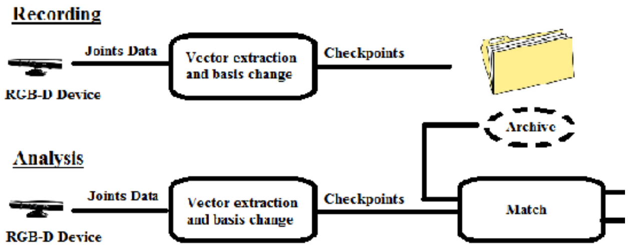


Figure 35: Checkpoints method overview, including recording and analysis phases.

MOVEMENTS TRACKING

After having body segments properly represented, the next step is to define how to keep tracking the segments displacement, in other words, the movement.

Our method proposes the concept of checkpoints for the capture of movements. A checkpoint contains a set of vectors that defines the movement during a time slice. Each set of vectors represents the state of the movement at a certain point in time. Therefore, a movement is defined by a sequence of states, i.e., checkpoints. Figure 36 illustrates this idea where poses are recorded over time during the performance of a walk. Therefore, to validate if the movement belongs to a checkpoint during a certain time slice we need to match the vectors of the current movement to the ones in the checkpoints.

It is important to notice that just registering these vectors over time is not enough since it will be almost impossible to exactly match them with the ones obtained during the movement execution. This occurs because of the device's capture rate that during movement analysis will capture frames that represent the movement in different stages when compared to when it was recorded. For example, if during the capture the checkpoints registered were one on the beginning of the movement and another on its end. Then, during the analysis, when comparing another movement execution, the captured frames were somewhere in the middle of it and another after the end of the registered movement; this would cause a mismatch since the vectors that are being analyzed are not exactly on the same position as the registered checkpoint. Secondly, due the fact that it is impossible for a human to execute the same exercise precisely every time, there is always some deviation on it.

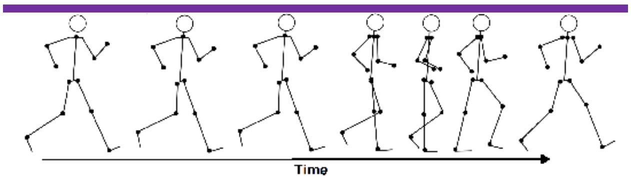


Figure 36: Poses captured over time during a walking motion.

In order to solve this problem, each time a checkpoint is registered, a range of tolerance can be defined for it. This range denotes an area around each vector captured in a checkpoint within which any other vector will be considered as belonging to it. Its use will be better explained in the following sections. Figure **37** shows a set of three checkpoints saved from a single vector and their respective ranges.

It is also important to notice that not always a full body movement tracking is wanted. For example, to track a wave motion it only requires tracking the respective forearm and hand vectors. So, it is also important that the technique allows choosing which subset of vectors will be considered while tracking, in other words, which vectors from the checkpoints are relevant. In the proposed technique choosing this subset is as simple as mark unwanted vectors in the checkpoints and then disregard them during the match process while analyzing the movement.

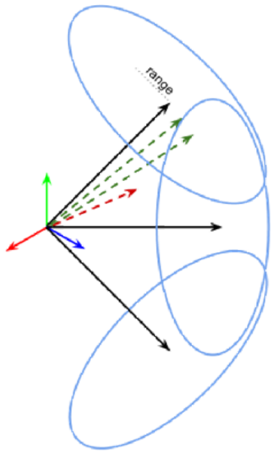


Figure 37: Movement recognition based on checkpoints registration and range of tolerance to allow functional movements interaction.

MOVEMENT REGISTRATION

The registration process is very simple; it consists of recording a set of checkpoints for a certain period of time (Figure 38), and exporting it to a file for further use.

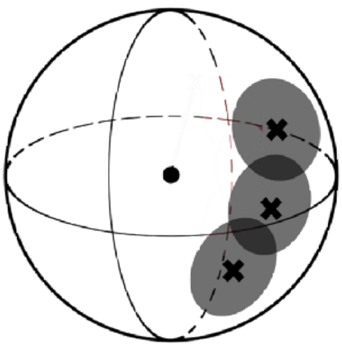


Figure 38: Checkpoints sequence registration.

Notice that since the checkpoints are saved at the device's rate, some of them may be registered more than once. This can occur due to the user simply not moving or making a slow motion in a way that does not have a displacement for two or more frames. So, for better results and simplicity, these redundant checkpoints (Figure 39a) should be also excluded, i.e. checkpoints that are the same or that are almost completely inside the range of another checkpoint are not recorded.

Also, these checkpoints cannot be totally separated one from another (Figure 39b). Firstly, there can be no spaces between two of them, i.e. two checkpoints so far from each other that there is no intersection between their ranges; this would create a space along the movement where it would be wrongly recognized as invalid. Also, they cannot be almost without intersection since this would create a narrow area of validation in the boundary between two of them. Thus, a small deviation on the movement would cause the vectors to be out of either checkpoint when near the boundary of two of them.

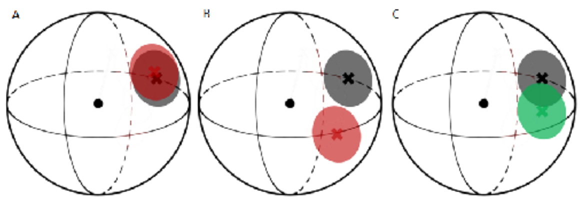


Figure 39: Registering cases: A) Redundant checkpoint; B) Distinct checkpoints with no intersection; C) Valid registration.

The problem stated above can be solved guaranteeing that there is always an intersection between two checkpoints. Another good approach is to consider a new checkpoint only if the new one's center is out of the range of the previous one. The new checkpoint which is shown in Figure 39c fulfills these two conditions. These requirements will force both checkpoints to have an intersection equivalent to almost half the area they denote, therefore, denoting a more constant area of validation. The checkpoints and their ranges were shown in **Figure 37**. Notice the area of intersection between them as well as that these checkpoints compose a more fluid area of validation than if they were distinct ones.

MATCHING

The task to match a movement with another previously recorded is more difficult since it is not just to check if the current execution is in determined checkpoint. It has to be robust enough to not lose track if one or more checkpoints are skipped or if the user starts to do it in a wrong way and then returns to do it correctly. It also has to identify it even if the gesture starts in the middle of what was registered.

In order to do the analysis, the system tries to match the current state to one of the checkpoints saved before. It is important to notice that since the skeletal representation is a set of vectors, where each one has its own basis, a subset of the skeleton can be set to be relevant to the recognizing. This way, to recognize a user waving his/her hand, the segments that are involved in the task has to be analyzed, the hand and forearm, for example. To match two vectors, a range of acceptability is needed because almost never they will be at the exact same position; also, it is very hard to a human to perform the movement exactly the same way all the time. In our first version (Chaves *et al.*, 2012) the saved states are discrete and each vector has its own range in a way that if the current movement's vector is within the range of a checkpoint, the current movement is validated and said to belong to that specific state (Figure 40). Doing this, the information about the stage of the movement is gathered, i.e. if the user is performing the beginning of the movement, or its final, or it is in some point in the middle.

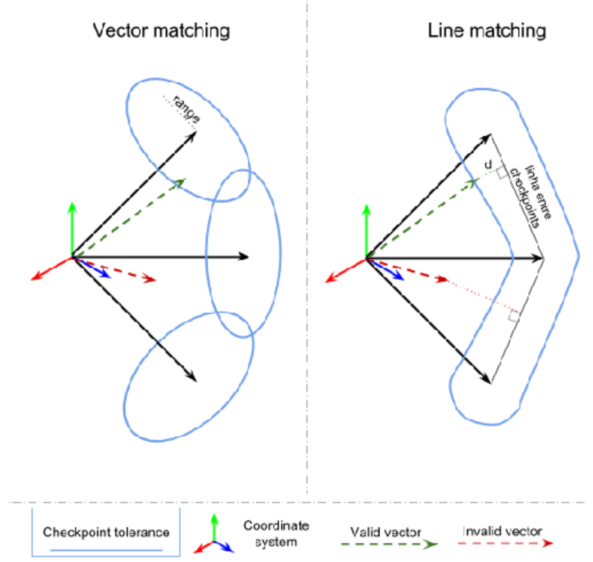


Figure 40: Checkpoint matching by vector and by line between the vectors.

This can be enhanced to give a continuous state instead of a discrete one by comparing the current movement's vector to a line that links two subsequent checkpoints and finding the closest spot in this line that validates the movement (Figure 40). This requires a little change when comparing the current vector to the checkpoints. Instead of getting a single checkpoint and checking if the current vector is within its range, it is taken two checkpoints and calculated the minimum distance to the line that connects them. **Figure 41** illustrates this process, where there are two checkpoints, C1 and C2, and also the vector from the current movement, P1 (**Figure 41**a). In order to compute the minimum distance from P1 to the line that connects C1 and C2, two other vectors are computed, C1P1 that is the subtraction between P1 and C1, and C1C2 that is the subtraction between C2 and C1 (**Figure 41**b). After this, it is calculated the projection of C1P1 on C1C2 (**Figure 41**c) using vector projection (Equation 4). This is the closest point between the vector of the current movement (P1) and the line that connects the two checkpoints (C1C2). Then, it is checked if the distance (**Figure 41**d) is greater than the range allowed. This distance is calculated by the norm (Equation 5) of the vector that is the subtraction between the projection and C1P1.

$$proj = \frac{C1P1 \cdot C1C2}{C1C2 \cdot C1C2} * C1C2 \qquad (4)$$

$$norm = \sqrt{x^2 + y^2 + z^2} \qquad (5)$$

.

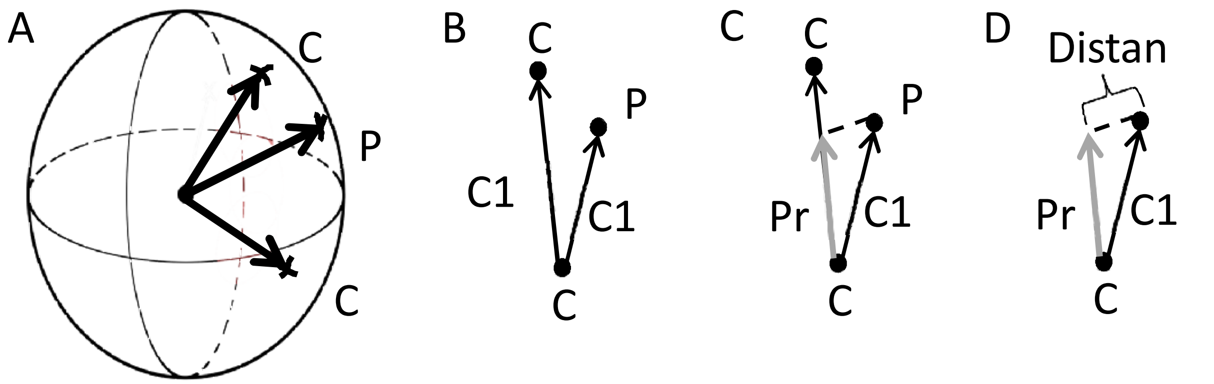


Figure 41: Calculating the shortest distance. A) Checkpoints and the current point; B) Auxiliary vectors; C) Projection vector; D) Shortest distance.

SEARCHING

It is also necessary to identify within which checkpoint the current captured movement is, i.e., to check if the movement stays the same as before or if it has moved to somewhere else along the course of the registered motion. Always searching the entire set of registered checkpoints for the one that best fits it should be avoided because of all the additional time consuming processing. Due the fact that a person's movement is continuous, the next checkpoint is more likely to be near the current one. Searching the entire set of checkpoints (Figure 42) is not efficient, although it solves the problem and always proves that the input does not fit anywhere else of the reference motion, if that is the case

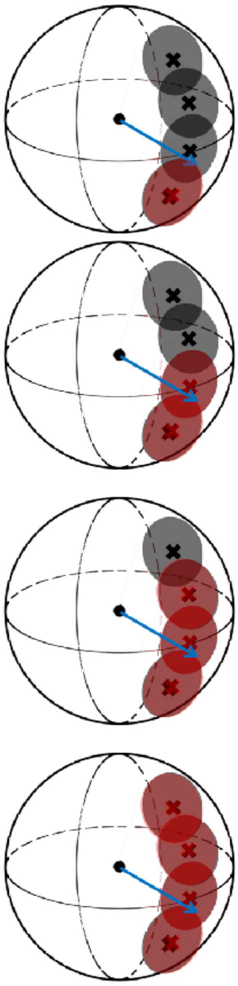


Figure 42: Continuous status searching method running all checkpoints in sequence.

To optimize it, the search begins around the current checkpoint and then expands it towards the farthest ones (**Figure 43**). When the program is initiated, it is assumed that the user will start from the beginning of the movement, this way it is assumed that the first checkpoint is registered as the current one. From this point forward, every time the input is not inside the current checkpoint range, the next and previous ones are the candidates and being so, it is checked if the input is within their ranges. If not, the search is extended to the two checkpoints forwards and two backwards, and so on until finding the checkpoint the input belongs or until there is no more checkpoints to be checked. Notice that it is not only the data about the movement validation that is given, but it is also possible to extract information about which part of it is being executed (% of the movement), if it is on the beginning, end or some position in the middle of that motion.

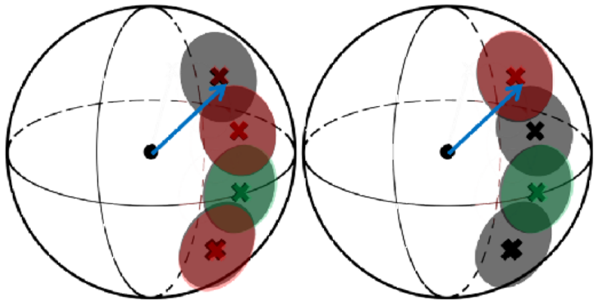


Figure 43: Optimized status searching method based on the position of the last checkpoint location (green area).

The information about which part of the movement is being performed can also be enhanced when using the lines approach. After localizing the segment and the exact spot in that segment that best fits the current movement, it is possible do sum up all the previous segments from the first CP until that spot and divide it by the total length of the movement (the sum of all segments). Thus, giving a continuous value that ranges from 0 to 1 and represents the exact part of the movement that is being performed.

7.5. SUMMARY

This chapter presented the two movement recognition techniques developed. Before implementing the methods the body representation to correspond to the segments which will be moving and the JCS following the ISB standard mapped were performed.

The two methods were developed aiming to enable interaction through an interactive system using movements which are commonly performed on therapy. The first is based on biomechanical concepts and allows the interaction through the therapeutic movements. These exercises are prescribed to accomplish very specific gains and should be performed precisely to achieve that. The second enables the use of functional exercises, which are performed on therapy aiming to recovery patient function and indecency.

These methods will be used in the next chapter to provide input information for the applications. These solutions are tools to allow test of the movement recognitions capability to work as input for interactive systems enabling them to interact using different movements. The applications also enabled to evaluate the benefits of using the biomechanical information provided by the method as guidance and correction.

8. Interactive Rehabilitation System: Ikapp

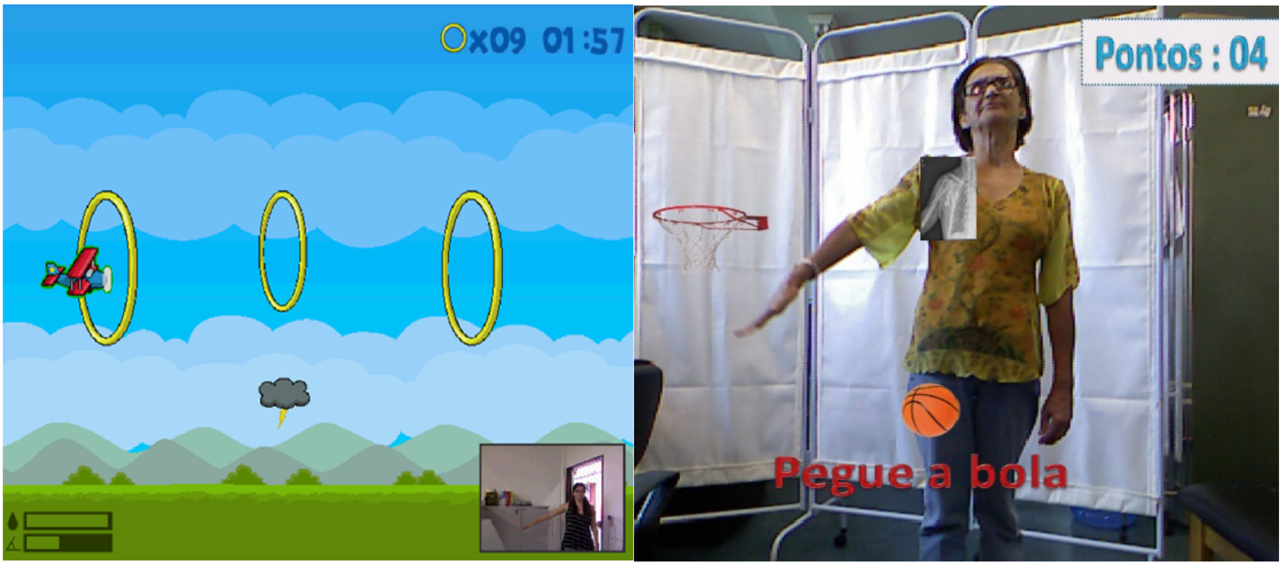


Figure 44: Interactive rehabilitation systems developed, based on virtual (left) and augmented reality (right).

The aim of this work is the development of a rehabilitation system more clinical related in order to improve motor rehabilitation process. To use the movements that are traditionally used on therapy the movements recognition techniques were developed. To provide the additional features and to allow the applications development we developed a rehabilitation support system, named Ikapp. The system is composed of three modules: game, report, and configuration.

During the development a support movement analysis library was implemented which is capable of extract information's of movement recognitions method. This library communicates with the Ikapp system which can use the data extracted to interact with the game, provide guidance and feedback and/or to do a report, or can use its configuration to set parameter in the library.

The movements recognitions developed are capable to provide movement information in real time. This knowledge about movement can be used in the systems to provide interaction. This way, the interactive system can be controlled by the movements used on the therapy, according to the methods recognition. The recognition can also provide biomechanical descriptions which can be used to guide and correct movement performance.

This section will present the movement analysis library and its interaction with the Ikapp by using two games as case studies. The first case study is a VR system, named reAIRbilitation, which will be presented in section 8.2 (left image in **Figure 44**). The second, mirrARbilitation is based on AR and is described in section 8.3 (right image in **Figure 44**).

The case studies here developed consist of interactive systems which make use of the established library as a tool for movement recognition. The systems have two main focuses: exercise performance according to clinical routine, including the biomechanical and the functional movements, and guidance and correction of the movement execution. This orientation can be useful as a complementary therapy and mainly to home care therapies, where the physiotherapist cannot supervise the patient and patients have to execute the rehabilitation program alone.

8.1. MOVEMENT ANALYSIS LIBRARY

The library developed is composed of methods which can easily access information from movement recognition techniques. The library also provides functions to easy access sensor information.

Since different technologies and methods can be used, in order to access the library it is necessary to set the movement recognition method and the skeleton tracking software that will be used. The skeleton tracking software can be chosen between OpenNI, Microsoft SDK (MSSDK) and MSSKD2. When this work started the OpenNI library was the only one available to access Kinect information. Due to that the first tests were performed with this version. This skeleton software method presents the disadvantage to require the psi position performed by the user, what cannot be performed by some of them due to physical limitations. After the Microsoft started to launch de SDKs versions and continuously updated them until the last version, the 1.8. When choosing the option MSSDK the system will use the version installed in the computer, which can be the 1.8 or older ones. With the release of the Kinect v2 the SDK 2.0 was provided. So, when using the movement analysis library developed here any of these three skeleton tracking methods can be used.

The functions of the movement recognition library are presented in the appendix B. The main functions will be described below (Section 0 to 0).

GET CURRENT STATUS

The getCurrentState() method returns the actual status of movement, biomechanical or functional.

In case of biomechanical movements it returns the actual angle measured according to the configuration. The error returned by this method includes the movement errors which can be used by the application, for example, to exhibiting warnings. The returned errors are: i. Movement out of the respective plane: sagittal, horizontal and frontal; ii. Arm or leg opened: for the axial rotations movements only; iii. Plane not defined: when the plane set in the configuration is invalid; iv. Angle not computed.

When recognizing functional movements the checkpoints technique returns the checkpoint status. When the movement is out of the checkpoint and its acceptable range, the method returns “the out of checkpoint” error.

GET MAXIMUM AND MINIMUM ANGLE

These two methods, getAngleMax() and getAngleMin(), extract the maximum and minimum angle determined by the user in the configuration file.

These values are used to establish limits for interaction in order to enable the interactive system to be adaptable to patient limitations. For example, the maximum angle which will be required on the game. This way the system can support patient capabilities and the actions on the system can be limited to these values.

UPDATE BIOMECHANICAL ANALYSIS

The updateBiomechanicalAnalysis() method integrates all the methods which perform additional movement evaluation. These methods should be called at each frame in order to work properly.

The functions that are integrated at this method include:

- Compute postural analysis: check the trunk alignment;
- Compute actual elbow straight: check if the elbow is stretched;
- Compute actual head straight: check if the head is aligned.

All these additional analyses are dependent on the value configured by user. The acceptable angle for each of these positions is set in the configuration file. If the movement is being performed with these postures besides the configured the function returns the error for each of them: postural error, elbow not straight and head not straight, respectively.

WRITE REPORT

The writeReport() function is responsible to present the biomechanical analysis results captured during the system execution in an accessible and documented way. The report provides therapeutic information about the patient´s performance during the use of the system.

While the system is running, the report module of Ikapp system is continuously receiving data from the biomechanical analysis and at the end of the game the statistics measurements are computed including: maximal angle, percentage of time which the movement was executed incorrectly, if the movement was performed with postural compensation. **Figure 45** shows the information provided by a game report after a patient uses the system for three minutes performing the shoulder frontal abduction of the right side movement.

The system can report about more than one movement at the same time, since this information is configured in the first use of the system. It can also provide a report of biomechanical movements even when functional movements are being used to control the game, this means that biomechanical analysis and checkpoints technique can run simultaneously.

Figure 45: Report file.

GET JOINTS VECTORS IN BODY COORDINATE

It was presented before that for rehabilitation applications it is important to use biomechanical conventions during movement description and evaluation. In order to enable interactive systems to recognize movements according with these standards, section 1.1 presented the Joint Coordinate System (JCS).

The getJointsVectorsInBodyCoordinate() method was developed to enable access to segments already in the biomechanical base. So, this method returns the array with the segments vectors in their respective JCS as established in section 1.1.

LOAD CONFIGURATION FILE

The configuration file is an important system characteristic. The library function which performs this action is the load(). The system configuration is done through a text file which is presented in appendix C. In this file the physiotherapist can choose one of a list of biomechanical movements to be used, for evaluation and/or interaction. The biomechanical movement is set by choosing the segment and the plane. The additional biomechanical and postural analyses are also defined in this file. The available configurations are:

- The segment which will perform the movement and on what side;
- The plane of movement;
- The maximal angle that will correspond to the maximum movement on the game/application;
- The Movement Tolerance Margin (MTM);
- Postural acceptable angle: for trunk, elbow and head;
- Axial rotation restrictions: arm or leg opening tolerance;
- The game/application duration in minutes.

For the functional exercises the configuration file is simpler and includes:

- Segments which will be considered during movement execution;
- MTM.

The system which is using the library can have its own configuration file and overwrite these configurations by using the set functions: i. set main movement, set postural range, set elbow minimum angle, set head minimum angle, set open arm or leg tolerance. This enables applications to have their configuration mode according to their interest.

8.2. CASE STUDY 1: REAIRBILITATION

The first system developed to validate the findings of this research was an interactive game where the main character could be controlled by the user movement. The game started with a first version named Dolphin´s adventure and then it was updated to the reAIRbilitation version. The steps of this process are presented in this section.

GAME MECHANICS

The initial game concept was to enable the patient to control the main character of a game using therapeutic (biomechanical) or functional movements, which are the same used during traditional therapy. The game´s mechanic has been developed to induce the therapeutic sequence of movements and repetitions.

In order to achieve that, game dynamics understands the patient's movements to control the vertical motion of the main character. The patient has to make the main character catch some elements and avoid others, both coming from the opposite direction of the screen. Positive and negative feedbacks are given depending on the success of the user on performing these tasks. This way the user has a real motivation to perform the necessary moves.

For rehabilitation applications, one important characteristic is that the movement that controls the character of the game could be scaled and graduated according to patient limitations. This way the maximal patient mobility will correspond to the maximal motion of the character. For example, the physiotherapist configures the game for shoulder abduction, which occurs in the frontal plane as explained before, and determines that the maximum ROM for the patient is 90 degrees. Using this configuration, the game will interpret and respond accordingly as a full movement when patient abduction is at 90 degrees.

The game configuration, including the movement which will be used to control the game and the maximum and minimum ROM, is set with the configuration file described before (section 0).

INTERFACE EVOLUTION

The interface of the system was designed in two phases. Firstly, a prototype was developed and then, after the system and this interface passed through user tests, the second version was made.

The first version of the game was focused on testing the hypothesis that a game specifically designed for physiotherapy rehabilitation with feedback for the patient would be valid. It was defined a simple game and set of requirements, thereupon it was necessary to test if this concept had value to the patients and to the physiotherapist. With this goal the first version of the game was created, the Dolphin's Adventure. As the focus of this version wasn't specifically on the user's satisfaction with the graphics, the effort on creating high quality graphics, meaningful story and characters and other well-known characteristics accepted by the games market wasn't considered.

With this prototype developed, tests were made to evaluate it, in which all the characteristics of the system (technology and interface) were considered. After the results of these tests and all the user feedbacks being collected, synthesized and studied, the development of the final version was initiated and then tested to measure the improvements made in the system compared with the first version. In this section will be described how these project steps were conducted, focusing on the graphic features and interface of the system. The tests and results will be described in chapter 10.

FIRST VERSION: DOLPHIN´S ADVENTURE

The theme of the first version of the game was chosen based on movement characteristics. As most of the moves to be made by the system's user should follow trajectories on the vertical axis, it was necessary that the character controlled by the user had its main moves on this axis too, making the system more intuitive. It was also important the use of a continuous movement enabling user to work all ROM during recovery. Thus, an aquatic environment was designed for the game.

Knowing that the game will be based on an underwater scenario, the main character was defined to be a dolphin, easily accepted as a friendly icon of this environment. **Figure 46** shows this character and the scenario. As explained in the game mechanics, the user will be induced to catch some elements at the screen in order to stimulate the movement. The characters chosen for this purpose were fish coins. Also to improve the interaction with the system and user motion, the element the user will have to avoid is a submarine and a piranha (**Figure 46**). While the dolphin will move on the Y axis, these objects will be moving on the X axis from right to left direction.

Figure 46: Dolphin's Adventure scenario and graphic elements.

Additional information and feedback were included. The score, game time, user's movement angle or status and a virtual mirror were added above all the elements to help the user understand and feel comfortable with the game mechanics. All the graphic elements created to represent this theme, game mechanics and feedbacks are presented in Figure 46.

SECOND VERSION: REAIRBILITATION

After the tests with the first version of the game, system limitations regarding the feedbacks provided, graphic elements presentation and positioning, and with the user´s satisfaction in general. Given the need for improvements, the game was redesigned to be friendlier.

Brainstorming, sketching and refining the chosen alternative were the strategies used to define the new main character, scenario and additional elements. This conception was performed with an interdisciplinary group composed of designers, physiotherapists and programmers.

After these sessions, an airplane was defined as the new main character, choose during the brainstorm sections. It was decided that the airplane scenario would present good relation to the movement control and the related additional elements would be useful in inducing movement. The airplane movement is performed keeping the same restriction of vertical movement's freedom (Y axis) used in the dolphin's. The scenario has been made cleaner than the previous version and provides more space to the other elements. The creation of the other elements was given with the same necessities pointed in the first version: interaction for controlling the game and movement stimulation.

To induce specific movement directions, rings were defined as the main must do steps for the patient. Stormy clouds are now the elements to avoid. To improve the dynamics of the game, fuel boxes must be picked up in order to make the plane keep flying. All these elements are presented in **Figure 47** and were chosen to make the user easily understand what to do without having to follow any instructions.

One important characteristic added to this second version of the game is the flexibility of the ring positions. The physiotherapist can set the positioning and timing of these rings in the configuration file in order to make the patient do a specific sequence of movements. For example, if during the therapy it is required an isometric contraction, where the patient has to maintain the movement by a certain number of time; in the game the therapist can use a sequence of rings to induce that, as shown in **Figure 48**.

Figure 47: Catching and obstacles objects to induce user motion in the reAIRbilitation game.

Figure 48: Isometric contraction being induced by rings positions in the reAIRbilitation game.

Based on some results extracted from the first prototype tests, there was a lack of feedbacks on the game. At the Dolphin's Adventure the user could not understand when he was doing the movements in a wrong way. To rectify this problem, visual and auditory feedbacks were added to the game, both triggered when the patient does anything different than what has been planned by the physiotherapist. The corrective feedback was provided in the game characteristics and also through instructive information. In the game the airplane stops and is highlighted in red. The instructions are provided by auditory and text messages saying to the user how to correct the movement. The same message is given in the two feedback types allowing users which were unable to read to receive the information by hearing it. These elements can be seen in Figure 49 with warning and instructional messages on the center bottom.

Figure 49: Corrective feedback with instructional sentence. "Estique o cotovelo" (Straight your elbow).

The second version presents the same game mechanics however with a friendlier interface. The game also contemplates additional characteristics such as enabling therapist to define the elements positions, stimulating specific movements. The reAIRbilitation also provides corrective and instructional feedback, which is important for rehabilitation applications. The new version was also upgraded to use all the classified movements, the first one was developed using only upper limbs. The **Figure 50** shows the reAIRbilitation being controlled by hip abduction movement.

Figure 50: reAIRbilitation game being controled by hip abduction and adduction movements.

8.3. CASE STUDY 2: MIRRARBILITATION

The second case study developed was based on AR. The aim here is to establish a system where the instruction and motivation to perform the exercise would be provided on the real world. The idea was based on the biofeedback concepts, where the patient auto visualization is shown to increase postural and movement control (Thikey *et al.*, 2012; Caudron *et al.*, 2014) improving their learning, performance and rehabilitation results (Tuff e Watson, 2005; Glick e Greco, 2010; Stanton *et al.*, 2011; Thikey *et al.*, 2012).

In order to do that, two system versions were developed. First a prototype was created where the concepts proposed were validated. The first prototype was tested with three different populations in order to get different opinions: elderly, adults and physiotherapists. The results of these tests are presented in chapter 10 and helped the definitions of the second AR version, the mirrARbilitation system.

After that, a second AR system, named mirrARbilitation, was developed. The mirrARbilitation was developed in cooperation with the NARVIS lab group (Narvis, 2015) from the Technische Universität München, in Munich, Germany, where the author spent part of her PhD. To define the interface and information disposal on the screen, physiotherapists, doctors and programmers performed a joint conception. Differently from the virtual world, the AR interface requires a specific design for each movement. Due to that, for this case study only the shoulder abduction movement was used. The choice was made based on the movement accuracy, being the shoulder abduction the more accurate movement analyzed with the Kinect, since there is no occlusion during its performance. Another characteristic which helped the choice was the fact that this movement has a bi-dimensional visualization, which makes it simple to develop an interface to validate the concept. These two systems are presented next.

First prototype

For AR systems a basic principle is the presence of the real world overlapped with the augmented synthetic content. For the first prototype version, which purpose was to validate the idea, the depth image was used. This way there was no necessity to scale the skeleton positions extracted from the depth image to the respective position on the RGB image. Since it was the first prototype developed before the release of Microsoft SDKs, this one was implemented using the OpenNI skeleton tracking.

Guidance for correct movement execution is one of the important system principles. In order to do that it is necessary to know the movement direction and aim and find a way to show these information to the user. The movement in question is the shoulder abduction. During its performance the user has to take the arm up while positioned laterally to the body. To induce this position a reaching object can be positioned laterally to the trunk at a distance reachable by the hand. For the first prototype a simple red square was used as a reaching object (**Figure 51**). The reaching object is positioned according to the shoulder position being the square height the shoulder Y axis and the X position correspondent to the shoulder X axis plus the arm size. Since the reaching object position is based on shoulder references it is able to follow the user motion.

Figure 51: Reaching object to induce user movement.

The correctness of the movement execution in a rehabilitation process is essential for the treatment efficacy. Due to this, the system is programmed to punctuate whenever the user executes the movement correctly. Angles measurements as well as arms and trunk alignment are used as criteria to describe the movement. Postural analysis and users compensations during movement can also be controlled through the system.

Since this was the first system developed during this work, it did not make use of the movement recognition library and the movement description was made individually. So, aiming to recognize correctly the shoulder abduction execution, the following descriptors and requisites were used: i. the shoulder abduction angle must be equal or greater than 90 degrees at the end of the movement; ii. the elbow angle must be similar or higher than 160 degrees (to ensure that the arm is well stretched); iii. the angle between the arm normal vector of the frontal plane must be within the range of 80 and 100 degrees in order to guarantee the lateral alignment of the arm; iv. the right and left shoulder height (Y coordinate) must be similar, with a range of 10%; v. the actual abduction angle must be higher than it was before; vi. in order to keep punctuating, user needs to go down with his arm (the arm has to go down 30 degrees of shoulder abduction), and perform again the complete movement.

With the movement description it is now necessary to tell the user when he performed the movement correctly or not. In order to inform him scores were created which increase each time the movement is executed correctly (**Figure 52**). In order to help the user to understand the movement dynamics, an additional instruction informing to return to the initial position was included when a score is achieved (**Figure 52** a and b).

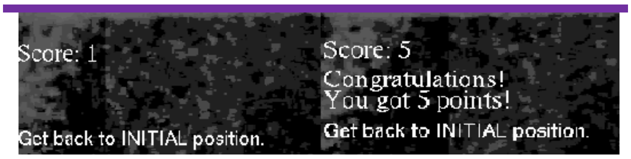


Figure 52: Feedbacks through scores return instruction and congratulation message.

In the motivational aspect, for each five points a congratulation message is given (**Figure 52** c). The number of points where the feedback will be shown can be chosen by the user. Additionally a movement status bar is presented and is loaded gradually according to the movement route (0 to 90 degrees) (**Figure 53**). Knowledge about movement status helps the user to know if he is in the right way.

As discussed before, when performing rehabilitation exercises it is not only important to show how to perform the exercise but also avoid wrong execution. In order to help with that warning messages were created. When the movement is being done in a wrong way, a red text telling how to correct it is presented below the score area. Movement correction is also enabled highlighting body parts which should be corrected (**Figure 54**).

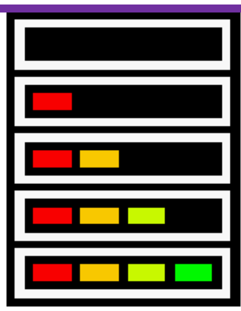


Figure 53: Movement status bar.

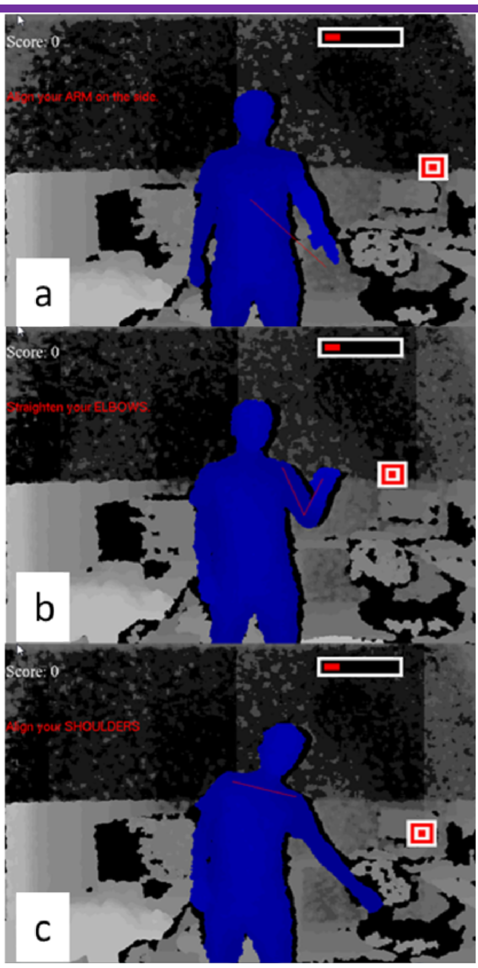


Figure 54 Warnings about wrong movement performance: body highlighting and instructions to correct it. A) Arm not aligned laterally. B) Elbow not straight. C) Postural inclination

MIRRARBILITATION

The purpose of mirrARbilitation was to improve the first prototype interface, interaction and functions. Meetings between therapists and programmers were done in order to define the new system characteristics.

As for the first prototype, the movement chosen for interaction was the shoulder abduction. However in the mirrARbilitation the movement recognition for interaction was performed using the movement analysis library developed. From the library the angle for the actual movement status and the wrong executions were extracted. This information was then used for interaction and feedback definition.

INTERFACE

The first change made on the interface was the use of the real image with the RGB information provided by the Kinect. It was defined that in the new version the dynamic movement would be induced not only by a reaching object but also with a catching object making user to return to the start position. This way the movement flow will be maintained. The catching and reaching objects chosen for this version were a ball and a basket (Figure 55). These objects were used to induce the movement and also to add a lucid aspect making the system more attractive.

Figure 55: Graphics elements of mirrARbilitation system.

Additional warning to inform subject to return to start position was included with the message “Take the ball” (**Figure 55**). Despite the object definition, mirrARbilitation enables a certain freedom: the catching and reaching images and text can be easily changed any time by overwriting the files in the game folder with the new ones and renaming them.

Differently from the first prototype, the mirrARbilitation system enables a reaching object to be set. The position can be configured according to the user's maximum range of motion or according to the angle which the physiotherapist desires patient to achieve. Since the position is depending on an angle, the reaching object is set at a position calculated according with shoulder position and arm size (Equation 6 and 7). Since the objects are located according to a body reference, the user is free to be in any place on screen. The only requirement is a full upper body view in order to allow appropriate movement analysis.

$$reachingObjectX = \text{shoulderX} + [\sin(aimAngle) * armSize] \quad (6)$$

$$reachingObjectY = \text{shoulderY} + [\cos(aimAngle) * armSize] \quad (7)$$

The score system and the congratulations message provided when achieving certain number of successful movements were both upgraded (**Figure 55**). The difference here is that when achieving the number of repetitions configured by the therapist the user crosses to the next level of the game. The next level is characterized by an increase on the position of the reaching object. The graduation of this improvement is also defined by the therapist, which chooses the number of degrees which will be added to reach the object position for the next level.

It is suggested that when the patient has conscience of his body function and mechanics he gets credulous about the therapy (Ni *et al.*, 2011). This additional believe improves patient engagement and motivation on therapy (Glick e Greco, 2010; Thikey *et al.*, 2012; Caudron *et al.*, 2014). Based on this concept, in order to show patient how joint mechanics is working and improving during movement, x-ray images taken from the patient were included. The x-ray images represent the shoulder anatomy during all range of motion. The respective x-ray image is shown according to movement angle. All interface elements together can be seen in **Figure 56**.

MOVEMENT CORRECTIVE GUIDANCE

Instructions to help avoid the wrong movement execution are an important characteristic of the systems here developed. For the mirrARbilitation system the best way to show this information through images was defined by the specialists. During the definition process it was established that the highlighting on body parts was not effective for patients. This kind of feedback brings a lot of information to the screen which is not immediately understood requiring processing to achieve comprehension. A large number of rehabilitation system users are old or have cognitive or visual impairments associated. Due to that, it was suggested writing warnings accompanied with a picture showing how correction should be done, probably a more clear way to instruct patient (Figure 56 d to f). For the shoulder abduction the instructions for wrong performance include: point less to the front and more to the lateral (when arm is out of the biomechanical movement tolerance, out of the plane); straight you elbow; align your trunk.

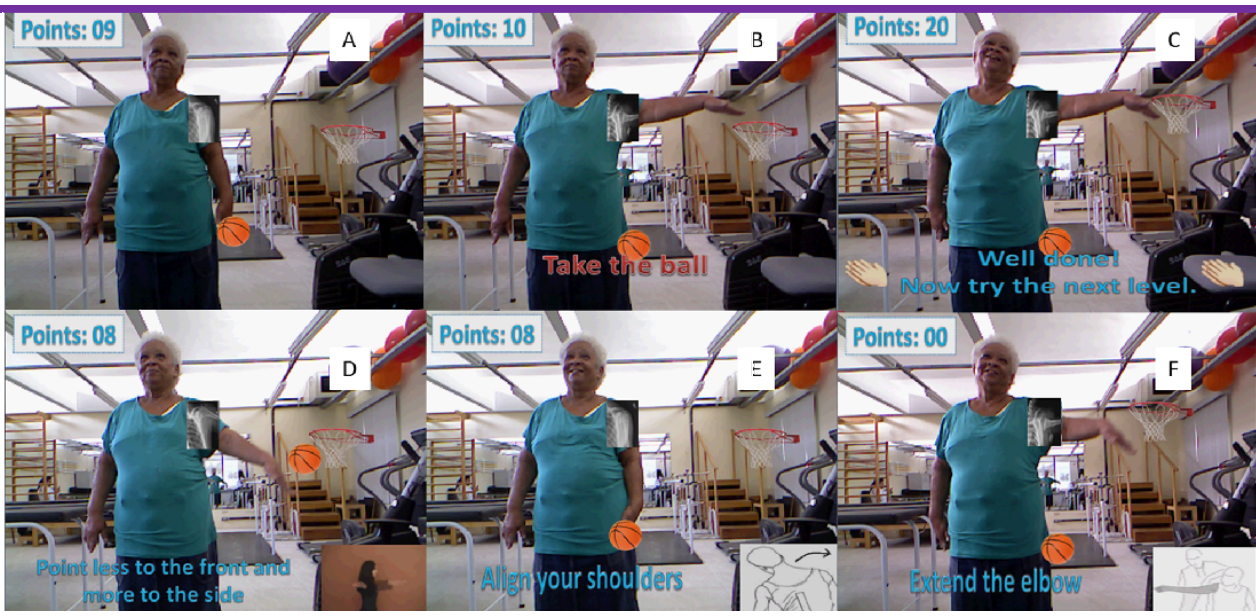


Figure 56: MirrARbilitation interface: A and B) Reaching and catching game dynamics; C) End of level with congratulation message; D to E) Warning and instruction for wrong movement's performance.

The error tolerance is the last additional feature supplemented on our system. It was created in order to improve usability and make it more adaptable to users' interests. This value defines the number of seconds which the system enables the user to be at the wrong position. The error tolerance is set in seconds in the configuration file. If the user does not return to the correct position before the tolerance time the system will ask him to reset the movement by returning to the start position.

8.4. SUMMARY

This section presented the applications developed using the movement recognition methods developed. First the movement analysis library, which integrates the two methods was presented. This library provides easy access to methods information. After the two applications which were developed using the Ikapp interactive rehabilitation system were presented. The Ikapp provides tools to integrate the movement recognition with the additional features such as configuration and report.

The VR solution developed started with a Dolphin's Adventure theme and was latter upgraded to the reAIRbilitation. In both the character is controlled by the therapeutic movement. Corrective feedback is provided in the upgraded version. The AR application shows elements on screen to induce movement and also gives corrective feedback when the movement is being performed wrongly.

The next two chapters will bring the results of the tests from this thesis. First the results for the movement recognition techniques will be presented, in chapter 9. Chapter 10 will bring the results obtained by testing the applications here presented.

9. RESULTS: MOVEMENT RECOGNITIONS

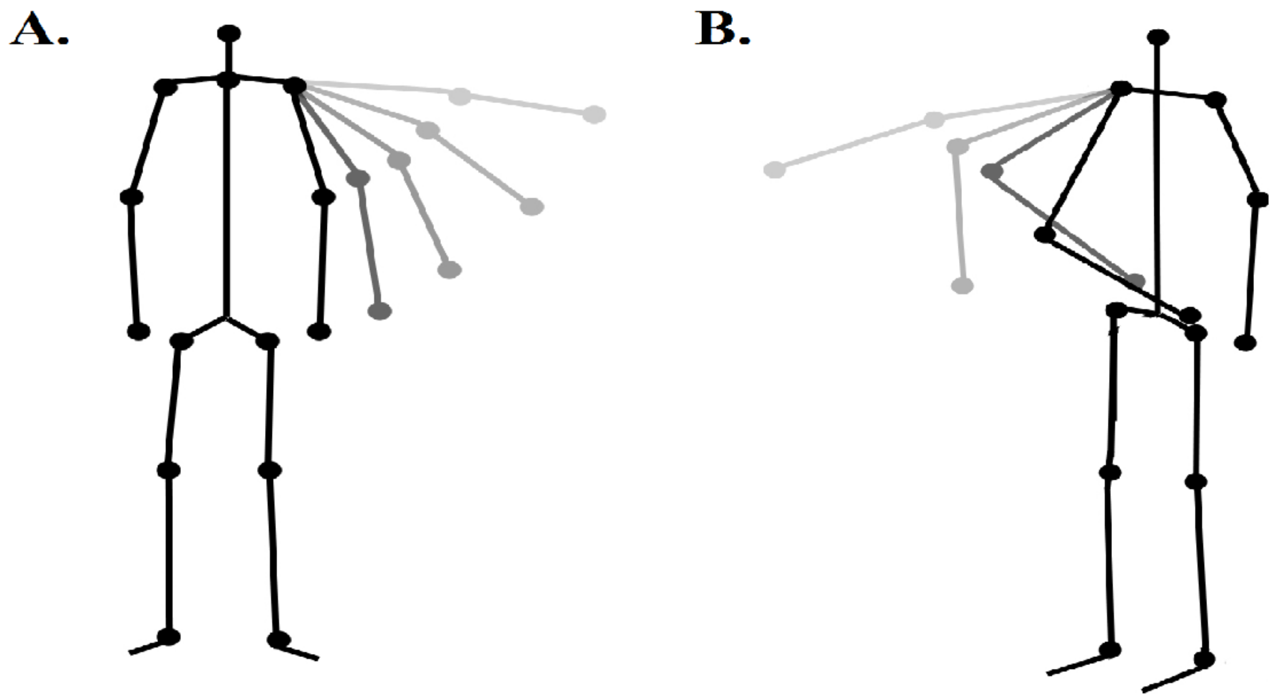


Figure 57: A biomechanical (A) and a functional (B) movement being performed.

After developing the movement recognition techniques it was necessary to evaluate them. The evaluations were done checking the criteria that are related to clinical necessities and performed involving the specialists in the area.

Intending to evaluate the movement recognition from both techniques, movements executed on traditional motor rehabilitation treatments were performed, including the classified biomechanical movements and the functional ones (Figure 57). The experimental protocol of these tests and their results will be presented now.

9.1. EXPERIMENT FOR BIOMECHANICAL MOVEMENTS

This section presents the experimental procedures performed to test the biomechanical movement recognition. The goal was to evaluate if the movement recognition technique is able to classify the biomechanical movements and this way detecting when they are being performed correctly or wrong. For that, the method was tested by performing all classified movements and checking the system capability to classify them correctly. It was measured by the percentage of correct exercises detected as right and wrong exercises as wrong ones.

To achieve that the movements were performed and analyzed using both Kinect versions, Kinect v1 and Kinect v2. The two Kinect were connected to a computer and the movements were performed by user standing in front of the sensor. The two Kinect were aligned in order to provide the nearest point of view as possible for the two sensors. The background was cleaned to allow skeleton tracking to work in the best condition. Figure 58 shows the setup used during the tests. Tests were performed on a computer with an Intel I7 4790k 4GHz processor, 32GB of RAM and Nvidia GTX 780 TI video chipset.

Figure 58: Setup for the biomechanical movement recognition tests.

In order to test the method, movements were performed in a correct and wrong way and the success rate of recognition by the system was scored. In order to guarantee that the movements were performed in a correct way the movements were executed by one physiotherapist specialized on biomechanics and with gymnastic preparation due to the fact that its practice and corporal conscience favors the performance of more precise movements. The person who performed the movements was carefully chosen and guided to perform them as perfect as possible since they would be interpreted as correct.

Each classified movement, described at section 0 presented at **Table 5**, was performed 100 times: 70 times correct (35 at normal and 35 at fast velocity) and 30 times wrong (out of its respective plane). The tests were recorded using Kinect Studio 1.8 and 2.0, from both Kinect versions, enabled by the SDKs (Microsoft, 2011). The movements recorded could then be evaluated by the movement recognition method using different MTM guarantying the same movement in the different tolerances avoiding bias. The tests with the different MTM were performed trying to find the more adequate value for it in each biomechanical movement, where tracking and recognition have lower fail rate. During all movement performance the system was evaluating its execution in real time. To evaluate the data and compute success rate, graphics with the angles during movement were plotted and value of -20 was assigned when the movement was out of plane. When at any part of the movement this value was found the movement was computed as a wrong exercise. Movements performed with user facing the sensor. For the movements where occlusion could be a problem, such as the ones which occurs at Sagittal plane, axial rotations and shoulder horizontal abduction tests were also performed with user positioned rotated around 30 degrees to do not occlude joints during movement.

In order to analyze the data obtained from tests the success rates were computed. A descriptive analysis with percentage for each movement at different MTM was performed to present data. For the correct movements the value represent the number of correct exercises recognized as right and for the wrongs one the percentage of movement mistakes detected correctly. Since there was no different groups none comparative test were required.

RESULTS AND DISCUSSION

The gesture recognition here proposed presented good capability to classify biomechanical movements for the majority of classified movements. Some joints presented limitation on its skeleton estimation being not possible to detect their movements. The method was also able to detect when the movement is being performed in a wrong way. This last feature is very useful for rehabilitation interactive systems which can make use of it to correct and guide patient during exercise (Da Gama, A. *et al.*, 2012a).

The use of movement angles measured using the segment and its JCS according with the ISB standards enabled to classify the movements according with the biomechanical concepts. It also allowed the recognition to work with user standing at different positions in relation to the sensor, including rotated and laterally displaced. This way, it is possible to provide the user a greater mobility during the use of the system, becoming one step closer to a natural interaction. Movements with different positions in relation to the sensor were also included in the correct performance test described before.

The results will present the recognition capability and success rate for each classified movements, and when necessary the limitations will be discussed. This section will first present the results by segment. For each movements the results for the Kinect v1 and v2 will be presented. Just after discussion about the adequate MTM and an analytical analysis about the two sensors version will be provide.

CERVICAL SPINE

The movement recognition showed good results in classifying the cervical spine movements. Table 6 presents the success rate for the cervical classified movements using different MTM for both Kinects. The two classified movements, lateral flexion and the flexion and extension, presented small range of motion, around 33 degrees to movements at frontal plane and 20 degrees at sagittal plane, what can lead to a limited use of the movement as interaction control, which may be not so dynamic.

Table 6: Movement recognition for cervical spine. Succsess rate (%) at different Movement Tolerance Margins (MTM) with kinect v1 and kinect v2.

Cervical spine							
Movements		**10 MTM Kinect**		**20 MTM Kinect**		**30 MTM Kinect**	
		v1	v2	v1	v2	v1	v2
Lateral flexion	Normal	100	100	100	100	100	100
	Fast	100	100	100	100	100	100
	Wrong	100	100	66.7	90.0	0	23
Flexion / extension	Normal	71.4	100	100	100	100	100
	Fast	80.0	100	100	100	100	100
	Wrong	100	100	100	100	100	56.0

All movements at this joint were well recognized with 100% of success rate for all correct exercise at 20 degrees of tolerance. At 10 degrees of tolerance the Kinect v1 presented lower success rate than the new sensor version, however yet scoring higher than 70%. The lower scores for the wrong movements that occurs at 20 degrees of tolerance for the lateral flexion probably is consequence of the small range of motion at the sagittal plane. If the movement at the opposite plane is lower than 20 degrees the user cannot perform the movement out of the plane. This way it is possible to conclude that the lower success rate for these wrong exercises are caused by motion on the opposite plane not achieving the tolerance value.

SCAPULAR GIRDLE - CLAVICLE

Table 7 presents the results for the scapular girdle. The scapular girdle movements were not possible to track using the first version of the sensor. This fact is a consequence of an absence of change on shoulder joint estimation during scapular girdle movements, as shown in Figure 59.

Table 7: Movement recognition for scapular girdle. Succsess rate (%) at different Movement Tolerance Margins (MTM) with kinect v1 and kinect v2.

Scapular girdle - Clavicle							
Movements		10 MTM Kinect		20 MTM Kinect		30 MTM Kinect	
		v1	v2	v1	v2	v1	v2
Elevation and depression	Normal	0	68.7	0	100	0	100
	Fast	0	65.7	0	100	0	100
	Wrong	0	100	0	100	0	100
Protrusion and retraction	Normal	0	0	0	100	0	100
	Fast	0	0	0	94,3	0	100
	Wrong	0	100	0	23.3	0	0

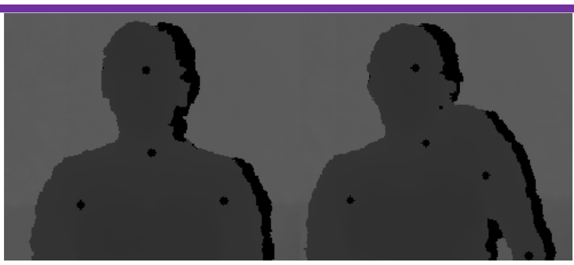


Figure 59: Shoulder joint estimation during scapular girdle elevation.

Using the Kinect v2 it is possible to track the movements at this joint. The range of motion detected is small, mainly for elevation and depression, 15 degrees, and 27 degrees for protrusion and retraction. The short range of motion produces the same situation that occurred for cervical spine being almost impossible to perform wrong movements besides the tolerance value, since the amplitude of the wrong movement is shorter than the tolerance. So the recognition of wrong movements for protrusion and retraction cannot be performed. The use of 10 degrees of tolerance at this joint present low success rate for the elevation and depression, and zero for the protrusion and retraction. Using 20 degrees of tolerance 100% of success rate was found.

The movement dynamics when using it for interaction can be limited due its low range of motion, mainly for the elevation. The use of 20 degrees tolerance is indicated. The correction, and this way accuracy of movement cannot be required when using the protrusion and retraction.

SHOULDER – ARM MOVEMENTS

The results for the shoulder movements' recognition are presented at Table 8. The movements at sagittal and frontal plane presented great success rate at 20 degrees. For the flexion and extension when using the Kinect v1 this result is better if the sensor is positioned 30 degrees from the user. Using 10 degrees tolerance the abduction and adduction continue working well, however with this tolerance the flexion movement works badly in both sensor. When using the sensor in diagonal the recognition for flexion and extension presents an improvement with the Kinect v2, but not for the first version.

Table 8: Movement recognition for the shoulder. Succsess rate (%) at different Movement Tolerance Margins (MTM) with kinect v1 and kinect v2 with sensor positioned frontally and diagonally.

Shoulder – Arm movements with frontal sensor							
Movements		10 MTM Kinect		20 MTM Kinect		30 MTM Kinect	
		v1	v2	v1	v2	v1	v2
Adduction / abduction	Normal	100	100	100	100	100	100
	Fast	80	77.1	100	100	100	100
	Wrong	100	100	100	100	100	100
Flexion and extension	Normal	14.3	60	100	100	100	100
	Fast	0	34.3	97.1	100	97.1	100
	Wrong	100	100	100	100	100	100
Horizontal adduction abduction	Normal	65.7	94.3	65.7	100	94.3	100
	Fast	11.4	80	60	91.4	80	97.1
	Wrong	100	100	100	100	80	86.7
Axial rotation	Normal	0	0	45.7	74.3	94.3	100
	Fast	0	8.57	57.1	82.9	97.1	100
	Wrong	100	100	100	100	100	100
Shoulder – Arm movements with diagonal sensor							
Movements		10 MTM Kinect		20 MTM Kinect		30 MTM Kinect	
		v1	v2	v1	v2	v1	v2
Flexion and extension	Normal	0	100	100	100	100	100
	Fast	0	88.6	100	100	100	100
	Wrong	100	100	100	100	100	100
Horizontal adduction abduction	Normal	77.1	94.3	100	100	100	100
	Fast	91.7	94.3	100	100	100	100
	Wrong	100	100	100	100	86.6	96.7
Axial rotation	Normal	14.3	17.4	25.7	77.1	100	100
	Fast	0	8.6	17.1	74.3	57.1	100
	Wrong	100	100	100	100	100	100

For the movements at the horizontal plane the shoulder horizontal adduction and abduction present reasonable recognition using the Kinect v1 and good results with the new sensor version. The main limitation was in the use of Kinect v1 for fast movements. Using the diagonal sensor position the movement is well recognized by the two sensors versions.

The axial rotation cannot be recognize with the 10 degrees of tolerance, probably due the difficulty of maintaining the arm on the parallel position without any additional reference. Using the 20 degrees tolerance only the Kinect v2 presented reasonable success rate on recognition with sensor in both position. Good recognition for both sensors was found using the 30 degrees tolerance.

The better results found for the Kinect v2 even in front of sensor in the occlusion situations show a better joint estimation performed by the new version on tracking movements when the joint is not being visible.

ELBOW – FOREARM MOVEMENTS

The elbow is a monoaxial joint and its anatomy enable movement only at the sagittal plane (Kisner e Colby, 2012). This means that the joint cannot perform the movement out of the desired plane and it is naturally performed perfectly at the sagittal plane. Due that 100% of success rate was found for all situations tested, these results are presented at Table 9.

Table 9: Movement recognition for the elbow. Succsess rate (%) at different Movement Tolerance Margins (MTM) with kinect v1 and kinect v2.

Elbow – Forearm movements							
Movements		10 MTM Kinect		20 MTM Kinect		30 MTM Kinect	
		v1	v2	v1	v2	v1	v2
Flexion / extension	Normal	100	100	100	100	100	100
	Fast	100	100	100	100	100	100
	Wrong	100	100	100	100	100	100

WRIST – HAND MOVEMENTS

The main problem in recognizing hand movements is the oscillation of this joint estimation. The results for this joint is presented at Table 10. For movements at the sagittal plane it is not possible to recognize a movement accordingly. The flexion and extension are reasonable recognized only using 30 degrees of tolerance since it is not being performed fast. At this tolerance it is not possible to detect if the movements is being performed in a wrong way. The wrong movements are performed at frontal plane and they have a range of motion smaller than the 30 degrees tolerance, what make not possible to detect the wrong movements. If the user wants to use the hand flexion and extension movement it is only indicated using the 30 degrees tolerance in a normal velocity and mainly when just interaction with no control of movement is required.

Table 10: Movement recognition for the wrist. Succsess rate (%) at different Movement Tolerance Margins (MTM) with kinect v1 and kinect v2.

Wrist – Hand movements							
Movements		**10 MTM Kinect**		**20 MTM Kinect**		**30 MTM Kinect**	
		v1	v2	v1	v2	v1	v2
Radio and ulnar deviation	Normal	31.4	60	31.4	100	57.1	100
	Fast	0	11.4	5.71	74.3	45.7	85.7
	Wrong	100	100	100	100	83.3	100
Flexion / extension	Normal	0	0	0	0	54.3	77.1
	Fast	0	0	0	0	0	5.71
	Wrong	100	100	26.7	96.7	0	0

The movements at frontal plane present better recognition using the Kinect v2. The radial and ulnar deviation can be well recognized using this sensor at 20 and 30 degrees tolerance. The Kinect v1 presents limited capability in detecting these movements, probably due the higher instability of the joint estimation.

SPINE

The spine movements are well recognized using both sensors at 20 and 30 degrees tolerance. The results are presented at Table 11. The Kinect v2 also presented good recognition using 10 degrees tolerance except for the fast movements. The main limitation for spine movements recognition is in the correction of the lateral flexion, which once again is restricted due short the range of motion at the opposite plane. This way the wrong movement did not achieve the tolerance angle to be detected. For the spine lateral movements when correction is required the Kinect v2 is indicated since it can work at 10 degrees tolerance where the wrong detections have good success rate. The flexion and extension movements at 10 degrees tolerance works well only using Kinect v2 at normal velocity movements. When using Kinect v1 the fast movements at sagittal plane should be avoid.

Table 11: Movement recognition for the spine. Succsess rate (%) at different Movement Tolerance Margins (MTM) with kinect v1 and kinect v2.

Spine							
Movements		**10 MTM Kinect**		**20 MTM Kinect**		**30 MTM Kinect**	
		v1	v2	v1	v2	v1	v2
Lateral flexion	Normal	42.9	88.6	100	100	100	100
	Fast	17.1	22.9	82.9	91.4	100	100
	Wrong	100	100	33.3	26.6	0	0
Flexion / extension	Normal	45.7	100	88.6	100	100	100
	Fast	14.3	57.1	54.3	100	100	100
	Wrong	100	100	100	100	86.7	96.7

PELVIS

The movements performed with the pelvis are very smooth. The joint estimation performed by the sensor is based on user pose.

During the pelvis movements very small changes on the user poses occurs, this way the joint estimation do not change. Due that, no movement is detected at this joint. The result was similar for the two sensor versions and the joint estimation during the movement can be seen in Figure 60.

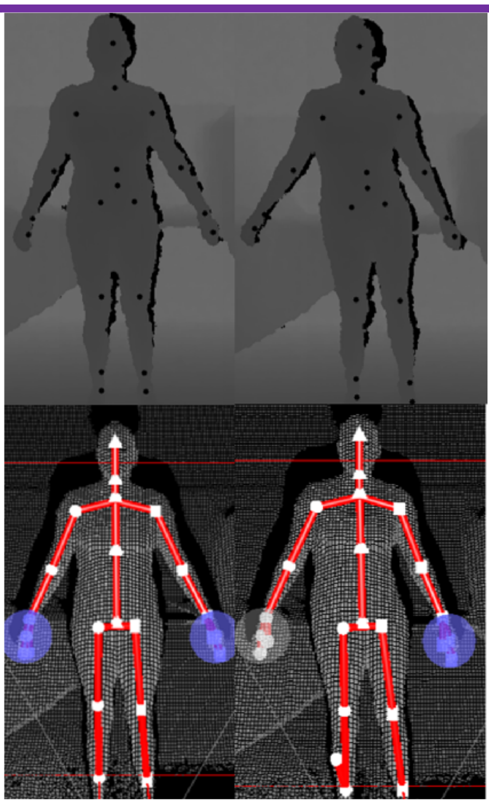


Figure 60: Skeleton estimation during pelvis elevation for Kinect v1 (above) and Kinect v2 (bellow).

HIP – THIGH MOVEMENTS

Results for this joint are presented at Table 12 including the tests with sensor positioned frontally and diagonally. Based on them it is possible to detect that the thigh movements can be all well recognized using the Kinect v2 at all MTM. For the recognition based on this sensor only the fast axial rotations at 10 degrees tolerance present low success rate. When using 30 degrees tolerance attention should be given to the lower movement accuracy required risking false positives.

Table 12: Movement recognition for the hip. Succsess rate (%) at different Movement Tolerance Margins (MTM) with kinect v1 and kinect v2 with sensor positioned frontally and diagonally.

Movements		10 MTM Kinect v1	10 MTM Kinect v2	20 MTM Kinect v1	20 MTM Kinect v2	30 MTM Kinect v1	30 MTM Kinect v2
Hip – Thigh movements with frontal sensor							
Adduc-tion / abduction	Normal	31.4	100	100	100	100	100
	Fast	20	100	100	100	100	100
	Wrong	100	100	100	100	100	70
Flexion and extension	Normal	100	94.3	100	100	100	100
	Fast	94.3	97.1	100	100	100	100
	Wrong	100	100	100	100	100	100
Axial rotation	Normal	0	85.7	0	100	0	100
	Fast	0	42.9	0	100	0	100
	Wrong	100	100	100	100	100	100
Hip – Thigh movements with diagonal sensor							
Flexion and extension	Normal	97.1	100	100	100	100	100
	Fast	97.1	97.1	100	100	100	100
	Wrong	100	100	100	100	100	100
Axial rotation	Normal	0	85.7	0	100	25.7	100
	Fast	0	65.7	0	100	0	100
	Wrong	100	100	100	100	100	100

When using the Kinect v1 almost all movements can be well recognized at 20 degrees tolerance, except the axial rotation. The problem with this sensor version to recognize the axial rotation is the skeleton tracking with the position required – the 90 degrees hip flexion. The knee joint estimation at this position is located down on the leg and the hip in a higher position. This combination makes the segment of the thigh positioned diagonally for down, making the 90 position not achieved. Figure 61 shows the skeleton tracking at this position for both Kinect sensors. After observing this it was performed a test using 40 degrees tolerance and at this case all movements were recognized. However the in general 30 degrees already present the problem of false positive, when using 40 degrees no accuracy can be guarantee.

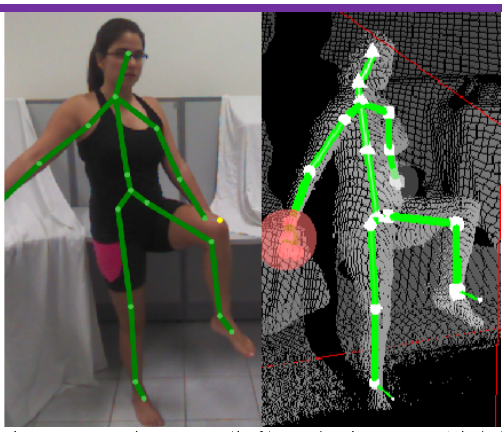


Figure 61: Kinect v1 (left) and Kinect v2 (right) skeleton tracking during axial rotation recquired position.

KNEE – LEG MOVEMENTS

The same that occurs with the elbow, the knee joint do not perform movement at the frontal plane (Kisner e Colby, 2012) resulting 100% success rate in all evaluated situations (Table 13). This anatomic characteristic make impossible to perform movement at the wrong plane. Differently form the elbow, the knee is a biaxial joint, however the second movement that this joint perform is the axial rotation which is not detected during skeleton estimation.

Table 13: Movement recognition for the knee. Succsess rate (%) at different Movement Tolerance Margins (MTM) with kinect v1 and kinect v2 with sensor positioned frontally and diagonally.

Knee – Leg movements with frontal sensor							
Movements		**10 MTM Kinect**		**20 MTM Kinect**		**30 MTM Kinect**	
		v1	v2	v1	v2	v1	v2
Flexion / extension	Normal	0	100	0	100	0	100
	Fast	0	100	0	100	0	100
	Wrong	0	100	0	100	0	100

Knee – Leg movements with diagonal sensor							
Movements		**10 MTM Kinect**		**20 MTM Kinect**		**30 MTM Kinect**	
		v1	v2	v1	v2	v1	v2
Flexion / extension	Normal	100	100	100	100	100	100
	Fast	100	100	100	100	100	100
	Wrong	100	100	100	100	100	100

ANKLE – FOOT MOVEMENTS

The foot movements could not be recognized using any of the Kinect versions due absence of movement at joint estimation. When using the Kinect v1 during the dorsiflexion the point estimate for the foot goes to the leg and during the plantar flexion it returns to the foot. The vector which connects the ankle to the foot do not change. This situation can be seen on Figure 62. For the Kinect v2 the shift of foot joint estimation to the leg does not occur, however the movement yet cannot be detected due absence of joint changes during movement (Figure 62).

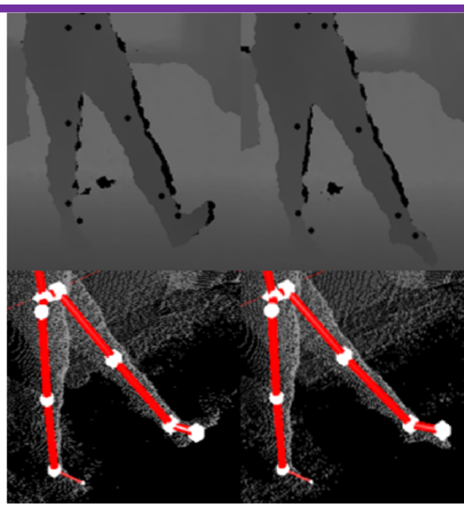


Figure 62: Skeleton estimation during foot movements for Kinect v1 (above) and Kinect v2 (bellow). The left image shows foot during dorsiflexion and the right the plantarflexion.

ADEQUATE MOVEMENT TOLERANCE MARGIN

With the results presented it is possible to notice that the use of 10º MTM makes the recognition unstable. This occurs because although the movements are described in planes, the performance of them exactly at the plane during all trajectories is utopic. Besides that, the joint estimation performed by the sensor can have little oscillations even to the joints which have good tracking, what can also lead the segment to out of the plane if the tolerance is very restrict.

The use of 10º tolerance should be used when extremely accuracy is required during movement, since it involves perfection. The movements which present good success rate at this MTM are: Cervical movements, shoulder abduction and flexion, the last one with the sensor at diagonal, elbow flexion, hip flexion, and knee flexion. The ones which worked well only with the Kinect v2 at this tolerance was: shoulder horizontal abduction and the hip abduction,

In an opposite way, the 30º MTM presented great success rate when detecting correct movements, since it gives more movement freedom. However it can in some case cause a false positive. When performing wrong exercises the system failed detecting them as correct at this range. This means that this range starts to give excess of freedom and lower control of movement accuracy. The movement which showed this false positive situation in higher degree includes: cervical movements, scapular girdle protrusion, wrist flexion, and spine lateral flexion.

The difficult in detecting the wrong movements was also found in some case when using the 20 degrees tolerance. This was caused in the joints which present the opposite movement with range of motion smaller than the MTM. Since the wrong movement could not even achieve the tolerance angle it could not be detected. This situation happened with the

The ideal MTM is located at 20º MTM, presenting 100% success rate in detecting correct exercises for almost all classified movements. The success at this range is more frequent when using the Kinect v2. The first version of the sensor present less success at this tolerance for movements where occlusion occurs, for example shoulder horizontal abduction. This fact shows improvements on the new sensor in relation to joint estimation when the joint is not visible.

It is important to notice that the success rate is related with the capacity of user to perform the movement in an accurate way. For example, shoulders axial rotation requires a fixed position which is difficult to maintain precisely without additional reference. In case where the movement is very difficult to be performed as standardized the use of larger MTM in interactive systems is suggested in order to provide more usability.

KINECT V1 AND KINECT V2

With the first Kinect launch in the end of 2010 a lot of studies applying this technology as a tool for develop interactive applications for motor rehabilitation started to be developed. Recently, in July 2014, Microsoft launched the new sensor version, the Kinect v2. The benefits of using such instrument which provides natural interaction associate with a portable and low cost characteristics is known. However which of the therapeutic movements work well or not when using this technology is not defined yet. Since this work developed a movement recognition which is capable to recognize the classified biomechanical movements for each joint and tested them it was possible to perform an analytical analysis about the Kinect applicability for rehabilitation purposes.

The use of the Kinect sensor as a skeleton tracking tool for biomechanical movements presented good results for the majority of movements classified, however limitations were found. Some of movements presented limited recognition when using the Kinect v1. However with the improvements of the new version, the recognition using the Kinect v2 worked better for all movements being able even to recognize some movements that were not possible with the first version.

Movements which could not be detected using the Kinect v1 but are recognized using the new version includes clavicle, wrist and knee movements, being the restriction of this last one only if the user is frontally for the sensor. There are some movements which could be recognized however with bad detection. These include the shoulder horizontal abduction, shoulder rotation, spine flexion and hip rotation. These movements presented better recognition when using the Kinect v2. The pelvis and ankle movements could not be detected using any of the sensors versions.

LIMITATIONS

Limitations are mainly related to the sensor and the markerless technique capability. One of the problems occurs when there is occlusion; there is an inaccuracy due to indirect estimation performed by the sensor when one body part covers the view of another. The new version of sensor works better on these situations, but yet are the movements with more difficult on recognition. The occlusion problem may be improved with the use of multiple sensors.

Another limitation is the detection of axial rotation. Since the system detects joint position based on pose estimation, the bone rotation around its own axis does not change the visual pose and no change on joint location is found. So, it is not possible to detect these movements by the method proposed. The additional method developed using a fixed position as reference to measure the angle was used for the two limbs main joints, shoulder and hip. Unfortunately the same could not be extrapolated to the other joints where axial rotation occurs due the absence of additional references.

9.2. EXPERIMENT FOR FUNCTIONAL MOVEMENTS

The functional movements are recognized using the checkpoint technique described before (section 7.4). In order to evaluate this technique as an interactive tool for rehabilitation, the reAIRbilitation game described before was used. The evaluation was composed of two phases, on objective and one subjective test. The objective phase consisted on how many goals the user achieved inside the game, representing how fine he/she could control the game and, thus, how well the recognition was. The subjective phase consists of therapist's usability opinion for each movement as Very Bad, Bad, Medium, Good or Very Good. The tests were performed using different tolerances.

The checkpoints recognition was tested with movements that are performed on rehabilitation but that are not contemplated by the biomechanical method, i.e., functional and multi-joint movements. The list of functional and multi-joint movements tested was extracted from a treatment protocol used by a physiotherapist clinic. The movements for upper limb are: i. Diagonal of Prorioceptive Neuromuscular Function (PNF): which is composed by a flexion, abduction and external rotation of shoulder with elbow extension; ii. Take hand to head (functional activity of comb the hair); iii. Take hand to back (functional activity of dressing); iv. Throw (functional activity of throwing some object); v. Take a glass and carry to mouth (functional activity of drinking); vi. Codman moment (circular shoulder movements with arm suspended). For lower limbs only two movements of routine clinic treatment are not contemplated by the biomechanical movement recognition and, so were included on the functional movements list: Kick and Squat.

The movements of the objective phase were performed by a physiotherapist specialized in biomechanics and with gymnastic preparation due to a better corporal conscience aiming to execute the movement more accurately. All the movements were tested using three tolerances: 10, 20 and 30 degrees. The subjective opinion was given by three therapists specialized in clinical practice. They scored each movement at each tested tolerance range as: Very Bad, Bad, Medium, Good or Very Good. The consensus of these three therapists was added to a results table presented in sequence.

All tests were performed on a Notebook Avell, 2.6 GHz processor (i7-3720QM), 8GB DDR3 of RAM and a video chipset GeForce GTX 670n. Tests were executed in an empty room, i.e., without any objects interfering in the Kinect tracking area, being only the user's body in the sensors field of view.

RESULTS AND DISCUSSION

The method presented good applicability when used in a rehabilitation system. According to the results, the recognition by Checkpoints proved to be a good solution for functional and multi-joints movements that are not covered by the biomechanical method. However, to be usable it requires tolerance ranges of 20 to 30 degrees. The results are presented at Table 14.

Due to the greater complexity of these movements compared to the biomechanical ones, the results showed the necessity of a high range value, being 20 to 30 degrees the range where there are better success rates. In order to complement this evaluation, and to check if these higher ranges will interfere on clinical applicability, it is also presented the subjective evaluation performed by physiotherapists which results are showed at the **Table 14**.

Table 14: Success rate and subjective evaluation of functional and multi-joint movements recognized by Checkpoints method

Movement	**Success Rate (Subjective evaluation)**		
Range	**10 º**	**20 º**	**30 º**
PNF Diagonal	20% (Very Bad)	40% (Medium)	100% (Good)
Hand to head	90% (Medium)	100% (Good)	100% (Very Good)
Hand to back	0% (Bad)	0% (Bad)	70% (Medium)
Throw	40% (Medium)	80% (Good)	90% (Very Good)
Glass to mouth	60% (Bad)	90% (Good)	100% (Good)
Codman	90% (Medium)	100% (Good)	100% (Good)
Kick	60% (Medium)	100% (Good)	100% (Good)
Squat	70% (Medium)	100% (Good)	100% (Good)

The most difficult movement to recognize was the hand to back, which presented a maximum of 70% of success rate at 30 degrees, being very difficult to track at lower ranges. This probably occurs due to the contact of hand with back which makes it difficult for the Kinect sensor to differentiate one from another. This result corroborates with physiotherapists evaluation which gave this movement the lowest evaluation with medium applicability at 30 degrees range. This problem also may be solved by the use of two Kinects for skeleton tracking, and as said before without necessity of change movement recognition techniques.

The movements which presented better recognition rates, with greater success rate even at the lowest range, were the hand to head and Codman movements. However, according to therapists, using only 10 degrees of range is not the best for clinical applicability. At the range of 20 degrees, most movements are good to clinical application and presented good success rate, except for the hand to back that had problems and PNF Diagonal which only has a good recognition at 30 degrees of range.

9.3. SUMMARY

This chapter brings the results obtained testing the two methods developed to recognize movements according with therapeutic needs. The biomechanical movement recognition technique presented good results in classifying these movements, mainly using the Kinect v2. Some limitations found using the Kinect v1 were improved using the new version, mainly related to movements of small joints and occlusion situations. The checkpoints technique was developed to complement the use for rehabilitation being able to recognize the functional movements that are also important on therapy. This method presented good recognition however requiring higher tolerance in movement perfection, what is not a big problem since the aim of functional movements is to recovery function and not a specific anatomic gain. For anatomic gains the therapist can choose the biomechanical ones. The two methods can be used simultaneously enabling to interact with functional movements and having one report about the biomechanical movement's range of motion.

Next section will present the results when using these methods in interactive applications. It will show how these recognitions can help providing information to guide and correct exercise.

10. RESULTS: APPLICATIONS

Figure 63: Patients using the dolphin´s adventure (left) and the mirrARbilitation (right).

Aiming to improve rehabilitation process with the help of VR and AR technology the systems presented in chapter 8 were developed. The idea to develop a system which can use the biomechanical movements that are already used in the rehabilitation process as interaction tool is new and promissory. So the systems here presented are only start examples of possibilities which can be explored further.

Due to that, diverse tests were performed in order to evaluate the systems. All the tests were transversal studies in order to evaluate the viability in using the movement recognition techniques developed as input for an interactive system. They also aimed to check how the methods help on providing information to movement guidance and correction. The tests will work not only to check system applicability but also to provide information and ideas for the continuous development of this area. Tests were performed with potential users, patients, healthy adults, elderly, physiotherapists and programmers. **Figure 63** shows patients using the systems. The opinion of all these populations can help to know how the development is going and suggest improvements for further researches.

The results of all the tests performed with the systems will be presented in this chapter through the results of published papers or in review process. The VR and AR first prototypes were tested with a few subjects. They results were used as base to upgrade the system and develop the first final versions, the reAIRbilitation and the mirrARbilitation, which were also tested by patients, therapists and developers. All these results and its respective publication will be presented here.

10.1. IMPROVEMENT FROM DOLPHINS' ADVENTURE TO REAIRBILITATION

This section will present the experimental test developed in order to evaluate the first prototype version, the dolphin adventure, and extract information to upgrade the system according to the results. This process on the development was presented at section 0. Here it will be shown the experimental process that helped on this and the different results between the two versions. These results were published at XI Brazilian Symposium of Games and Digital Entertainment, in 2012 (Freitas *et al.*, 2012) , which received a full paper honors.

The evaluation was performed in 57 users, including physiotherapists, computer developer and general populations. All users tested both games versions, the Dolphin's Adventure and the reAIRbilitation and answered a usability 1-5 Likert scale questionnaire. The user's opinion in the two versions are presented by the number of users which gave each score. These results are presented for all subjects and for each category. A comparison between the total score received for each question at each game was also performed using Wilcoxon test (Da Gama *et al.*, 2013). The detailed protocol is presented below.

EXPERIMENTAL PROTOCOL

In order to improve the development of the system, it was submitted to user evaluation to receive feedback from them and, this way, improve the system's characteristics and usability. The system was applied to three different population groups where each person's opinion and suggestions on how to improve it were collected. First, tests were applied with the first prototype version, which was upgraded according to evaluation and necessities. Following a second test was performed with the new system's version.

The required population was composed of 57 subjects being 20 from physiotherapy area, 19 computing area and 18 general population. The therapists were included to enable suggestions about system therapeutic effect and application, while computer specialists could give a more technical opinion. General population was added to evaluate general aspects of usability and motivation of system applicability.

All users participated of two encounters, dedicating one for each version of the system. In each encounter, all the users answered a survey consisting of eighteen questions from which a subset of nine are considered and analyzed in this work. The selected questions can be split among four major aspects, being each question related to one of the following core subjects: control sensibility (question 1), therapeutic domain (questions 2 and 3), welfare (questions 4 and 5) and ludic value (remaining questions 6, 7, 8 and 9). At the questionnaire end a space for suggestion were available.

Here follows the applied questions: 1) Did you feel that you could control the game? 2) Do you perceive the therapeutic function of the system? 3) Did you feel that the game helped you to correctly perform the movements? 4) Did you feel comfortable during the playing experience? 5) Did you find that the game is easy to play? 6) Do you think the game was fun? 7) Would the game improve your motivation to perform exercises? 8) Did you enjoy the game scenario? 9) Did you feel challenged?

Each question could be answered, rating, according to a 1-5 Likert scale. In addition, a score was assigned for each question by considering the sum of all ratings of the respective question. This score allows a fast overview of the total of answers, considering all users. This measure also helps to achieve a fast comparison between two stages in which the same question was answered, this way giving a fast overview of the impact of the second tested version over the first one.

To validate differences a statics analysis was performed with the Graph Prisma 5.0 software. The the kolmogorov-smirnov test was used to verify the data distribution. No normal distributions were found. Due to this fact, a comparison performed with the Wilcoxon test for paired non-parametric data (Da Gama *et al.*, 2013). The tests were considered with 95% of significance level and expressed through probability (p) value.

RESULTS AND DISCUSSION

As presented before, both versions of the game were tested and evaluated by a set of users. All users participated of the two encounters, one for each version of the system, with a 30 days' time interval between the encounters dedicated to implement the pointed improvements. In each encounter they answered the previous described questionnaire.

The **Table 15** shows the scores obtained on the first and second encounters for each specific question as well as for the grouped aspects and for the overall results. This way, it is possible to perform a fast analysis of which topics are well evaluated by the users by comparing the obtained score to the reference score measures (maximum, intermediate and low score of respectively 275, 165 and 110). Besides, it is also possible to acquire a first notion of the improvement the system experienced by correlating the scores of the 2nd and the 1st encounter as shown in the last column in **Table 15**.

Table 15: Score of each topic in the 1st and 2nd encounter.

Aspect or Question	1st Time Score	2nd Time Score	2nd / 1st Score	p value
Question 1	207	253	122%	0.0002
Question 2	238	246	103%	0.3133
Question 3	187	243	130%	0.0001
Question 4	180	241	134%	0.0001
Question 5	234	266	114%	0.0005
Question 6	189	235	124%	0.0001
Question 7	223	253	113%	0.0006
Question 8	222	256	115%	0.0001
Question 9	198	205	104%	0.4049

In **Figure 64** it is shown a chart for each one of the four aspects (grouping the respective questions of each aspect). Each chart presents the number of occurrences (vertical axis) of each rating (horizontal axis), presenting both the first and the second encounter results (labeled as 1st and 2nd time). The same analysis was performed for each group and is presented at Figure 65.

As an initial overview, it is noticed in **Table 15** that the users on the second encounter better evaluated all topics presented on the questions. It also can be seen in **Figure 64** that great part of the users migrated their ratings from a lower value to 5, in fact in the overall results the number of 5 ratings is 125 greater in the second encounter. Independently of the first tested version, in a more absolute analysis, by considering that the total of answers of all questions is 495 and 445 of those, i.e. 89.9%, were a 4 or 5 rating (**Figure 64**), revealing a significant satisfaction from the users with the second version of the system.

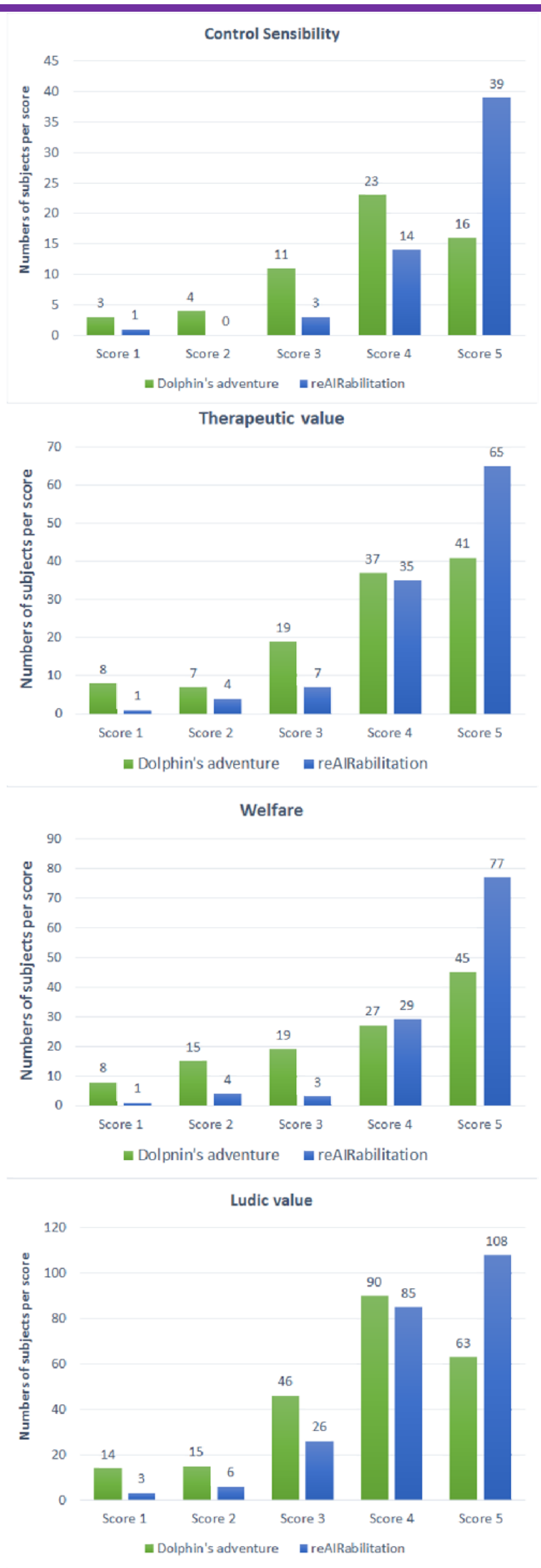


Figure 64: Numbers of subjects which gave the respective score at each category evaluated.

Specifically, the questions 2 and 9 did not reach a significant growth in the second evaluation and so the second evaluation does not provide enough statistics data to declare that the second version of the system presents a better resolution for these topics. However, the question 2 already presented a high score of 238 in the first evaluation thus, being understandable its low growth since the maximum limit were already too near. On the other hand question 9 reveals that game aspects of challenge still have a significant space for improvements since both evaluations of the users showed an intermediate score near 200.

Furthermore, questions 3, 4 and 6 revealed the lowest result in the first evaluation and so, a major need for improvements compared to the other topics. Question 3 revealed the need of a feedback system that was implemented for the second version of the system, providing audio and visual information directed to assist the user during the execution. Question 4 by its turn revealed that the random criteria used to define whether or not an obstacle or a bonus coin should appear forced the users to perform too much isometric movements, e.g. keeping the arm raised for too much time.

The second version of the system was prepared in a way which all positive and negative elements (e.g.: thunder clouds, gas and golden hoops) appears in game inducing the user to switch the exercise mode between slow and fast movements as well as some rest time. One advantage of the new design of these elements is that it helped the user to visually recognize more quickly which elements he should avoid, which he should pick and which he should pass through its center. At last, question 6 revealed a space for improvement about the fun during the playing experience. As can be seen in **Table 15** the interface improvements, plus some adjustments for the second version of the game solved partially this problem.

One of the reasons that may be responsible for the better results related to question 1 is that the version of the used Microsoft Kinect SDK was updated, and so, the precision of the tracking algorithm was increased. Besides that, the new design of the main character may favored a better visual idea of control. Before, in the first version, the player controlled a pink dolphin which was animated constantly moving in its own space and so, its movement should confuse the user whether the movement was obeying his commands or just being performed by the game itself. The remaining questions (questions 5, 7 and 8) also revealed that the redesigned graphical interface had a good impact on users about the easiness of play, the motivation to play during the practice of therapeutic exercises and the visual aspect of the presented scenario.

When analyzing separately by group the results are similar (Figure 65). The control sensibility presented higher scores for the computer developers group. Therapeutic value was approved with the scores votes concentrated mainly in the 4 and 5. The welfare presented similar results for all groups. The ludic value was better evaluated by the therapists being the computer developers the ones which gave lower scores to this category. This probably occurs due the more familiarity of this group with games making it more critic in this field.

The first test showed that the system attended the requirements at least minimally, but needing to be improved in some points. These issues were tackled resulting in a second version of the prototype, which had improvements mainly on its interface. This new interface is cleaner and friendlier, what may helped users to understand better what to do and being funnier as well. It also had the improvement on the feedback given to the patient when he/she is doing a wrong movement. This is an important feature since the system main purpose is to assure the correct execution of physiotherapeutic exercises. All these improvements reflected on the second round of test, where the second prototype had higher grades in all evaluated aspects. These results show the importance of a user centered design approach on the development of this kind of applications, putting the patient needs as guidelines of the product's development. The improvements made on the second version of the system showed to be an effective way to enhance the user's experience and, by this way, increasing the chances of a successful physiotherapeutic treatment.

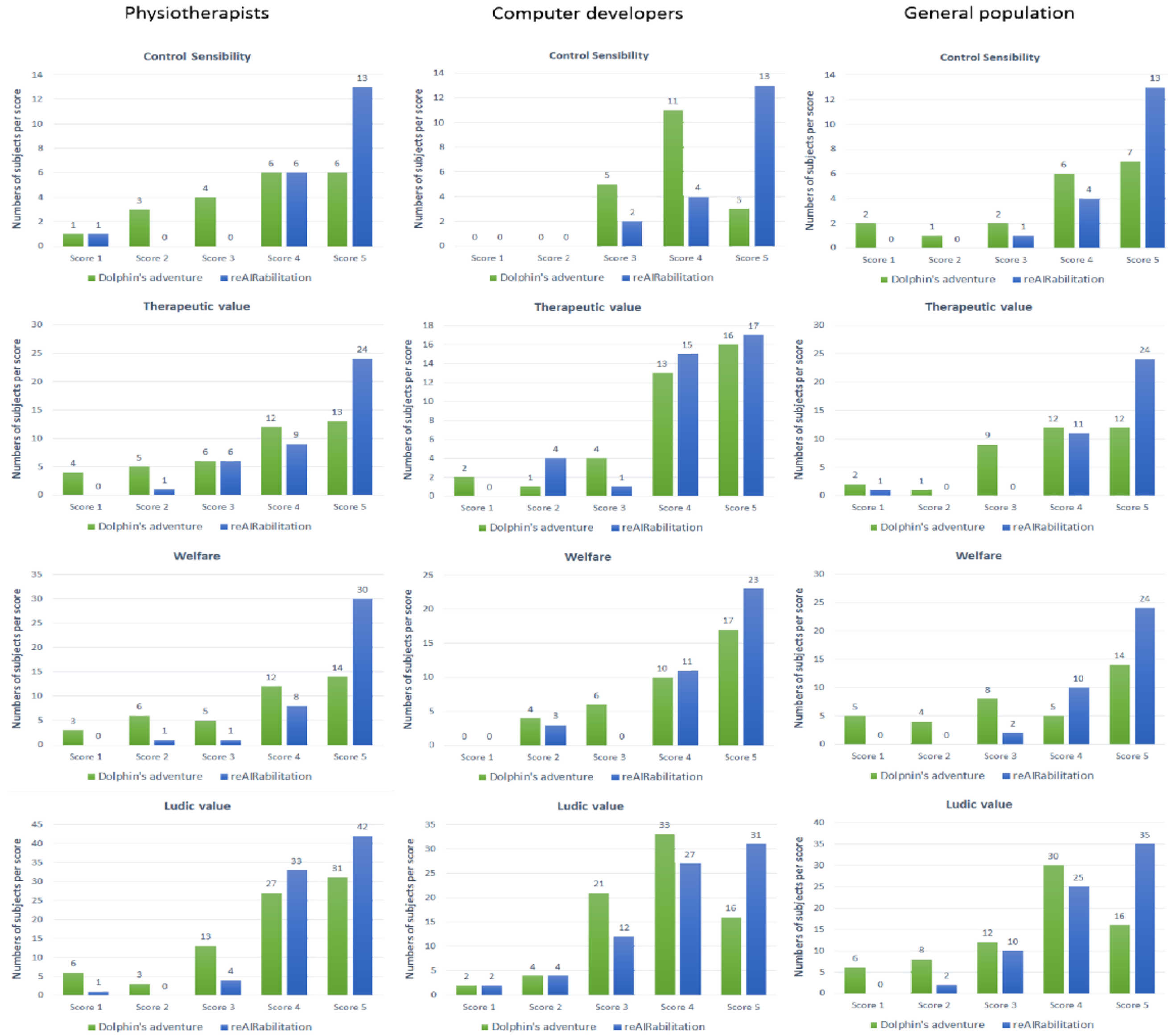


Figure 65: Numbers of subjects which gave the respective score at each category evaluated per group of subjects.

10.2. PATIENTS TESTING REAIRBILITATION

After evaluating the system usability and upgrading it the next step was the test in patients. The paper with these results is in review process to be further send to publication in the journal: Computer Methods and Programs in Biomedicine.

This test was performed in 27 stroke patients which used the system once. After that they answered a usability and a sociodemographic questionnaire. The results will be presented by the percentage of satisfied and unsatisfied patients for each category. Additional results which presented significant difference detected by the chi-square test will be presented (Da Gama *et al.*, 2013). They include satisfaction relation with the educational level and family incoming and the effort level with the stroke cause. The detailed experimental process is described below.

EXPERIMENTAL PROTOCOL

These tests were performed using the upgraded version, the reAIRbilitation, described at section 0.

POPULATION

Patients of both genders, aged from 30 to 80 years, with upper limb hemiparesis and clinical diagnosis of isquemic or hemorrhagic chronic stroke (>6 months) were recruited through waiting lists of hospital and local clinics. All of them were able to actively move the shoulder and do not exhibited cognition deficit measured through the Mini-mental state examination (MMSE) (Almeida, 1998). To subjects with lower level of education, minimal score of MMSE had to be 20; while to subjects with higher level of education minimal score was 24. The exclusion criteria were moderate cognitive or visual impairment, severe auditory impairment, epilepsy, labyrinthitis, visual hallucinations and non-controlled hypertension or any condition that prevent the interaction with the tool. All of the patients were informed about the nature of the study and provided written informed consent to participate. The study was conducted in accordance with the Declaration of Helsinki and approved by the local ethics committee (CAAE-00657012.6.0000.5208).

STUDY DESIGN

A cross-sectional study was performed in patients with chronic stroke in order to assess the usability, applicability and limitations of the rehabilitation support system Ikapp. Also, patient satisfaction and the influence of sociodemographics aspects over interactive systems usability were analyzed.

In the first appointment, demographic and clinical data were collected through a socioeconomic questionnaire to characterize the sample. After, patients were submitted to a test of interaction with Ikapp and then answered the usability and satisfaction questionnaire with the purpose of finding functionality, creating opinions and suggesting some modifications for the tool.

After a previous configuration of the system by the physical therapist, patient played the reAIRbilitation game for four minutes. The Airplane movement was controlled by abduction or adduction of the paretic shoulder. Shoulder abduction resulted on airplane elevation, while shoulder adduction resulted on airplane drop in the virtual environment. The graphics elements arranged at different heights has the objective to induce isometric and isotonic contraction, as well as work coordination. This organization also provided the possibility of patient rest because some obstacles were placed close to the ground. Thus, the tool provided the development of specific treatment according the patient needs.

During the game, warning phrases appeared when the patient did some postural compensation or wrong execution. Thus, a visual feedback was provided in real time to movement correction.

QUESTIONNAIRES

SOCIOECONOMIC QUESTIONNAIRE

The socioeconomic questionnaire was created to the present study based in some questionnaires used in trials with the intent to analyze the applicability of other technological device (Suda et al., 2009). This questionnaire is composed of 13 subjective questions about sociodemographic individual aspects such as: educational level; family incoming, previously contact with games. These information were used to correlate with game usability.

USABILITY AND SATISFACTION QUESTIONNAIRE

Usability and satisfaction of patient during contact with the game was measured by a questionnaire which was specifically developed to this study based on literature (Van Velsen et al., 2007; Fitzgerald et al., 2008; Yusoff et al., 2010). Questionnaire is composed of Likert scale-type questions from 1 to 5 and subjective questions for users provide extra suggestions for improvements. Questions topics include: 1. Motivation in using the game; 2. Comprehension of the aim; 3. Interest in including game on treatment routine; 4. Physical effort during the exercise; 5. Therapeutic values of the system; 6. Corrective feedback helped correction; 7. Scenario. Scale 1 to 10 was used to graduate the airplane control through body movements and home exercises with game assistance.

STATISTICAL ANALYSIS

For the socioeconomic data a descriptive analysis was done. Description of quantitative variables was performed through central tendency and dispersion (mean and standard error) and categorical variables described with frequency measures. For the Think Aloud Protocol analysis, two or more people verify the information of each subject and reported in a descriptive way the observation and comments.

The five-point Likert scale-type questions of usability questionnaire were dichotomized by the software SPSS version 18.0 and analysis was done through chi-square test. Answers "very unsatisfactory, unsatisfactory or neutral" of questions 1, 2 and 7 were classified as "not satisfied" and answers "very satisfactory or extremely satisfactory" classified as "satisfied". Answers "very unsatisfactory, unsatisfactory or neutral" of questions 3, 5 and 6 were classified as "no" and answers "very satisfactory or extremely satisfactory" classified as "yes". Question 4, answers "very unsatisfactory, unsatisfactory or neutral" were classified as "little" and "very satisfactory or extremely satisfactory" were classified as "much".

To investigate the relation between the data from usability and socioeconomic questionnaire, the chi-square test (Fisher exact) (Da Gama *et al.*, 2013) was applied associating variables such as motivation, corrective feedback, therapeutic value, physical effort, understanding and prior interaction with video games. All correlation between these two questionnaires were performed and just the significant ones will be presented.

RESULTS AND DISCUSSION

Of the 61 medical charts of post-stroke patients previously analyzed, only 27 of them were included according to inclusion/exclusion criteria. Table 16 shows participant characteristics (gender, age, number/time since onset of stroke, manual preference, hemiparesis and MMSE score).

Table 16: Sample characteristics

Gender, n (%)	
Male	19 (66.7)
Female	8 (33.3)
Manual preference, n (%)	
Right	26 (96.3)
Left	1 (3.7)
Hemiparesis, n (%)	
Right	12 (44.4)
Left	15 (55.6)
Age, in years *	59.11±1.98
Numbers of stroke events*	1.37±0.17
Stroke time, in months*	68,15±19.73
Mini-mental state examination **	26.37±0.42

*Data presented in mean ± standard error;
**Defined by the Mini-mental state score.

Table 17 shows socioeconomic questionnaire data where 48.1% of the sample persons had a low level of schooling and 59.3% of the participants had a family income of at most 03 minimum wages. In relation to communication access, all patients have television at home, 51.9% of them did not have a computer and 74.1% had no internet access.

Table 17: Sociodemographic data of stroke patients included on study (n=27)

Education level, n (%)	
Illiterate	2 (7.4)
Basic education	13 (48.1)
High school	8 (29.6)
Higher education	4 (14.8)
Family incoming, n (%)	
Until 3 wage	16 (59.3)
Higher than 3 wage	11 (40.7)
Television, n (%)	
Have	27 (100)
Do not have	0 (0)
Computer (%)	
Have	13 (48.1)
Do not have	14 (51.9)
Internet access, n (%)	
Have	7 (25.9)
Do not have	20 (74.1)

Table 18 shows the usability and satisfaction items. The game scenario, Interest in including game on treatment routine, physical effort and motivation had the highest level of satisfaction. Lowers satisfactions was found for the corrective feedback where 48% of users opined that it did not helped in correcting exercise. The scores for airplane control through body movements and home exercises with game assistance had mean of 8.29±0.38 and 8.66±0.42, respectively.

The subjective question asked user suggestions about scenario improvements and asked them if they prefer to do the traditional therapy, the game therapy or both. Analyzing these questions it was demonstrated that 95% of the patients would not change anything on the game scenario and most of them (25) would like to do conventional exercises combined with virtual games.

Table 18: Usability and satisfaction questionnaire data

Motivation, n (%)	
Satisfied	23 (85.2)
Unsatisfied	4 (14.8)
Comprehension, n (%)	
Satisfied	21 (77.8)
Unsatisfied	6 (22.2)
Treatment inclusion, n (%)	
Yes	23 (85.2)
No	4 (14.8)
Physical effort, n (%)	
Few	25 (92.6)
A lot	2 (7.4)
Therapeutic value, n (%)	
Yes	25 (92.6)
No	2 (7.4)
Corrective feedback helped, n (%)	
Yes	14 (51.9)
No	13 (48.1)
Scenario, n (%)	
Satisfied	27 (100)
Unsatisfied	0 (0)

Erro! Autoreferência de indicador não válida. shows a statistical association between level of schooling and understanding of the game (p=0.013). Post-stroke patients with a higher level of schooling were more satisfied (100%) on the item “understanding of the game” than patients with a lower level of schooling (60%). Furthermore, the association between level of schooling and corrective feedback showed a statistical significance (p=0.031) in which 66.7% of the participants with a lower level of schooling were unsatisfied and 75% of the participants with a higher level of schooling were satisfied on the item “corrective feedback”. This can lead to the hypothesis that the discontent revealed about corrective feedback may be attributed to an inappropriate format or a wrong way to present the visual information.

The association between level of schooling and motivation provided by the game did not show significance (p=0.809). However, data indicated high levels of motivation provided by the game not depending on the level of schooling of sample persons. 86.7% of post-stroke survivors with a lower level of schooling were satisfied and 83.3% of the participants with a high level of schooling were also satisfied.

Table 19: Satisfaction differences at the different educational levels for game comprehension, perception of corrective feedback and motivation.

	Educational level		p
Educational level	**Basic education**	**High school and higher education**	
Game comprehension			
Unsatisfied	6 (40)	0 (0)	0.013
Satisfied	9 (60)	12 (100)	
Corrective feedback helped			
Unsatisfied	10 (66.7)	3 (25)	0.031
Satisfied	5 (33.3)	9 (75)	
Motivation			
Unsatisfied	2 (13.3)	2 (16.7)	0.809
Satisfied	13 (86.7)	10 (83.3)	

As shown in **Figure 66**, the value of (p=0.021) demonstrated that there was an association between family income and understanding of the game. Post-stroke survivors with a higher level of family income (above 3 minimum wages) were 100% satisfied with “understanding the game” while 62.5% of the survivors with a lower level of family income (at most 3 minimum wages) were satisfied.

Figure 67 shows that there is no significant association between motivation provided by the game and previous contact with video games. Post-stroke patients that had previous contact with video game were less satisfied (80%) than patients that never had contact with video games (88.2%). However, both groups demonstrated a high level of satisfaction.

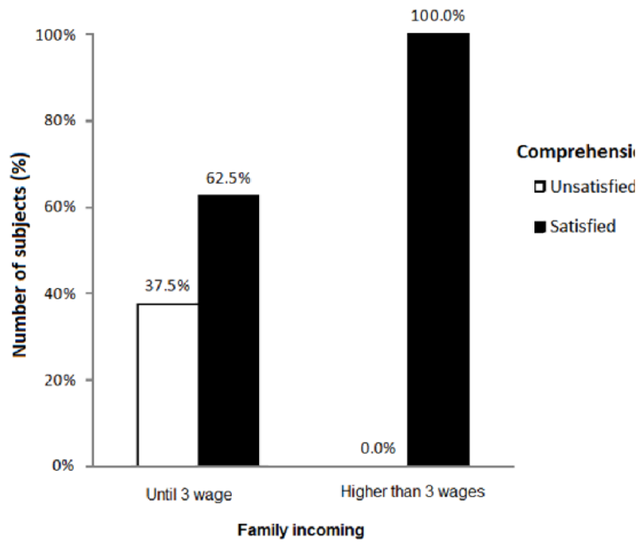


Figure 66: Patients satisfaction degree in relation to game comprehension according to family incoming.

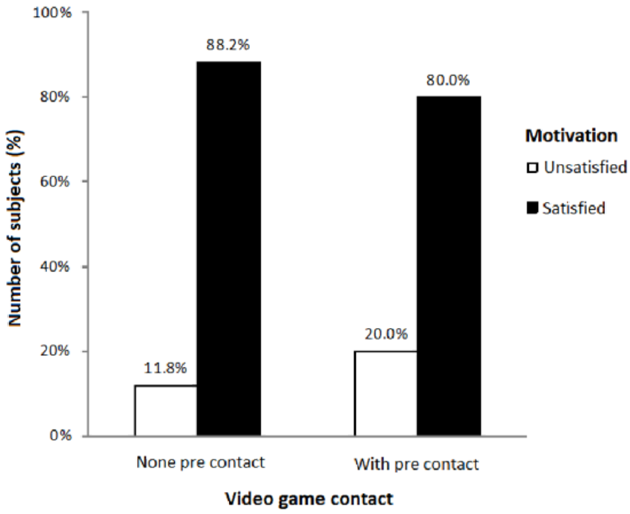


Figure 67: Patients motivation according to previously contact with video games.

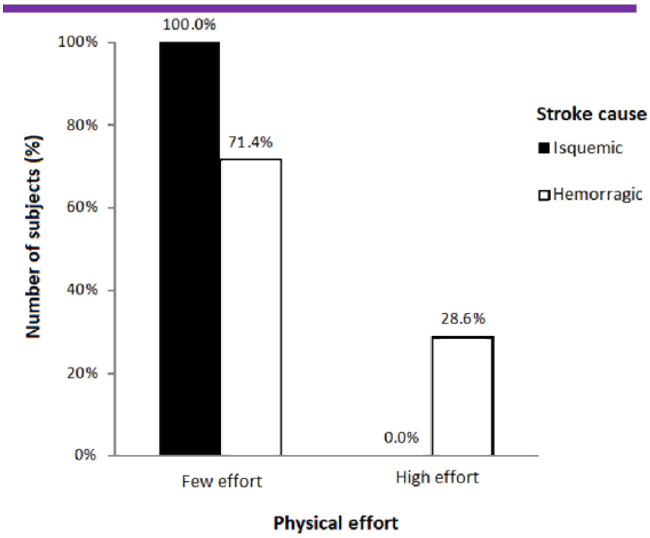


Figure 68: Level of effort sensation while using the games according to stroke causes.

The association between type of stroke and physical effort required by the game had a significant value (p=0.013). As shown in Figure 68, all patients that had an ischemic stroke reported less physical effort while 28.6% of patients who suffered a hemorrhagic stroke said that the game required a high physical effort during the interaction. This probably occurs due the fact that hemorrhagic strokes are normally stronger (Grysiewicz et al., 2008) resulting in higher difficult in performing exercises. For other items of usability questionnaire no association with socio demographics variables was found.

Outcomes of our research showed that sociodemographic factors such as level of schooling and family income may have influence on levels of satisfaction using interactive systems. However, there is a few data on literature about this theme and other researches must be performed with a higher number of volunteers.

As shown in our results, there was an association between level of schooling and understanding of the game and between level of schooling and corrective feedback. These results corroborate with Kang and colleagues (Kang *et al.*, 2008) which evaluate level of satisfaction according to sociodemographic variables when using a simulate shopping of everyday life and treated people post stroke. There was a clear relation between virtual performance of patients and level of schooling and also an association between virtual performance and previous experience with computers.

According to results, the reAIRbilitation seems to be a promissory tool for post-stroke rehabilitation support. Items such as motivation, treatment inclusion and interaction with virtual environment obtained a high rate of satisfaction in the patients' opinion. The system had an easy utilization, even for people with important physical limitations.

10.3. FIRST AR PROTOTYPE

The first AR prototype was tested in order to validate the idea and further develop the AR system. The result of these tests was published as a full paper in the main Brazilian conference of VR and AR, the XIV Symposium on Virtual and Augmented Reality, in 2012 (Da Gama, A. *et al.*, 2012a). It also resulted in a poster at the IEEE Symposium on 3D User Interface in the same year (Da Gama, A. *et al.*, 2012b).

The first AR prototype evaluation was performed by 10 users, 3 physiotherapists, 4 adults and 3 elderly. They were asked to try the system and at the end answer a usability questionnaire and give feedback about the system. The data was analyzed and presented descriptively as average and standard deviation. A test on the movement detection was performed by doing correctly and wrong movements and checking system success in categorizing them correctly.

EXPERIMENTAL PROTOCOL

Motor rehabilitations system can be largely applied for different kinds of pathologies and rehabilitation programs including traumatic, neurologic and geriatric therapies. In order to evaluate the system applicability user tests were applied on three different populations: three physiotherapy professionals, four adults and three elderly subjects who are members of geriatric physiotherapy groups and potential users of the system.

The physiotherapists group was asked to make a technical analysis of the prototype including application benefits and movement correction capability. On the other hand, the adults represent the general user groups, introduced mainly to evaluate the system entertainment, easiness-of-use and analysis of the movement learning process through the system. Finally, the elderly group, which are already realizing motor rehabilitation therapy being a potential user group for the system, participated on this study.

Firstly, individuals were submitted to use the prototype and then a questionnaire was applied, which was based on VRUSE questionnaire made for a VR based system (Roy, 1999) and a website usability questionnaire (Roy, 1999; Nupe, 2006) moreover merged with a questionnaire for an AR rehabilitation system proposed by Alamri and partners (A Alamri *et al.*, 2010). The detailing of the questionnaire is described below.

USABILITY QUESTIONNAIRE

The usability questionnaire used in the tests is composed of three parts where the user should evaluate each defined criterion, pointing a score from one to five followed by some complementary questions.

The questionnaire first section asked about user reaction to prototype use, what they felt by using it, in a scale from 1 to 5 using the following options: from terrible to wonderful, frustrating to satisfactory, discouraging to stimulant, hard to easy and rigid to flexible.(Roy, 1999)

The second part was dedicated to evaluate the interface. The interface letters size was evaluated (from low to highly legible), as well as the stimulus (few to a lot), the information organization, the used terms, the clarity of information (this last varying from confuse to clear) and uniform distribution of information over the display area (never to always) (Nupe, 2006).

The last part aimed the technical characteristics, analyzing fun perception by the user, depth perception, real environment recognition as part of the exercise, motivation to complete exercise, exercise comfort, easiness to understand how to perform the correct movement, orientation assistance for movement comprehension (these varying from few to a lot), task execution (from easy to hard), instruction clarity (confuse to clear) and environment configuration (boring to interesting) (A Alamri *et al.*, 2010).

Lastly there were some questions to identify user learning and interest. The asked questions were: "Would you like to play it again?", "Does the prototype help you to learn the correctness of movement?" and "How to improve system? Suggestions?".

RECOGNITION TESTS

With the purpose of analyzing if the angle measurement was equivalent to clinical uses, a comparison with a goniometer was performed by a physiotherapist (K Hayes, 2001). Goniometry is a technique for measuring ROM in degrees, mainly dedicated to human body articulations amplitudes. The goniometer has two movable arms connected by one axis, which is provided with an angle measurement device. Each goniometer arm is directed to one body part of the studied articulation, which compose the angle in question and it is positioned according to existing protocols elaborated to standardize the measure. By using a plastic, 41cm, universal goniometer, the active movements were measured. The shoulder abduction goniometry is performed by aligning the goniometer with the lateral epicondyle of the humerus, the middle of the posterior glenohumeral joint line, and a vertical line in the sagittal plane (K Hayes *et al.*, 2001; K Hayes, 2001).

The Kinect sensor presents a limited horizontal field of view, dependent of user distance from it (Primesense, 2011). In order to evaluate the robustness to occlusion, tests were executed with the user alternating between being inside and outside of the field of view. Moreover, positions with the user inclined in front of the sensor and laterally positioned in relation to the sensor were tested, aiming to verify user freedom of movement when using the prototype, which is important during rehabilitation. Seated position was also tested simulating some patients which are unable to remain standing during whole therapy, and to attend paraplegic patients as well.

Finally, the recognition and score system was evaluated by a physiotherapist due to the fact that its practice can predict movement's compensations and deviations made by patients during rehabilitation process. Prototype successes and failures were computed from different movements executed correctly and wrongly, 50 and 60 respectively.

Ten repetitions of each kind of wrong movement were developed: anterior and posterior elevation (out of frontal plane), shoulder abduction with flexed elbow, reverse movement (up to down), course deviation and trunk lateral inclination (postural compensation) for each side. Tests and results of present study were executed after a first evaluation of the prototype where some wrong movements were detected as correct. Based on it improvements were made including the normal vector reference and route analysis. The resulting requirements list was implemented in order to improve the system, and these advancements are already presented at this article.

RESULTS AND DISCUSSION

The developed prototype, using Kinect as a natural interaction tool for rehabilitation proposes, showed to be responsive to users' movements (including little ones) and effective on the evaluation of the movement correctness and indication aiming its adjustment. These characteristics can be used to improve AR and VR technologies on motor rehabilitation, optimizing treatment process.

Evaluating system performance, the mean execution time of the total processing of each frame was 71.56 milliseconds, varying from minimum of 53 to maximum of 171. From this mean, 71.20 milliseconds correspond to OpenNI skeleton extraction and display routines, and 0.46 to mapping and movement analysis (**Table 20**). These results show good processing times, since performance is an important characteristic in order to achieve a natural interaction. In general, it is recommended to not exceed the execution time of 150ms (Valli, 2005), this way, the presented system fulfills this requisite with a substantial margin.

Table 20: Performance test: execution time

Process	Average	Minimum	Maximum
Total Execution	71.56 ms	53 ms	171ms
OpenNI	71.20 ms	53 ms	171ms
Mapping Movement Analysis	0.46 ms	≈ 0 ms	65 ms

SENSIBILITY AND ANGLE ACCURACY

In order to evaluate the possibility of using the angle measured by the system as a therapy measure, the angle measured by the proposed system was compared with the data registered by the goniometry, which, as said before, is a clinical tool for it. Both angles were computed simultaneously ten times on different shoulder abduction angles. These data showed similar results, presenting four degrees of mean variation between Kinect and goniometry measurement (**Figure 69**). To evaluate this difference, One-Way ANOVA test was executed (Da Gama *et al.*, 2013), analyzing this mean variance, then obtaining a probability value (p) of 0.848.

Goniometry evaluation was chosen due to its practical and clinical use (K Hayes, 2001). As a manual angular measurement it presents good reproducibility with a variation of 2 to 7 degrees, however, this accuracy is dependent of examiner ability (A M Bovens *et al.*, 1990). Furthermore, the low difference found can be justified by the prototype reference points for angle computation, in which articulations are detected by computational methods while goniometry makes use of anatomical points.

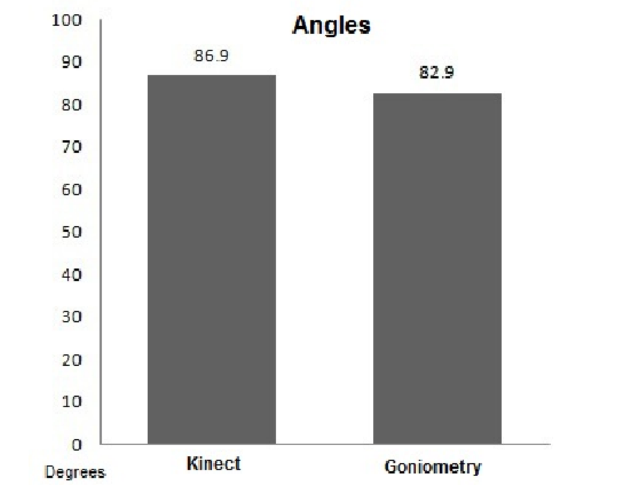


Figure 69: Angles average through Kinect and manual goniometry (p=0.848)

Mapping and Movement Recognition

The movement recognition was based on angles measurements. The presented prototype aims mainly to make therapy execution more precise with interactivity for user. For it, the proposed system uses correct movement recognition avoiding development of wrong exercises and compensations.

During execution of correct movements, following all determined criteria, all were recognized correctly and punctuated, as showed in the Table 2. None of the wrong exercises were recognized as correct, meaning that the system achieved 100% of success rate, obtaining none false positives and false negatives occurrence during the recognition process (**Table 21**). This ratio was achieved due to the fact that the prototype enables a complete movement description, including arm and shoulder position, alignment and their evaluation during all route.

Table 21: Correct movement recognition statistics

Movement	Executed	Recognized	Successes (%)
Correct	50	50	100
Wrong	60	00	100

Movement angles and its relation to the thorax normal vector enabled the user body analysis at different positions in relation to the sensor, including inclined and lateral positions. This way, it is possible to provide the user a greater mobility on system use, moving one more requisite towards a natural interaction. A correctly performed movement being executed on different angles from sensor can be viewed in **Figure 70**a and **Figure 70**b. These movements were also included at correct performance test described in **Table 21**.

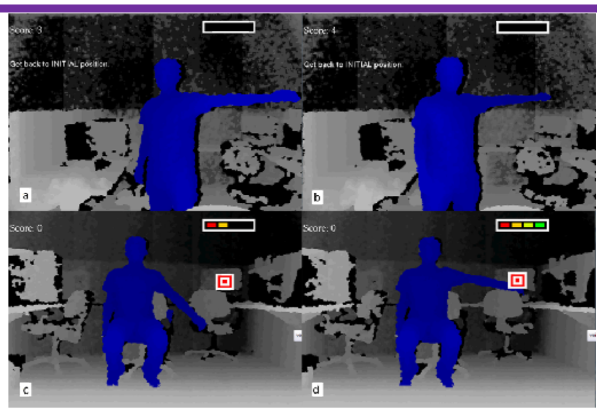


Figure 70: Correct movement executed a) anterior inclination; b) posterior inclination; c - d) seated position

Later, the robustness to occlusions presents favorable results. From ten executed tests, all of them recovered the user after a total occlusion (caused by the user walking out of the sight of the sensor and then returning to his last valid position). This way, it turns to be possible that the user walk away from the scene for up to ten seconds without the need of a recalibration (Primesense, 2011). One more time, it is important to notice the presence of users' freedom during the use of the system, not requiring their attention uninterruptedly during the session. As recommended by Valli (Valli, 2005), the user must not feel attached to the interface. In order to achieve a more comfortable interaction it is demanded that the user feels free as long as possible.

Different degrees and kinds of limitations and pathologies are submitted to rehabilitation process. Due to this, a simulation of a wheelchair and a seated patient (incapable to stand up) (**Figure 70**c and **Figure 70**d) were executed. The system also succeeded on these cases obtaining the same result of the standing position. This can be explained mainly because the precision of the upper body tracking was not affected on the tested sequences. However, for future research using lower limbs, the seated position can be a limitation.

From 20 postural compensations executed during tests, none were detected as a correct movement. Postural compensations can be commonly performed by patients to make the arm elevation easier. This way, this misuse was recognized by the system as a wrong movement and was not computed, showing prototype efficacy to avoid it. Indeed, this is the most common compensation found on rehabilitation processes, and, according to Rainville and partners (J Rainville, 1997), it can promote pain and reduce the motor ability. Thus, trunk compensation control is extremely important in order to prevent both problems.

USABILITY

The prototype was used by three different populations, a total of ten subjects, to test its usability and its efficacy on rehabilitation support. **Table 22** presents the mean of usability scores for each category from the questionnaire which has a scale of 1 to 5 (weak and strong, respectively).

The first test was applied with adults to evaluate general usability and interaction. From four subjects, three learned to execute the correct movement with some prototype help and the other one got it right since the first execution, without any need of external guidance. This group marked a low score for the letter size on the presented interface (3 points, which means a low readability), and great score to playability and depth perception (4.5 points for both).

Table 22: Usability questionnaires scores for each group

	Physiotherapist	Adults	Elderly
Subjects (n)	03	04	03
Average Age (years)	26.00	18.75	72.66
Playability	4.33	4.50	4.00
Satisfaction	5.00	4.00	5.00
Easy	4.66	4.25	5.00
Fun	4.33	4.25	4.00
Motivation	5.00	4.00	5.00
Environment	4.00	4.25	4.33
Guidance help for movement execution	5.00	3.75	4.33
Legible	1.66	3.00	3.66
Stimulus	2.66	3.75	4.00
Information clarity	5.00	4.25	2.00
Depth perception	4.00	4.50	4.00
Real environment recognition as part of the exercise	5.00	4.25	3.66
Instructions	4.33	3.50	4.00

The following tests were performed with three elderly subjects due to the wide actuation of motor rehabilitation on this population. In a similar way to the first adults group, one subject executed the movement correctly on their first try and the other two learned it through the system guidance. The criterion with lower score for this group was the clarity of the information (achieving 2 points only) and the greater score was related to the satisfaction and motivation provided from prototype use (5 points for both).

The last evaluation was performed on a group of three physiotherapy professionals, in order to gather technical opinion about the system and the application itself. The movement execution was aided with the prototype guidance on all three subjects' tests. The pointed negative aspects were mainly related to the letters size and the stimulus (1.66 and 2.66 points respectively) and the positive evaluation from physiotherapists were most about the user satisfaction, the system guidance (towards the improvement of movement execution), the real environment recognition as part of the exercise and the information clarity provided by the prototype (5 points all).

User evaluation showed that the correction and guidance provided by the system were executed with efficacy. However, some interface improvements are needed in order to achieve a better usability for the application. Some of those improvements are related to the messages letter size and the information clarity, mainly on exercise guidance. Therewith, postural and biomechanical correction and orientation during treatment execution is possible with a good patient acceptability, and who should be more motivated to execute therapy correctly.

This work introduced a movement recognition method based on therapeutic movements developed using Kinect sensor information to guide and correct it.

The implemented prototype showed efficacy when detecting correct therapeutic exercises, avoiding wrong movements during the rehabilitation process, this way preventing lesions and optimizing the treatment. The proposed prototype demonstrated levels of precision and sensibility which enable the adaptation for physical limited subjects.

Moreover, visual feedback supplied by the system favored interaction and promoted a better execution of the exercise. Future researches comparing the prototype application on patients with and without feedback supply can analyze this efficacy. Based on positive reports from users and also on prototype precision and efficacy as natural interaction tool for rehabilitation purposes, it is pretended to apply this technology for development of a complete AR rehabilitation system, considering users opinion to improve it, as legibility and clarity of information.

10.4. mirrARbilitation

The upgrade of the prototype described above resulted on the mirrARbilitation system. The system was tested in patients, physiotherapists and developers. A paper to be send to publishing at Medical & Biological Engineering & Computing is being reviewed.

The mirrARbilitation evaluation was composed of three phases: exercise without the system, with the system and again without it. At each phase users were asked to perform the movements until they feel tired. It included 33 participants including physiotherapists, developers and patients. The number of subjects was computed by using sample computation test at GPower 3.1 software (Faul, 2007). The main outcomes are the percentage of right exercises performances and the number of repetitions. These data were compared between the three phases by using ANOVA and Friedman test, being this last one used when there was at least one nonparametric data in the comparison (Da Gama *et al.*, 2013). These tests were performed with all subject and also categorized in the three groups. Usability questionnaire was also applied and its results presented in average and standard deviation. Detailed procedure is described below.

EXPERIMENTAL PROTOCOL

The user test was planned with the main goal to evaluate the effect in using the interactive system which uses the movement recognition technique which provides biomechanical analysis, and this way information to corrective feedback, in order to improve exercise quality. It was done by checking if the user learns how to perform the exercise correctly with the system help. It was also a goal to test user engagement by the number of movements' repetitions performed. In order to check these two goals it is necessary to ask the user to perform the exercise with and without mirrARbilitation for comparison. And finally, the third goal is to evaluate fun, motivational and interface aspects provided by the system and ask users opinion about the system therapeutic value. Knowing that, the following protocol was established in four phases as described below.

The phase 1 aimed to test subject's natural movement based only on therapist instructions. It simulated user performance at home after a therapeutic section. In order to do this, a physiotherapist instructed the user on how he/she should do the exercise and then he/she performs the exercise alone until gets tired.

The phase 2 tested the mirrARbilitation usage allowing to check the engagement and the system capability to induce the correct movement. The same instruction about how to perform and the number of repetition was given (until feel tired).

The instruction to perform the exercise "as many times as possible" was given in order to check patient engagement on exercise. It was hypothetical that with the use of the game the patient would be distracted and then he/she would feel the fatigue later. The system capability to induce the correct movement is analyzed comparing the number of correct movements in both phases. In order to know if the movements were being performed correctly in the first phase, the movements performed were recorded with the Kinect Studio, provided by the Microsoft SDK. Further this record was used for the movement analysis.

An additional phase 3 was added, where the user performed the movement again without interacting with the system. This phase had two goals: i. to check if the number of repetitions changed before and after the phase 2 in order to evaluate if fatigue interferes on it; ii. to evaluate if the differences in the correctness of exercise between phase 1 and 2 occurs due to system help or because the user is learning how to do it correctly from repetition. The same Kinect studio recording for further analysis made at phase 1 was done at this phase.

The phase 4 was the usability questionnaire. Here questions about fun, therapeutic effects and interface characteristics were asked. The questionnaire was composed of Likert scale items and some subjective questions where user could give their opinion about the system. The objective questions should be answered on a scale from 1 to 5. For the subjective questions users were allowed to answer freely.

PARTICIPANTS

The goal of this study was to evaluate the user exercise engagement, system capability to help on correct movement performance, therapeutic value and system technical and interface characteristic. To test the first two items any subject could be included, however in order to provide also information about the others aspects the user selection was restricted to patients, physiotherapists and developers. It included patients which could benefit from the shoulder abduction exercise, since that is the movement used in this study. Physiotherapists were included since they could provide their point of view about the system's therapeutic value. The developers group was limited to the ones with experience on games and/or interactive systems since they could give better feedback about technical and interface aspects. All tests procedures have been approved by the responsible institutional ethics committees (CAAE-00657012.6.0000.5208) and all participants gave written informed consent.

The number of participants to include on this work was statistically computed after the first ten user tests. Based on them, GPower 3.1® software (Faul, 2007) was used to compute the number of subjects required for study. The calculus was performed using the category of sample size computation for repetitive measure studies and it used 95% for both, significance and power. The computation was done based on the two main outcomes of the study, the comparison between number of executions and the success rate with and without the system.

For the number of executions, the sample size computation result was 11 subjects while for success rate 27 subjects should be required. So, the larger sample was chosen and 27 subjects were recruited. Later, the study was expanded to 33 volunteers in order to categorize them in groups with the same proportion of users in each: 11 physiotherapy, 11 patients and 11 games and/or interaction system developer.

DATA ANALYSIS

All the acquired data was statistically analyzed using the IBM SPSS Statistics 20® (Ibm, 2011) and they are described at results section. To evaluate the patient engagement, a comparison between the number of repetition of phase 1 and 2 was performed. To check if the system helped user to perform movements in a correctly way the success rate representing the percentage of right movements during section was used. Also, since it was hypothesized that differences between phase 1 and 2 would be found, a third phase as reference was added. Thus, the number of repetitions and the success rate between phase 1 and 3 was performed in order to check if the differences between phase 1 and 2 occurred due the system use or due others bias.

Statistical tests started with the Kolmogorov–Smirnov test in order to check data distribution and categorize the variables as parametric or non-parametric (Da Gama *et al.*, 2013). After this, it was detected that all variable presented parametric characteristics except for the number of repetitions at phase 3. For the parametric data the mean comparison between the phases were done with the ANOVA test for repeated measure and for the non-parametric ones the Friedman repeated measure test was performed (Da Gama *et al.*, 2013). So, the comparisons of success rate were performed using the ANOVA and the number of repetitions tested with the Friedman test. The numbers of repetition and success rate were described in terms of mean and standard deviation. In order to provide more detailed analysis, data was also described and compared at each user categories: physiotherapists, patients and developers. Comparison between the number of repetitions and success rate was performed at each group. The Kolmogorov-Smirnov test showed normal distribution of all these data at each group. So, all comparison inside the groups were done using the ANOVA for repeated measure. For the patients, since they have only two measure the comparison was made using the paired T-student (Da Gama *et al.*, 2013). The Likert scale questions were also described in terms of mean and standard deviation and they were also detailed by group.

RESULTS

This work developed an AR rehabilitation system to improve patient engagement during exercise performance and the movement quality, providing instructions and feedbacks which helps patient to execute them in a correct manner. The system developed was presented on methods section.

As described before, the patient exercise engagement was evaluated by the number of repetition with and without the system. The average number of times that user did the movement improved significantly with the use of the system, p < 0.000 (**Figure 71**). Comparing the performance before and after the use of the system there was no difference (p = 0.394).

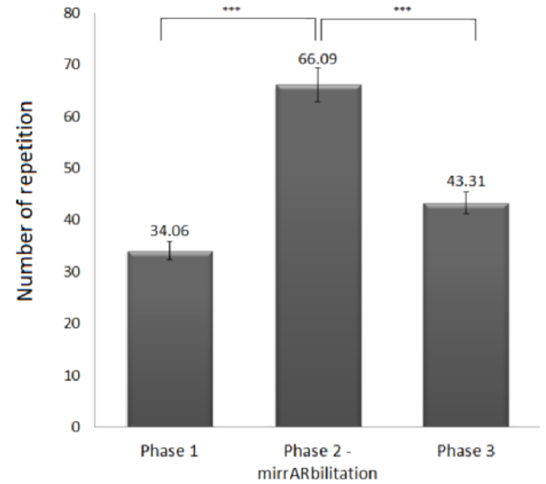


Figure 71: Average number of repetitions at each test phase. ***p<0.001 at Friedman test.

Making the same analysis by group, all of them presented an increase on the average number of repetition, p < 0.000 (Figure 72). However, for the patients this difference was not significant (p = 0.093). This group did not perform the exercises again on phase 3 due their limitation. Since the phase 3 was to work only as a ground truth, the others groups were enough to do that, being unnecessary to require this effort from patients.

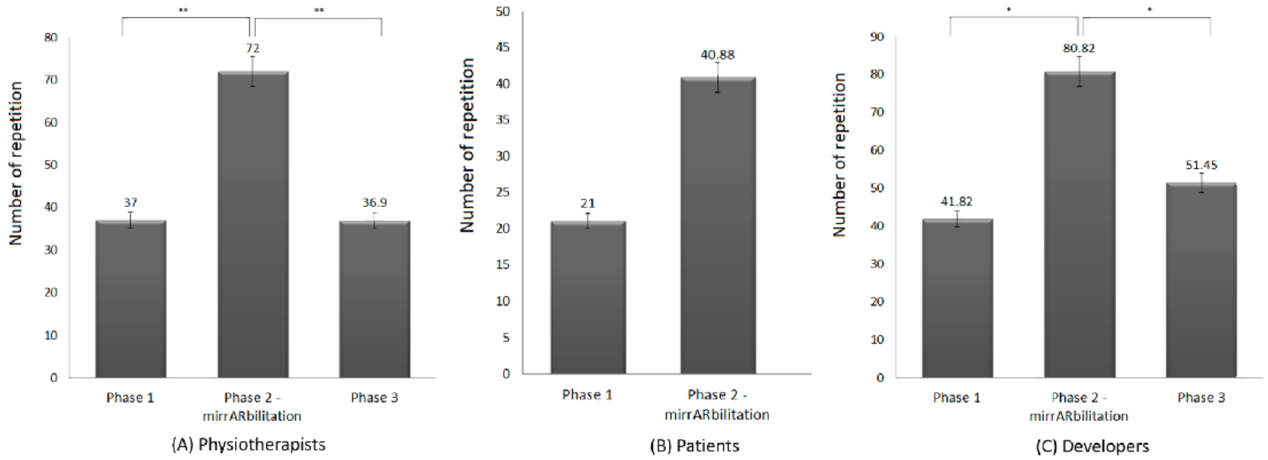


Figure 72: Average number of repetitions at each phase for the (A) physiotherapists, (B) patients and (C) developers groups. *p<0.05 ** p<0.01 at ANOVA test.

To evaluate the mirrARbilitation capability to induce the correct exercise performance the success rate was evaluated. This measure represents the percentage of exercises that were performed correctly. The results show a percentage improvement of correct movement exercises with the use of the system, p = 0.004 (Figure 73). No significant difference was found between the two moments without the use of system, phase 1 and 3 (p = 0.881). Additional result which is relevant to notice is the minimum value of success rate at each circumstance: phases 1 and 3 had 0%, i.e., there were at least one subject on those groups that did not perform a correct exercise not even a single time; on the other hand, phase 2 had a minimum of 73.68%.

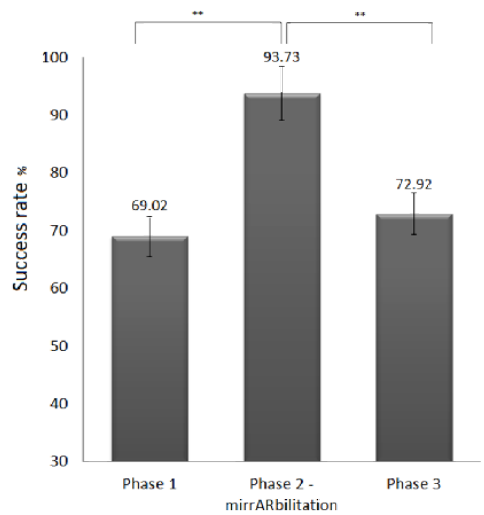


Figure 73: Average percentage of correct exercise at each phase. **p<0.01, test.

The average success rate by group followed the same tendency (Figure 74). However, for the physiotherapist group the difference between phase 1 and 2 (p = 0.099) and between 2 and 3 (p = 0.143) was not significant. Nevertheless, the minimum values continued drastically different between the phases even at this specialized group: phase 1: 6.67%, phase 2: 89.39% and phase 3: 9.09%.

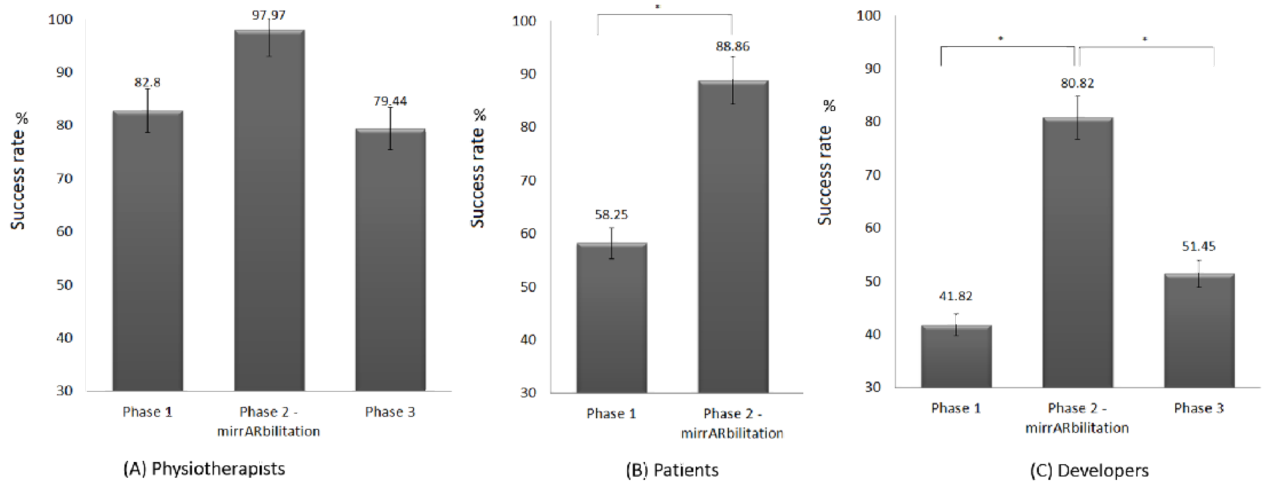


Figure 74: Percentage of correct exercise performed at each phase. (A) physiotherapist, (B) patients and (C) developers group. *p<0.05 at ANOVA test.

Two patients, both post-stroke, were not able to use the system due their physical limitations. Their flexion pattern prevents them on doing elbow extension. Without this movement the interface was not adequate to induce the movement and they got confuse. Since their arm did not reached the basket they tried to turn the trunk and rotate it in order to position their hand on the reaching object place instead of doing shoulder abduction, as shown Figure 75.

The usability questionnaire results are presented on Table 23 including the fun and motivational aspects, therapeutic value and interface and AR characteristics. Table 23 presents the results for all subjects and also at each group. Fun and motivation aspects were approved by the users with mean score higher than four points for all questions. The lowest scores at this aspect were found from the developers groups and the highest ones were from the patients. The answer to the question "would you like to play again?" was affirmative for 84.4% of users, 15.6% answered "maybe" and none had any interest at all. Regarding only the patients group, 100% described that they would like to play again.

Figure 75: Patient having difficult in interacting with the interface due physical limitations

The therapeutic value received a high score evaluation with a mean higher than four points for all groups in all aspects evaluated. The Interface and AR aspects were the ones less approved with mean score lower than four for majority of questions. Even so, organization and clearance of information were still approved by users (4.06 and 4.47 points respectively).

Table 23: Results of questionnaire answers for the fun and motivational aspects, therapeutic value, and interface and AR characteristics. Values described in mean and standard deviation for each group and the total.

Question	All subjects	Groups: Physiotherapists	Groups: Patients	Groups: Developers
Fun and motivational aspects				
Did you feel happier performing with the game than without?	4.19 ± 0.53	4.30 ± 0.48	4.00 ± 0.45	4.27 ± 0.65
Was it fun?	4.12 ± 0.89	3.72 ± 1.01	4.73 ± 0.65	3.91 ± 0.70
Would it be good to have the game as part of your therapy?	4.00 ± 0.62	4.10 ± 0.87	4.09 ± 0.30	3.81 ± 0.60
Did you feel motivated to complete the exercises?	4.19 ± 1.03	4.00 ± 1.26	4.60 ± 0.84	4.00 ± 0.89
Therapeutic value				
Did you believe in the therapeutic effect of the game?	4.30 ± 0.58	4.36 ± 0.67	4.27 ± 0.65	4.27 ± 0.47
Did the system help You to detect wrong exercises?	4.31 ± 0.69	4.64 ± 0.50	4.20 ± 0.42	4.09 ± 0.94
Did the system help You to correct wrong exercises?	4.16 ± 0.81	4.54 ± 0.69	4.00 ± 0.67	3.91 ± 0.94
Did the orientation provided help on exercise?	4.37 ± 0.87	4.63 ± 0.67	4.36 ± 1.03	4.10 ± 0.87
Would it be good to have this system as a home exercise tool?	4.75 ± 0.51	4.90 ± 0.30	4.60 ± 0.70	4.73 ± 0.47
Interface and AR characteristics				
Did You like the scenario?	3.54 ± 0.79	3.45 ± 0.82	4.09 ± 0.54	3.09 ± 0.70
Were the letter sizes legible?	3.90 ± 1.13	3.36 ± 1.20	3.67 ± 1.22	4.64 ± 0.50
Was the information organized?	4.06 ± 0.91	4.00 ± 0.77	4.60 ± 0.70	3.63 ± 1.02
Was the information clear?	4.47 ± 0.62	4.45 ± 0.69	4.60 ± 0.52	4.36 ± 0.67
Did the game provide a depth perception?	3.84 ± 1.11	4.00 ± 1.00	4.10 ± 1.29	3.45 ± 1.03
Did You feel the real world participation?	3.91 ± 1.27	4.18 ± 1.07	4.45 ± 0.82	3.00 ± 1.49

DISCUSSION

The mirrARbilitation system was developed aiming to improve the rehabilitation process through AR technology using a gesture recognition tool which allows movements to be analyzed according to biomechanical conventions making the system more clinical related. Based on the results the system seems to have efficacy on improving engagement and helping to correct exercise.

A lot have being discussed about patient engagement on rehabilitation exercise with the use of interactive systems, although none objective evaluation was performed by the studies. These studies normally evaluates patient motivation through questionnaire and user general opinion, and their results showed positive motivational aspects of interactive systems for rehabilitation (Ave *et al.*, 2013; Galna *et al.*, 2014). The outcomes here presented reinforce this hypothesis objectively showing an increase on the number of exercise repetition with the use of the system. The absence of difference between the two phases that did not use the system corroborate in showing that the improvement found occurs due system application.

The number of repetitions improved around 50% with the use of the system, achieving cases where the user performed 100 repetitions more while using the system. Analyzing it by group, it was detected less effect on the number of repetitions for the patients group. Probably it occurred due the fact that the fatigue is more critical for this group, by physiologic causes, while for the other two the psychological effect of the repetitive exercise should had worked as main role to stop exercise. This shows the high effects of interactive systems on diverting patient from the boring aspect of therapy making them more engaged on the exercise. A study developed by Chuang et al (Chuang *et al.*, 2003) corroborate with this result showing exercise performance improvements during a cardiopulmonary cycling test. They found an increase on exercise duration, distance traveled and energy consumption with the use of a VR system to distract the user from effort. Improvement in cycling performance was also detected by Kim et al (Kim *et al.*, 1999) who detected an increase on cycling speed and better postural performance during cycling.

The importance of doing exercises correctly has being shown. The movements are planned to achieve specifically joint gain and its execution in a correct way can improve the therapy efficacy. Besides that, the wrong exercise is not only less effective (Rainville *et al.*, 1997) but also can lead to new injuries (Sparks *et al.*, 2009). The mirrARbilitation system showed efficacy on helping user to perform the exercise correctly. This was shown by the higher percentage of correct exercise with the use of the system compared to the situations without it. There was no difference between the two moments where the movements were performed without the system, showing that the improvement on success rate found is not caused by the learning effect. However, the physiotherapists group did not presented significant increase on the success rate. This probably occurred due the natural correct performance of movement at this population due their technical knowledge about biomechanics.

More than helping on improving success rate the use of the mirrARbilitation as a guidance tool prevented user from doing the exercise completely wrong. With the use of the system the worst case of all groups still presented a percentage of correct exercise higher than 70%. In the other hand, without the use of the system there were situations where user performed the entire exercise wrongly (0% success rate). This result showed the importance of movement guidance and correction when using interactive systems for rehabilitation purposes. Patient attention to the motor activity is important not only to avoid the wrong exercise but also to achieve better cerebral plasticity for the movement (Merians *et al.*, 2006; Eng *et al.*, 2007). So, interactive systems which are able to provide correct movement performance can help on this.

The usability evaluation showed the positive aspects of the system and also its limitations for further improvements. The fun and motivational aspects pleased the users; however, the opinion about the fun criteria was not so consensually. For the physiotherapists and developers the system is not so fun scoring the "Was it fun?" question lower than 4 points while for the patients it was highly approved (4.72 points). This probably occurs due to the simplicity of the game which was developed as a case of study focusing on providing the therapeutic requirements. In order to develop a system which offer fun for any population profile a large variety and elaborated games should be developed using the recognition proposed.

The mirrARbilitation system presented efficacy on helping users to perform exercises correctly. This was shown and discussed with the improvement of success rate on movement performance. The usability questionnaire reinforces these results. Users agreed that the system helped to detect the wrong exercises, and agreed that system orientation helped them to correct it. The movement performance in a correct way is especially important to allow system application for patients at unsupervised situations (Merians *et al.*, 2006; Danny Rado *et al.*, 2009; Da Gama, A. *et al.*, 2012a). Therefore, this system seems to be very effective not only for clinical environment but also for home rehabilitations as a complementary tool or to allow access to patients who are not able to access rehabilitation centers (Merians *et al.*, 2006). The use of this tool as a home exercise system was approved by all users, being this one the aspect of therapeutic value that received highest score (4.75 points).

The mirrARbilitation system was based on AR concepts providing instructions and orientation. The choice of developing an AR system was based on the fact that the auto visualization during movement performance can improve patient corporal conscience (J W Buker *et al.*, 2010) which may lead to more effective therapy. Positive aspects of real world participation was shown by Perani et al (Perani *et al.*, 2001) who detected that actions which are performed on natural environment activate additional visuospatial network on cortex which are not activate in the virtual ones.

It has being shown that the efficacy of physiotherapy treatments is improved with visual feedback offered by AR and VR systems (A J Espay *et al.*, 2010), mainly because it is given a better guidance for the movement execution and a stimulus for doing it. Therefore, to provide a more efficient tool, a feedback system was implemented. At this work, the possibility to guide a correct movement was consequence of a movement recognition based on biomechanical concepts (Da Gama *et al.*, 2014). Thus, the specific movements which should be performed to achieve certain gain could be used with this tool. Studies suggests that for rehabilitation purposes it is important for the system to be directly related to rehabilitation goals (Merians *et al.*, 2006) requiring a precise motor performance with the use of specific body segment that the therapists want for a particular motor activity (Ustinova *et al.*, 2013).

Based on the usability test it is possible to notice that the main system limitations are on the interface aspects. Upgrade on game and visual aspects are required. These improvements include scenario and font size adequacy. Despite these problems, the interface limitations information provided was clear for the users and did not affect system efficacy. The tool here developed seems effective for rehabilitation proposes, however game focusing design would lead to a more attractive interface. Future works with game design can also improve the interfaces to adapt the interactive context and allow the use of the others movements which are already recognized by the biomechanical movement recognition method.

It is important to notice that interest in the scenario is different according to the population. For example, for patients the scenario chosen in this first prototype was approved but this is not so true for physiotherapists and mainly for interactive and game developers. This suggests that the best case is the production of different scenarios for different target populations. However, when developing for rehabilitation, some considerations should be taken, for example, in rehabilitation practice, the optimal lighting and contrast, and the elimination of glare, are just as important as providing adequate magnification (Cooper *et al.*, 2006). When developing for patients, mainly neurologic ones, two-dimensional view is more appropriate for most of the them due their difficult in depth perception in 3D interfaces (Khademi *et al.*, 2013).

One of the main limitations of commercial systems is the lack of ability to scale skills levels for the population with disabilities (Ustinova *et al.*, 2013). Therefore, the configuration features such as the reaching angle and required movement accuracy were included on this work. This adaptable characteristic was approved by the physiotherapist during the tests, increasing system therapeutic value. An additional advantage provided by this system is its markerless nature as others rehabilitation systems requires the user to hold an object which not always can be achieved by patients (Ustinova *et al.*, 2013).

Limitations of this work are mainly related to the game interface. During the tests a difficulty was detected while the system was used by the patients with flexion pattern. These patients are not able to perform elbow extension, thus, being not capable of reaching the object. This made the interface not suitable for these patients. The tolerance of movement can be changed to not require elbow extension; however, the tests showed that it was not enough. A change on the interface which makes the movement intuitive in this case of elbow flexion is required.

Despite the fact that the movement recognition here used is able to detect the different limbs' biomechanical movements, only one of them was used in this study. Even so, it showed the efficacy and the value of a system which can recognize, guide and correct a biomechanical movement. These results show benefits of the system opening doors to the continuity of this field with the development of new versions based on this recognition but including others movements. A system with a different game paradigm can also be further developed in a more embracing way allowing interaction using all movements recognized in only one system. The main difficulty here is to find an interface or a game concept which can use all the movements.

10.5. SUMMARY

This chapter finishes this work by showing the use of the movement recognition technique here developed as a tool for rehabilitation interactive systems. The recognition according to the biomechanical standards provided information's which could be used to guide and provide corrective feedback to users. The method also make possible to interact with system using the biomechanical movement status as a control to interaction. The user studies performed showed the acceptability of such system with therapeutic value approved by therapists and patients. The use of the guidance and corrective feedback helped users to perform movement correctly and avoiding users to perform it completely wrong. It is very useful tool to develop home rehabilitation system where patient will be without supervision needing help to perform the exercise correctly. The VR and AR applications here developed were studies of case to check the methods capability to provide useful information's. Now that the positive aspects of using the biomechanical recognitions for rehabilitation application was shown, researches and development focusing on games aspects to please different populations and long term adherence is needed.

11. CONCLUSION

This work achieved the proposed goal in recognizing patient movements according to the biomechanical standards and developing a system more clinical related.

The idea of developing a system which can use biomechanical movements as an interaction tool is new and promissory. Based on the preliminary results obtained in this work it is possible to conclude that the development of an interactive system based on a clinical context seems to have successful acceptability.

The use of biomechanical movement description to perform motion recognition enabled the interactive system to be used through exercises which are normally performed on therapy. It makes systems more related to the reality of the application. The information provided by the movement recognition could be used to provide feedback in the application to guide and correct the exercises. The benefits of this guidance provided was shown in the applications. The orientation avoided users to perform exercises completely wrong, presenting at least 73% of right exercises when the instructions and correction were provided, while without the guidance some users performed 0% of correct movements.

The recognition based on biomechanical standards also enables evaluation using a measure which is known by the therapist. This makes it easy for the physiotherapist to interpret and draw conclusions based on the data provided by the system. The movement recognition method showed good efficacy in classifying the biomechanical movements correctly. Majority of movements presented great success rate of recognition, mainly at 20º MTM. When accuracy is required in the application, attention should be given when using the 30º MTM due to the possibility of false positives. Some movements could not be recognized mainly due absence of joint estimation change during movement, for example foot movements. Some of the movements which could not be recognized using the Kinect v1, due the improvements on the sensor could be detected using the Kinect v2, for example the clavicle elevation.

The advantages in using the ISB standards are not only in terms of movement recognition, but also in the interaction characteristic. The use of JCS enabled the user to have a free position in relation to sensor, since the axes references were based on the body information.

Due to the fact that the biomechanical movement recognition did not contemplate the functional movements, which are also important during the rehabilitation process, the checkpoint method was developed. This method presented good success rate and clinical applicability in recognizing functional and multi-joint movements based exercises.

The movement analysis library was developed aiming to integrate the two movement recognitions methods and allow their use by any application. During this thesis two case studies were developed to check the benefits in recognizing patient movements according with biomechanical standards. The movements detected according with biomechanical descriptions provided information to guide and instruct how to correct wrong performances that were used in the two applications developed, the reAIRbilitation and the mirrARbilitation. Both systems had their therapeutic value approved by users, including therapists and patients. The recognition methods based on therapeutic movements worked well in both applications.

The applications developed enabled the integration between the methods here implemented with the additional requisites listed. All the requirements were included in the applications. One exception is presented in the AR systems which cannot be used with the diverse therapeutic movements recognized. This occurs due the fact that for the AR interface it is necessary ways to guide and warn the different movements according with user position. This way a layout for each movement is required.

The application of the reAIRbilitation system on different populations showed successful acceptance by users. The specialists approved the therapeutic uses. The patients showed high acceptance in the using of a virtual environment during the rehabilitation process. More than 85% demonstrated high motivation in having such technology added to their rehabilitation routine. The first AR prototype tests also present good acceptability and usability for rehabilitation purposes.

The tests with the mirrARbilitation system showed that it was effective in improving user engagement on exercise, where users almost double the number of repetitions with the system (from 34.06 to 66.09) and in the quality of it. Using the AR guidance, users increased their success in performing the movement correctly from 69.02 to 93.73%. The system also prevented the users from performing the exercises completely wrong, what occurred in some case without using the system, while with the system the worst case was higher than 70% of right movements. . This is very useful in preventing lesions and optimizing treatments, mainly for further home use. Motivational and therapeutic value was approved by the users.

The aim of this work focused on the technology to provide ways to recognize movements that are used on therapy according to the biomechanical standards. The case studies were used to check if the idea and the information provided by the methods were useful to enable interaction and guidance. With the benefits shown, it is now suggested that systems for rehabilitation purposes follow the movement recognition method here proposed. This will give to all systems the clinical relation advantage. Additionally, since it was based on biomechanical international standards, it will facilitate further studies comparison and conclusions.

This work also showed the benefits of an interdisciplinary work and problem centered design. The systems were developed trying to better relate with clinical needs. This resulted in a system which enables therapists to use the movements that they already planned to use in the system and also get the system evaluation report according to clinical terms.

This work performed a wide study about the use of interactive systems for motor rehabilitation. These systems can be applied in the clinical environment to motivate patients in doing the exercise and also optimize therapist time. The system here developed can already be used in a clinical environment, and was tested in that scenario . However, one of the larger applications for these systems are in home rehabilitation. In order to enable such system to be took home the system is required to perform the different therapeutic movements and control of wrong exercises and the technique here developed showed to be very useful. Nevertheless, to be applied at home there are more requirements to be fulfilled as tele remote control, system automaticity and game diversity. Since a large number of patients are old or with low familiarity with technology, the ideal case is the system work as a plug and play device. This way the user does not have to know how to use a computer, making system simple to use. Additionally, the system should be connected to the therapist in order to enable therapists to accompany the patient and configure exercises and others configurations on the system. Another important characteristic in order to make such system ready to be used at home is the game variability. If it will be prescribed to be used everyday it is very important that the system provides different games to motivate the patient in long term.

11.1. FUTURE WORK

The major problems detected in our movement recognition solutions are related to occlusion and tracking limitations that may be solved with the use of two Kinects. It is suggested researches on the use of two Kinect sensors simultaneously in order to obtain one single skeleton as a result. The skeleton composition by two Kinects may also be beneficial for another limitation of this sensor for rehabilitation application that is the anatomical accuracy. Better joint estimation may be achieved using two sensors instead of one.

Future works on development of interactive systems using the biomechanical movements' recognition focusing on game aspects should be performed. It should also include interface aspects in order to design games with interest to different potential populations and capable of using different movements. The variability in games is an important aspect since the rehabilitation process can be long, this way the system needs to take user attention in a prolonged way. The diversification on the games is important not only to avoid the accommodation in long term but also to provide curiosity for different populations. The games interest for children, young, adults and elderly are different and all should be contemplate since any age can be a rehabilitation patient by different causes.

Socialdemographic characteristics also results in different games comprehension, as was shown in the reAIRbilitation tests. This shows that the development in the games aspects for rehabilitation purposes has to be deeply worked considering the different aspects which influence game adherence by different populations.

It is also suggest a development of a complete system using the interaction method here proposed. The complete system should not only to use the therapeutic movements to interact and provide exercise control but also allow the additional features discussed such as remote control and plug and play characteristic. We also suggest addition of auditory feedback, not only corrective as performed here, but stimulating and guiding to simulate the therapist presence, for example: "Go ahead."; "Don´t give up, you are almost there.". This feature should be very useful mainly for home applications where the therapist is not present.

When performing this study we detected some improvements which could be performed in the usability tests. Since the real application of the system at home is important, it is suggest to ask therapists after usability tests if they think the system is ready to be applied at home, and why. When applying such system in patients where the pain is a limit in exercise performance it is adequate to ask the pain visual analog scale before and during the exercise. We also suggest the development of an adapted version of System Usability Scale (SUS) (Usability, 2015) to rehabilitation applications, including directed question in relation to therapeutic effects and also with cautions in the terms used since some patients have limited comprehension. It is also recommended to test the patients' ability to turn on the system by their one.

In order to improve the knowledge about the long term applications effects on patients rehabilitation it is necessary the development of randomized clinical trials. The study should be done by comparing two or more groups with one of them using the systems in patients in the rehabilitation routine. The engagement on therapy and therapeutic effects should be analyzed.

Here a VR and AR system was developed to evaluate the efficacy of using the methods in both situations. It is now suggested a comparison study analyzing differences on therapy with the use of VR and AR systems. This should be done analyzing not only therapeutic effects but also patient motivation and corporal conscience acquired. It is hypothesize that the AR systems provide more corporal conscience and motor learning which are beneficial for therapy. In the other hand the VR can provide more ludic environments which can engage more patient in long term. All these aspects should be investigated.

11.2. CONTRIBUTIONS

The main contribution of this works was the development of a method to recognize the therapeutic movements following the biomechanical standardization. The method made possible to interact in VR and AR system using movements that are commonly performed during therapy given the therapist the possibility to choose which movement will be used according with the patients' needs. The technique also provided tools to the applications which use it to have information about the movement performance which could help in guiding and correct it. This resulted in improvements on movement quality when using application which were based on the method. The development of a movement analysis library with the methods developed allow the use of the technique in diverse applications.

This thesis also provided a systematic review about motor rehabilitation using Kinect (Da Gama, Fallavollita, Teichrieb*, et al.*, 2015). This paper can help researchers on the area in defining their questions and methodologies. This review showed that the main limitation of the research on this field are in the methodology quality of the studies. At the end of this work we elaborate a paper with QualSyst score of 95%, while the mean at this area is 47.7% (Da Gama, Fallavollita, Teichrieb*, et al.*, 2015). This paper will be submitted at Medical & Biological Engineering & Computing.

The results of this thesis shows the Kinect sensor limitations for rehabilitation applications. It also demonstrated which movement are adequate recognized when using this sensor. These results are show using the two Kinect version and the improvements and the movements which can be used using the new version is also shown.

PUBLICATIONS

The results of this work were published in conferences in the VR, AR, user interface, games and biomedical engineering areas. Besides the publications this work resulted in some awards.

The reAIRbilitation received awards from the main Brazilian game conference: Honors "Games for Change" at Independent Games Festival, Brazilian computer society; and Best Game on "Other Platforms" category in the same event.

The papers resulted from this work are listed below. From them one received best paper award (Chaves *et al.*, 2012) at the XIV Symposium on Virtual and Augmented Reality and other honors mention for full paper (Freitas *et al.*, 2012) at the XI Brazilian Symposium of Games and Entertainment.

The results obtained in the last months of this work will yet be send to publication in journals. The results of mirrARbilitation system will be submitted at "Medical & Biological Engineering & Computing". The movement recognition technique results including all movements classified with the two Kinect sensors will be send to publication to the journal "IEEE Transactions on Biomedical Engineering".

JOURNAL PAPER ACCEPTED TO BE PUBLISHED IN FEBRUARY 2015:

- DA GAMA, A. E. F.; FALLAVOLLITA, P.; TEICHRIEB, V.; NAVAB, N. "Motor Rehabilitation Using Kinect: A Systematic Review." Games for Health: Research, Development, and Clinical Applications, 2015.

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- Marques-Oliveira, D.; Da Gama, A. E. F.; Baltar, A.; Carneiro, M.; Cardoso, A.; Chaves, T.M.; Teichrieb, V.; Araújo, C.;

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APPENDIX A: ISB STANDARD

The movement description standardized by ISB is first composed by general concepts containing definition of global reference frame, segmental local of mass center and global and local displacement and references. These descriptions are found in the first standard [1] that works as framework for further joints statements. After the first statement the main joints were standardized by each specific committee and their JCS and movements were then described [2, 3]. This section will present the main concepts and rules for movement description and the reference and composition of JCS from the main joints. Further these rules and references will be translated and adapted to be used by the markerless movement recognition techniques proposed in this thesis.

All description from bilateral joints will be described according with the right side, so for the left side the description is the same however it is necessary to invert the horizontal vector direction (z == -z), mirror the raw position data with respect to the sagittal plane. Then, all definitions from right side are applicable to left side.

All descriptions in the ISB standard are performed starting in the anatomic position with proximal and distal segments aligned. From the start position rotations are described using Euler angles at each coordinate. The rotations of the distal coordinate system should be described with respect to the proximal coordinate system. And all rotation directions have to respect the right hand rule. All JCS should follow the coordinate system described below in the global reference system.

ISB FRAMEWORK FOR STANDARDIZATION

GLOBAL REFERENCE SYSTEM

The global reference system was defined in order to provide a global frame with the directions of the global axes being consistent independently of subject or activity that is being study and also investigator independent [1].

- System:
  - X, Y and Z.
- Standardization:
  - Right hand orthogonal axes with the Y parallel with the gravity vector and positive direction pointing upward. X and Z axis are perpendicular to Y axis;
  - X axis is normally defined in the direction of travel or work, example during gait this direction is pointing forward and is how it is standardized here;
  - When in an inclined point Y maintains its direction and X and Z stay in the same horizontal plane of inclination.

REFERENCE SYSTEM IN THE LOCAL CENTER OF MASS

Change the reference system to the local center of mass of each segment is required to describe pose of them. It will include position and orientation of each body part in relation to global body [1].

- System:
  - X, Y and Z.
- Standardization:
  - Right hand orthogonal axes with origin at segmental center of mass with X being positive for anterior direction, Y axis to proximal and Z respecting the right hand rule;

- Segments positions to proximal-distal and medio-lateral direction are defined base on anatomic position;
- To use the right-hand rule for both sides it is necessary to maintain Z direction for the right which results in t pointing laterally in the right side and medially for left side.

JCS ISB STANDARDIZATION FOR MAIN JOINTS

THORAX JCS

- Origin: Located at suprasternal notch;
- Y axis: Line connecting the midpoint between 8th thoracic vertebra and processus xiphoideus and midpoint between 7th cervical vertebra and suprasternal notch pointing upward;
- Z axis: Perpendicular line to the plane formed by the four points: 7th cervical vertebra, 8th thoracic vertebra, processus xiphoideus and suprasternal notch;
- X axis: Common axis perpendicular to Y and Z axes, pointing forwards.

CLAVICLE

Due the limited numbers of bony landmarks possible in the clavicle, thoracic JCS is used to help in Clavicle JCS at X axis.

- Origin: Located at sternoclavicular joint;
- Z axis: Line connecting sternoclavicular and acromioclavicular pointing laterally;
- X axis: Line perpendicular to Z axis and Y axis from thorax pointing forward;
- Y axis: Common axis perpendicular to Z and X axes, pointing upward.

SCAPULA

- Origin: Located in the acromial angle;
- Z axis: Line connecting trigonum spinae scapulae to acromial angle, pointing laterally;
- X axis: Perpendicular line to the plane formed by scapular inferior angle, acromial angle and connecting trigonum spinae scapulae, pointing forward;
- Y axis: Common perpendicular line to Z and X axes point upward.

GLENOHUMERAL (SHOULDER)

This standard describes the humeral movement in relation to thorax. ISB standard proposes two JCS methods for this joint. Here only the more accurate is presented.

- Origin: Glenohumeral center (GH);
- Y axis: Line connecting the GH and the midpoint between the two epicondyles (EL and EM);
- Z axis: Perpendicular line to the plane formed between the Y axis from shoulder and the elbow Y axis (described on section 0) pointing to the right;
- X axis: Common perpendicular line to Y and Z axes, pointing forward.

ELBOW (FOREARM RELATIVE TO HUMERUS)

The ISB standard for the elbow also include the radio ulnar JCS and movements, however since it is not possible to differentiate with the markerless technique, these description will not be included here. So only the elbow complex JCS and forearm movements in relation to humerus will be described.

- Origin: Located at the caudal medial point coincident with ulnar styloid;
- Y axis: Line connecting ulnar styloid and the midpoint between lateral and medial epicondyle;
- X axis: Perpendicular line to the plane of ulnar styloid and radial styloid and the midpoint of lateral and medial epicondyle, pointing forward;
- Z axis: Common perpendicular line to Y and X axes pointing to the right.

WRIST

To describe the global wrist motion the movement of second or third metacarpal in relation to radius is the ISB typically reference. The ISB standard also describes the movements that occur between the carpal and phalanges bones in relation to each other. However, since these joints are not included in the markerless skeleton tracking of Kinect it will not be presented here. However some studies has being focusing on hand recognition for rehabilitation proposes [4, 5]. It is suggested that they also perform a translation of ISB to unify their language as well.

- Origin: Midway between base and head of 3th metacarpal;
- Y axis: The parallel line to the line which connects the center of distal head of metacarpal to the midpoint of its base;
- X axis: The line which together with Y axis will form a sagittal plane that splits the metacarpal into mirror images;
- Z axis: Common perpendicular axis to Y and X.

Ankle

The ankle joint complex is composed of two synergic joints: Talocrural and Subtalar which connect the leg bones (Tibia and Fibula) to the Talus and the Talus with the foot bone, the Calcaneus, respectively. Spite of the fact that for a complete standard measure these two joints should be evaluated separately, during dynamic activities, such as walk and running, and the landmarks accessed for external measure only enable the categorization of this complex as one functional joint. Due this fact the standardization was performed for the ankle complex which include the movement integrate of this two joints together. The ISB standard suggests the development for these two joints separately later.

- Z axis: The line connecting medial and lateral malleolus pointing to the right. This axis is fixed to tibia and fibula;
- Y axis: The line of tibia and fibula long axis in neutral configuration pointing cranially;
- X axis: The common axis perpendicular to Z and Y axis.

Knee

The Knee JCS statement was performed before the ISB standard and worked as inspiration for its development. However since it was not based on the framework the axes direction pattern publish there was different. However to not promote confusion here the axes will be changed to be equivalent to the standard. In the knee JCS statement, Y is pointing forward, Z upward and X laterally. The equivalence will be made changing Y for Z position, Z for X position and X to Y position. Being Y', X' and Z' the adapted axes we can resume: X' = Y; Y' = Z; Z' = X.

- X' axis: Common perpendicular line to femoral longitudinal axis (femoral head to the midpoint between lateral and medial condyle) and the line connecting posterior surface of these femoral condyles.
- Y' axis: Line connecting the midpoint between the two intercondylar eminences and ankle center;
- Z' axis: Common perpendicular line between X' and Y'.

Hip

According with the function that is being performed the hip movement mechanics vary. Due this fact there is different reference system for this joint including different anatomical landmarks and reference axes. However it is recognized that due the difference of inside movement and external movement, none of the references represents the optimal description for this joint. This way, the standard developed by ISB described this joint choosing the easily accessible landmarks from palpation or from estimation methods.

- Z axis: The line parallel to a line connecting the right and left anterior superior iliac spine, pointing to the right;
- Y axis: The line joining the midpoint between the medial and lateral femoral epicondyles and the center of rotation (Origin) pointing cranially;

- X axis: Common perpendicular axis to Z and X.

Spine

Differently from all described joints, the spine is composed of several subsequent intervertebral joints which together enable the trunk movements. The spine is composed of 24 vertebrae from which 7 are cervical, 12 thoracic and 5 lumbar. These bones are connected through the intervertebral joint which is composed of an intervertebral disc and two zygoapophyseal joints.

Additional joints are presented on the spine connecting it with the other body parts. The first cervical vertebra articulates with the occipital bone, the thoracic vertebrae connect with the ribs in both sides and the last lumbar vertebra articulates with the sacrum.

The ISB standard is described concerning the intervertebral motion. However the principles of this joint can be extended to regional and overall spinal motion. Due the pattern of motion that occurs between two consecutives vertebrae, which is dependent on the combination of applied forces, and since no fixed axis exist, ISB standards determines that it is only possible to define an instantaneous axis of rotation.

- Z axis: Position in the proximal vertebra it is represented by the parallel line connecting two similar landmarks on the basis of right and left pedicles pointing to right;
- Y axis: The line crossing the center of distal vertebra pointing cranially;
- X axis: The perpendicular axis to both, Z and Y axes.

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APPENDIX B:

MOVEMENT ANALYSIS LIBRARY FUNCTIONS

Movement recognition library: functions and their respective actions.

Function	Action
Methods for both movement recognition techniques	
unsigned int load(string path)	Load the configuration files
float getCurrentState()	Get the actual movement status (angle or checkpoint)
int getMax()	Return the maximum angle performed or the total status for checkpoints
int getMin()	Return the minimum angle performed
Methods exclusive for biomechanical movement recognition	
int updateBiomechanicAnalysis (jointsVectorArray allJoints, jointsArray joints, bool outOfCheckpoint)	Integrate the methods that should be called at each frame: computePosturalAnalysis(), computeActualElbowStraight(), and computeActualHeadStraight()
int getAngleMax(int goalIndex)	Get the maximum angle set on the configuration file
int getAngleMin(int goalIndex)	Get the minimum angle set on the configuration file
int getPosturalAngle()	Get the actual angle of trunk posture
float posturalErrorStatistic()	Compute the postural error statistics (% error)
void writeReport()	Write the report with the movement analysis
int getMainMovementPlane()	Get the main movement plane configured to be used
int getMainMovementVector()	Get the main movement segment
int getActualMainMovementAngle ();	Get the main movement angle
void setMainMovement (int vectorOfMovement, int plane, int planeMTM);	Set main movement choice to overwrite the default configuration
void setPosturalRange (int toleranceAngle);	Set the postural range to overwrite the default configuration
void setElbowMinAngle (int toleranceAngle);	Set the elbow minimum angle required to overwrite the default configuration
void setHeadMinAngle (int toleranceAngle);	Set the head minimum angle required to overwrite the default configuration
void setOpenArmOrLegTolerance (int toleranceAngle);	Set functions to overwrite the configuration made by the file when required by system
Methods exclusive for checkpoints technique	
int exportCheckpoints (string path)	Export the checkpoints to a file
int addCheckpoint()	Add a checkpoint, register it
void setRange (int joint, float range)	Set the movement tolerance for the checkpoint
void setIsTracked (int joint, bool isTracked)	Set the segment which will be considered on the checkpoint for analysis
Methods for sensor and skeleton information recovery	
void getJointsVectorsInBodyCoord (jointsVectorArray data[10], int *size)	Return the body segments vectors in their respective joint coordinate system
void getJoints (jointsArray data[10], int *size)	Return the array with joints points
void getRGBResolution (int *width, int *height)	Return the width and height of RGB image
void getDepthResolution (int *width, int *height)	Return the width and height of depth image
int update()	Update RGB, depth and skeleton information

POINT * getSkelInScreenCoord (int width, int height)	Return the screen X and Y coordinate of each joint
bool isTracked()	Check if any user is being tracked
BYTE* getRGB()	Return array with actual RGB frame pixels
USHORT* getDepthMap()	Return array with actual depth frame pixels
USHORT depthPixelToDepth (USHORT packedPixel)	Extract de depth absolute value of a depth pixel
USHORT depthPixelToPlayerIndex (USHORT packedPixel)	Extract information if the depth pixel belongs to any user
void depthPixelToRGB (USHORT *depthArray, LONG *colorArray)	Return the correspondent RGB pixel of a depth poin.
void setTilt (int angle)	Set sensor inclination

APPENDIX C: CONFIGURATION FILE

```
# CONFIGURATION FILE:
# Name of report file (without space):
reports/test
# Type the plane movement tolerance margin. How far from the plane the segment can go? (in degrees)
20
# Type the maximum angle required for interaction (in degrees):
90
# Type the minimum angle required for interaction (in degrees):
10
# Type the postural tolerance (degrees value which will you allow patient to tilt laterally)
8
# Type the elbow minimum angle required (in degrees). If none control is need please type 0.
0
# Type the head allowed inclination (in degrees) – For scapular girdle exercises. – If none control is need please type 360.
360
# Type the arm or thigh opening allowed during axial rotations (in degrees) – Indicate: 10 to 30 degrees.
30
# Choose the number of biomechanical movements which will be evaluated during use of system (Aim number):
3
# Type one segment and ne plane for each aim. The first aim typed will be the one used for interactive system. The additional aims will be evaluated on report together with the interaction one. Help is provided at the end of the file with the segments and plane option.
# Aim 1:
# Segment:
arm_right
# Plane
Frontal
# Aim 2:
# Segment:
arm_right
# Plane
Sagittal
# Aim 1:
# Segment:
arm_right
# Plane
Horizontal

### Segments options: ###
# clavicle_right / clavicle_left / arm_right / arm_left / forearm_right / forearm_left / hand_right / hand_left
# neck / thoracic_spine / lumbar_spine
# pelvis_right / pelivis_left / thigh_right / thigh_left / leg_right / leg_left / foot_right / foot_left

### Planes options: ###
# frontal / sagital / horizontal / axialrotation
```