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INTERACTIVE THERAPEUTIC SYSTEMS FOR FALL PREVENTION USING COMPUTER VISION TECHNOLOGIES

Ines Ayed

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Doctor by Universitat de les Illes Balears and Ecole Supérieure des Communications de Tunis

To my family . . .

Declaration

I, Ines AYED, declare that this thesis titled, "**INTERACTIVE THERAPEUTIC SYSTEMS FOR FALL PREVENTION USING COMPUTER VISION TECHNOLOGIES**" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed: Ines AYED
Umeå, November 2019.

Dr. Antoni Jaume-i-Capó of the University of Balearic Islands and Prof. Adel Ghazel of the Higher School of Communications of Tunis, declare that the thesis titled "**INTERACTIVE THERAPEUTIC SYSTEMS FOR FALL PREVENTION USING COMPUTER VISION TECHNOLOGIES**", presented by Ines AYED to obtain a doctoral degree, has been completed under our supervision and meets the requirements to opt for Dual degree (Cotutelle) Doctorate.
For all intents and purposes, we hereby sign this document.

Signed: Dr. Antoni Jaume-i-Capó
Palma, November 2019.

Signed: Prof. Adel Ghazel
Tunis, November 2019.

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For my family, THANK YOU!

Abstract

In late years, vision-based technologies gained much interest among researchers and healthcare practitioners. For instance, the use of low cost and interactive devices such as Microsoft Kinect became increasingly popular in rehabilitation and physical therapy contexts. Much of this interest has been directed toward elderly population since they are more prone to loss of balance and falls that induce in its turn substantial social and healthcare costs. However, the use of these technologies without previous validation may not be considered safe and effective for this particular category since most of the applications in the market are not primarily designed for them.

Therefore, this thesis aims to propose and validate interactive systems based on computer vision technologies for improving balance and preventing falls among elderly people.

At the beginning, we conduct an extensive systematic literature review about vision-based serious games and virtual reality systems used for motor rehabilitation. The search is based on Kitchenham guidelines and answers defined research questions in an effort to properly cover the main features of this field. As a result, we provide the main figures, trends, technologies, and target groups, among other details addressed by researchers. Additionally, we propose a research methodology to assist engineers in the design and report of their clinical studies since these aspects were disregarded in many research studies.

Next, we design and develop a set of prototype games for balance rehabilitation. To achieve that, we follow specific framework and design features that deal with the development of serious games for rehabilitation. Moreover, we closely collaborate with physiotherapists along our work process regarding the multidisciplinary nature of this field. To objectively evaluate the feasibility and effectiveness of our games, we conduct a case study where two older women undergo a 5-week intervention program in a Tunisian elderly house. Results are promising suggesting that game-based rehabilitation can be useful for improving balance in elderly people and can be incorporated in a fall prevention program.

At the end, we develop a system for measuring the Functional Reach Test (FRT); one of the most used clinical tools to assess the balance of older adults. In fact, it is recommended to assess the capabilities of the user or measure the outcomes of a therapy using reliable clinical tests to properly select or adapt a therapy. For that purpose, we conduct two experiments to

validate the use of Microsoft Kinect for measuring the FRT. We compare the FRT measures computed by our system using Kinect with those obtained by the standard method i.e. manually. Findings suggest that Microsoft Kinect is reliable and adequate to calculate this balance test.

Resumen

En los últimos años, las tecnologías basadas en la visión han ganado mucho interés entre los investigadores y los profesionales de la salud. Por ejemplo, el uso de dispositivos interactivos y de bajo coste como Microsoft Kinect se ha hecho cada vez más popular en contextos de rehabilitación y terapia física. Gran parte de este interés se ha dirigido a la población de edad avanzada, ya que son más propensos a perder el equilibrio y caer, lo que a su vez provoca grandes costes sociales y de salud. Sin embargo, el uso de estas tecnologías sin una validación previa puede no considerarse seguro y efectivo para estas personas, ya que la mayoría de las aplicaciones disponibles en el mercado no están diseñadas ellas.

Por lo tanto, esta tesis pretende proponer y validar sistemas interactivos que usan tecnologías basadas en la visión para mejorar el equilibrio y prevenir caídas entre las personas mayores.

Al principio, realizamos una extensa revisión sistemática de la literatura sobre juegos serios y sistemas de realidad virtual basados en la visión y utilizados para la rehabilitación motora. La búsqueda se basa en las pautas de Kitchenham y responde a preguntas de investigación bien definidas para cubrir adecuadamente las características principales de este campo. Como resultado, proporcionamos las principales cifras, tendencias, tecnologías y participantes, entre otros detalles que los investigadores han abordado. Adicionalmente, proponemos una metodología de investigación para asistir a los ingenieros en el diseño y la presentación de sus estudios clínicos ya que estos aspectos no se han tenido en cuenta en muchos estudios de investigación.

A continuación, diseñamos y desarrollamos un conjunto de prototipos de juegos para la rehabilitación del equilibrio. Para lograrlo, seguimos características de diseño específicas que se ocupan del desarrollo de juegos serios para la rehabilitación. Además, colaboramos estrechamente con fisioterapeutas a lo largo de nuestro proceso de trabajo con respecto a la naturaleza multidisciplinaria de este campo. Para evaluar objetivamente la viabilidad y la eficacia de nuestros juegos, realizamos un estudio de un caso en el que dos mujeres mayores se someten a un programa de intervención de 5 semanas en una casa de ancianos en Túnez. Los resultados son prometedores, lo que sugiere que la rehabilitación basada en juegos serios

puede ser útil para mejorar el equilibrio en personas mayores y puede incorporarse a un programa de prevención de caídas.

Finalmente, desarrollamos un sistema para medir la prueba de alcance funcional (FRT); una de las herramientas clínicas más utilizadas para evaluar el equilibrio en adultos mayores. De hecho, se recomienda evaluar las capacidades del usuario o medir los resultados de una terapia utilizando pruebas clínicas confiables para seleccionar o adaptar adecuadamente una terapia. Para ello, realizamos dos experimentos para validar el uso del dispositivo Microsoft Kinect para medir el FRT. Comparamos las medidas de FRT calculadas por nuestro sistema utilizando Kinect con las obtenidas por el método estándar, es decir, manualmente. Los resultados preliminares sugieren que Microsoft Kinect es confiable y adecuado para calcular esta prueba de equilibrio.

Resum

En els darrers anys, les tecnologies basades en la visió per computador han obtingut un gran interès entre investigadors i professionals de la salut. Per exemple, l'ús de dispositius interactius i de baix cost com Microsoft Kinect es va fer cada vegada més popular en els contextos de rehabilitació i teràpia física. Gran part d'aquest interès s'ha dirigit a la població gran, ja que és més propensa a la pèrdua d'equilibri i de caigudes que generen importants costos socials i sanitaris. Tanmateix, l'ús d'aquestes tecnologies sense validació prèvia pot no ser considerat segur i eficaç per aquestes persones, ja que la majoria de les aplicacions que podem trobar al mercat no estan dissenyades pensant en elles.

Aquesta tesi pretén proposar i validar sistemes interactius que usen tecnologies basades en la visió per computador per millorar l'equilibri i prevenir caigudes entre persones grans.

Al principi, realitzem una extensa revisió sistemàtica de la literatura sobre jocs seriosos basats en la visió i sistemes de realitat virtual utilitzats per a la rehabilitació motora. La cerca es basa en les directrius de Kitchenham i en respostes a preguntes de recerca definides amb l'objectiu de cobrir adequadament les principals característiques d'aquest camp. Com a resultat, oferim les principals tendències, tecnologies i grups d'orientació, entre altres detalls tractats pels investigadors. A més, proposem una metodologia de recerca per ajudar els enginyers en el disseny i l'informe dels seus estudis clínics, ja que aquests aspectes no es van tenir en compte en moltes investigacions estudis.

A continuació, dissenyem i desenvolupem un conjunt de prototipus de jocs per a la rehabilitació de l'equilibri. Per aconseguir-ho, seguim característiques específiques del marc i del disseny que tracten el desenvolupament de jocs seriosos per a la rehabilitació. A més, al llarg del nostre procés de treball col·laborem estretament amb fisioterapeutes destacant el caràcter multidisciplinari d'aquest camp. Per avaluar objectivament la viabilitat i l'eficàcia dels nostres jocs, realitzem un estudi de casos en què dues dones grans passen per un programa d'intervenció de cinc setmanes en un centre per persones majors de Tunísia. Els resultats suggereixen que la rehabilitació basada en jocs pot ser útil per millorar l'equilibri en persones grans i es pot incorporar a un programa de prevenció de caigudes.

Finalment, desenvolupem un sistema per mesurar la prova d'abast funcional (FRT); una de les eines clíniques més utilitzades per avaluar l'equilibri dels adults majors. Es recomana

avaluar les capacitats de l'usuari o mesurar els resultats d'una teràpia mitjançant proves clíniques fiables per seleccionar o adaptar-la adequadament. Amb aquest objectiu, realitzem dos experiments per validar l'ús del dispositiu de captura Microsoft Kinect per mesurar el FRT. Comparem les mesures de FRT calculades pel nostre sistema utilitzant Kinect amb les obtingudes pel mètode estàndard, és a dir, manualment. Els resultats suggereixen que Microsoft Kinect és fiable i adequat per calcular aquesta prova d'equilibri.

Résumé

Ces dernières années, les technologies basées sur la vision ont suscité un vif intérêt chez les chercheurs et les praticiens de la santé. Par exemple, l'utilisation d'appareils peu coûteux et interactifs tels que Microsoft Kinect est devenue de plus en plus populaire dans les contextes de rééducation et de thérapie physique. Une grande partie de cet intérêt a été dirigée vers les personnes âgées, car elles sont plus sujettes à des pertes d'équilibre et à des chutes qui entraînent à leur tour des coûts sociaux et de santé importants. Cependant, l'utilisation de ces technologies sans validation préalable peut ne pas être considérée comme sûre et efficace pour cette catégorie particulière, car la plupart des applications du marché ne sont pas conçues pour elle.

Par conséquent, cette thèse vise à proposer et à valider des systèmes interactifs basés sur la vision pour améliorer l'équilibre et prévenir les chutes chez les personnes âgées.

Au début, nous effectuons une revue systématique de la littérature sur les jeux sérieux et les systèmes de réalité virtuelle basés sur la vision et utilisés pour la réadaptation motrice. La recherche est basée sur les directives de Kitchenham et répond à des questions de recherche bien définies dans le but d'examiner correctement les principales caractéristiques de ce domaine. En conséquence, nous fournissons les principaux chiffres, tendances, technologies et groupes cibles, parmi d'autres détails abordés par les chercheurs. Aditionellement, nous proposons une méthodologie de recherche pour assister les ingénieurs dans la conception et le rapport de leurs études cliniques car ces aspects ont été négligés dans des nombreuses études de recherche.

Ensuite, nous concevons et développons un ensemble de jeux prototypes pour la réhabilitation de l'équilibre. Pour ce faire, nous suivons des règles et des concepts spécifiques qui traitent du développement de jeux sérieux de rééducation. De plus, nous collaborons étroitement avec les physiothérapeutes tout au long de notre processus de travail vu le caractère multidisciplinaire de ce domaine. Pour évaluer de manière objective la faisabilité et l'efficacité de nos jeux, nous avons mené une étude de cas dans laquelle deux femmes âgées participaient à un programme d'intervention de cinq semaines dans une maison de retraite tunisienne. Les résultats sont prometteurs, ce qui suggère que la rééducation basée

sur les jeux sérieux peut être utile pour améliorer l'équilibre des personnes âgées et peut être intégrée dans un programme de prévention des chutes.

À la fin, nous développons un système de mesure du test d'équilibibre le Functional Reach Test (FRT); il est l'un des outils cliniques les plus utilisés pour évaluer l'équilibre chez les personnes âgées. En fait, il est recommandé d'évaluer les capacités de l'utilisateur ou de mesurer les résultats d'une thérapie à l'aide de tests cliniques fiables pour sélectionner ou adapter correctement une thérapie. À cette fin, nous menons deux expériences pour valider l'utilisation de Microsoft Kinect pour la mesure du FRT. Nous comparons les mesures de FRT calculées par notre système à l'aide de Kinect avec celles obtenues par la méthode standard, c'est-à-dire manuellement. Les résultats suggèrent que Microsoft Kinect est fiable et adéquat pour calculer ce test d'équilibre.

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Publications in journals

1. Ayed, I., Alcover, B. M., Bueso, P. M., Varona, J., Ghazel, A., & i Capó, A. J. (2017). Validación de dispositivos RGBD para medir terapéuticamente el equilibrio: el test de alcance funcional con Microsoft Kinect. Revista Iberoamericana de Automática e Informática industrial, 14(1), 115-120. (JCR IF = 0.471)

   Contribution: Ines Ayed developed the system, participated in performing the experiments, and contributed in writing and revising the paper.

2. Ayed, I., Ghazel, A., Jaume-i-Capó, A., Moya-Alcover, G., Varona, J., & Martínez-Bueso, P. (2018). Feasibility of Kinect-Based Games for Balance Rehabilitation: A Case Study. Journal of healthcare engineering, 2018. (JCR IF = 1.261)

   Contribution: Ines Ayed participated in the design of the experiment, helped in recruiting the participants and conducting the experiment, and contributed in writing and revising the paper.

3. Ayed, I., Ghazel, A., Jaume-i-Capó, A., Moya-Alcover, G., Varona, J., & Martínez-Bueso, P. (2019). Vision-Based Serious Games and Virtual Reality Systems for Motor Rehabilitation: A Review Geared Toward a Research Methodology. International journal of medical informatics. (JCR IF = 2.957)

   Contribution: Ines Ayed participated in selecting the manuscripts, proposing the research methodology, and applying the Downs and Black checklist. She also contributed in writing and revising the article.

Publications in conferences

1. Ayed, I., Ghazel, A., Jaume-i-Capo, A., Moya-Alcover, B., Varona, J., & Martinez-Bueso, P. (2016, September). Fall prevention serious games for elderly people using RGBD devices. In 2016 8th International Conference on Games and Virtual Worlds for Serious Applications (VS-GAMES) (pp. 1-3). IEEE.

   Contribution: Ines Ayed participated in the design of games, was responsible for all the development of the games, and contributed in preparing and presenting the poster.

2. Ayed, I., Moyà-Alcover, B., Martínez-Bueso, P., Varona, J., Ghazel, A., Jaume-i-Capó, A., & López, F. J. P. (2016). RGBD-based Serious Games for Fall Prevention in Elderly People. Cognitive Area Networks, 1(3), 91.

   Contribution: Ines Ayed participated in the games' design, and contributed in writing and revising the paper as well.

3. Ayed, I., Moyà-Alcover, B., Martínez-Bueso, P., Varona, J., Ghazel, A., & Jaume-i-Capó, A. (2016, July). Balance Clinical Measurement Using RGBD Devices. In International Conference on Articulated Motion and Deformable Objects (pp. 125-134). Springer, Cham.

   Contribution: Ines Ayed participated in the system design, did all the development in this work. She also participated in writing the article and made its oral presentation.

4. Ayed, I., Alcover, G. M., Martínez-Bueso, P., Varona, J., Jaume-i-Capó, A., & Ghazel, A. (2016, September). Juegos serios para la prevención de caídas en personas mayores mediante el uso de dispositivos RGBD. In Proceedings of the XXVI Spanish Computer Graphics Conference (pp. 95-100). Eurographics Association.

   Contribution: Ines Ayed participated in the design process, did all the development in this work. Ines Ayed also participated in writing and revising the paper, and finally made the oral presentation of this article.

Other publications

1. Moyà-Alcover G., Ayed I., Varona J., Jaume-i-Capó A. (2019) RGB-D Interactive Systems on Serious Games for Motor Rehabilitation Therapy and Therapeutic Measurements. In: Rosin P., Lai YK., Shao L., Liu Y. (eds) RGB-D Image Analysis and Processing. Advances in Computer Vision and Pattern Recognition. Springer, Cham

   Contribution: Ines Ayed contributed in writing and revising the chapter.

2. Ayed I., Jaume-I-Capó A., Moya-Alcover B., Perales F.J. (2019). Vision based interaction game for revising the periodic table, EDULEARN19 Proceedings, pp. 9376-9382.

   Contribution: Ines Ayed developed the interactive game, contributed in writing the paper, and made the oral presentation of the work.

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- Ludi Play for Children with Disabilities training school "Play and Toys for All", Heerlen (NL), Apr.18th -21st, 2017.

List of acronyms

A-MMSE	Arabic-Mini Mental State Examination
ADL	Activities of Daily Living
COM	Center Of Mass
CP	Cerebral Palsy
CT	Controlled Trial
FRT	Functional Reach test
GresCom	Green & Smart Communication systems
HCI	Human-Computer Interaction
MDRT	Multi-Directional Reach Test
OT	Occupational Therapist
RGBD	Red Green Blue Depth
SDK	Software Development Kit
SLR	Systematic Literature Review
UCD	User-Centered Design
UCT	Uncontrolled Trial
UGIVIA	Computer Graphics, Vision, and Artificial Intelligence Group
VBI	Vision-Based Interaction
WHO	World Health Organization

Chapter 1

Introduction

1.1 Motivation

Back to 2014, I was awarded with a predoctoral scholarship to conduct a research work in The Computer Graphics, Vision, and Artificial Intelligence Group (UGIVIA) at University of Balearic Islands in Majorca. The group's research topics include serious games, Human-Computer Interaction (HCI), Virtual Reality (VR) and Augmented Reality (AR), Human motion analysis and synthesis, among others in the field of computer vision and computer graphics. The thesis proposal initially suggested studying noninvasive serious game for balance rehabilitation and objectively investigate the game's clinical usefulness to improve therapy. It was hypothesized that there would be a significant improvement in balance and gait function of adults with cerebral palsy (CP) upon receiving a rehabilitation intervention using an interactive system. In fact, a PhD thesis related to that topic was defended in 2016 [117]. The mentioned thesis work was considered our base point that we built upon it since the design and development of interactive serious games for rehabilitation have some features that are different from other types of games. In addition, the previous experience of the group members in earlier clinical studies helped in both designing and conducting the experiments to investigate the feasibility of the applications of this work and assess its effectiveness. Concurrently, I am enrolled at Higher School of Communications of Tunis where I belong to Green and smart communications systems lab (GresCom). Though the lab's main research areas do not include serious games and health-care applications, it was open for collaborations and possible extensions in that regard. Furthermore, Tunisia, comparing to other Arab countries, is having a transition in its population age structure where the percentage of elderly category is getting higher. As a consequence, the topic of this thesis started to make sense relating the serious games for rehabilitation and elderly people.

1.2 Context and problem statement

In late years, the use of vision-based systems has been extended to be deployed in rehabilitation and healthcare applications. As a matter of fact, these systems are based on video cameras where the body movements of the user can be tracked and his image can be captured and displayed on a screen, thus an interaction with the system can take place in a natural manner and without the need of body markers. This was possible thanks to the wide availability of low cost depth cameras that are efficient providing high resolution and good accuracy in tracking body movements [201].

In general, rehabilitation and healthcare systems and applications are mostly focused on elderly people since aging entails reduction in body muscles mass and frailty in bones, which makes this category more vulnerable to instability and falls. Falls in its turn induce high social and healthcare costs that burden both concerned individuals and society, besides to affecting the quality of life of the old person and his caregivers. In order to mitigate these negative consequences, the World Health Organization (WHO) Heidelberg Guidelines for Physical Activity for Older Persons recommended regular participation of elderly people in physical activity thanks to its acquired benefits on physiological, psychological, and social levels. In fact, exercising and performing physical activity on a regular basis help preventing and/or lowering the risk of falls whether in community or home settings [127]. Furthermore, obtaining clinical information about the user using balance clinical tests has been shown important to detect and measure the risk of falls degree and therefore customize the proposed rehabilitation program accordingly.

However, the repetition required by regular exercising makes the activities proposed in fall prevention programs boring. As a consequence, elderly people get demotivated and abandon the program and therefore the therapy benefits are lost. Several studies have demonstrated that serious games using vision-based systems for balance rehabilitation offer motivating and engaging experience for elderly population. As many elderly people may have difficulty in holding physical devices, free controller interaction offered by vision-based systems like Red, Green, Blue plus Depth (RGBD) devices is preferred. In fact, video games programs using vision-based systems have shown promising results in rehabilitation however more investigation is needed in this regard. In addition, displacement to get the therapy and/or to measure the clinical outcomes of the therapy taken supposes a difficulty for elderly individuals to access the therapy. Validating computer vision technologies for clinical tests for fall prevention is considered as an interesting topic that requires further investigation and experimentation. The same RGBD device could be then used by elderly people for a fall prevention program at home and used by the specialist as well to assess the effectiveness of the program. At the end, some steps are recommended to be followed to provide an effective therapy, these steps are indicated in Figure 1.1.

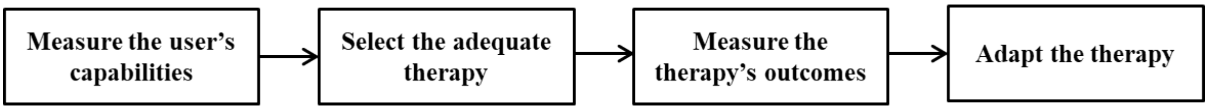


Fig. 1.1 Steps in a therapy.

1.3 Research objectives

In this work, we tried to cover the rehabilitation therapy and measurement phases an older adult could get through in a fall prevention program. To do so, we have collaborated with physiotherapists since this area requires interdisciplinary and mutual work involving both engineers and physiotherapists. With the aim to achieve the awaited results, we set the following objectives:

- Objective 1: Conduct a systematic literature review on vision-based serious games and virtual reality systems used for motor rehabilitation.

  A review of the current state of a research topic, also known as a systematic review [82], is a mechanism for identifying, evaluating and interpreting all relevant research available to a topic, a thematic area, or a phenomenon of interest. Before carrying out a systematic review, a need must be identified. In this work package, the most important activities will be (1) the definition of the specific questions of the research topic that the systematic review will treat and (2) the definition of the research protocol where the basic review procedures are defined. In order to carry out the review, the greatest number of related studies must be found using an impartial search strategy. In fact, the rigor of the research process is a factor that distinguishes the systematic reviews from traditional reviews. Once the research is complete, the selected studies are evaluated by their real relevance in order to identify the works that provide direct evidence about the research topic. To reduce the probability of bias, the selection criteria has to be decided during the definition of protocol. The final phase of the systematic review will involve writing the results of the review and its dissemination. Below are some of the main sub-goals:

  1. Definition of research questions
  2. Search of studies

3. Evaluation and analysis of the research studies included
4. Extraction of results and conclusions

- Objective 2: Objectively investigate the game's clinical usefulness to improve therapy by designing and developing serious games for balance rehabilitation for elderly people.

  Falls have a great impact on elderly people's life. The most important consequences include loss of autonomy and a high social-health expenditure as indicated earlier. Changes in movement patterns with age require a specific physiotherapy program to improve balance. Studies show that balance training is a good method for preventing falls among older people because balance deterioration experienced by this aging category is directly related to falls [42]. Serious games can be therefore used for balance rehabilitation. Sub-goals of this objective include:

  1. Design of noninvasive games for the prevention of falls in elderly people
  2. Design validation by therapists
  3. Improvement of the design of the games after validation
  4. Implementation and development of the games designed
  5. Design of the clinical study to be carried out

- Objective 3: Validate RGBD devices for a balance clinical measurement: the Functional Reach Test (FRT).

  For a treatment to be effective, it is necessary to measure its clinical outcomes using reliable and valid tests. There is a wide set of tools and tests that allow physiotherapists to measure the progress of a patient, but there are few mechanisms to evaluate the effectiveness of a rehabilitation treatment at home without the equipment and tools that can be found in hospitals or rehabilitation centers [49, 60, 61]. For this reason, although a patient performs the treatment for the prevention of falls at home through interactive games, in the end, the patient is required to visit every now and then a physiotherapist, or vice versa, in order to measure his therapeutic evolution and adjust the therapy accordingly. The current lines of research go in the direction of studying the validity of the different human motion capture sensors that exist in the market to perform therapeutic measures [53]. It is intended to validate the calculation of some of the tests that allow physiotherapists to measure the evolution of patients using existing capture devices, such as RGBD. Similarly to serious games in objective 2, sub-goals of this section include the follow:

1. Design of an interactive system for measuring the FRT
2. Implementation and development of the system
3. Validation

1.4 Methodology

To attain the objectives defined for our thesis project, we followed the following methodologies. On the one hand, we used Kitchenham guidelines for performing a Systematic Literature Reviews (SLR) in software engineering to properly evaluate and interpret all available research relevant to the research topic and cover its main features and aspects. On the other hand, the processes of design and development of noninvasive games follow the methodology of the User-Centered Design (UCD) and the norms ISO9241, parts 210 and 400. The UCD seeks, through iterations on a prototype (context analysis, identification of requirements, design of solutions, and evaluation), involving the user as soon as possible in the process and evaluating the usability and clinical validity of the system on multiple occasions until obtaining an effective end system that is efficient and satisfactory for the user within its use context. Therefore, the serious games for the prevention of falls and the system for therapeutic evaluation will be used as a framework to apply the development and evaluation of these scientific-technological methods. More specifically, the methodology will be based on experiments to measure the usability and clinical validity of the noninvasive games developed from the early stages. The experiments will be carried out according to the current methodology of the research area, the definition of experiments, the exposition of the research hypotheses, the collection of the data of the experiments, and the statistical analysis of the data to demonstrate the hypotheses carried out.

1.5 Contributions

The contributions of this thesis work can be summarized in three main points:

1. Systematic literature review: Through conducting a well defined search of research studies that examined the feasibility and effectiveness of vision-based serious games and virtual reality systems in motor rehabilitation, we were able to:
    - Provide a comprehensive summary of the state of the art in this area
    - Propose a research methodology that helps engineers better design and report their clinical trials in future works

2. Serious games for balance rehabilitation: Following the methodology described above, we were able to:
   - Design and develop a set of prototype games that contribute in minimizing the risk of falls among elderly people
   - Conduct a case study to investigate the feasibility and effectiveness of the developed serious games in a Tunisian elderly house using Microsoft Kinect
3. Validation of RGBD sensors for measuring the Functional Reach Test (FRT): Concerning balance assessment of older adults, we got to:
   - Design and develop a system for measuring the FRT using Microsoft Kinect
   - Validate this system with a sample of users

1.6 Thesis outline

The thesis is structured into three main chapters besides to Introduction (Chapter 1) and Conclusions (Chapter 5). The second chapter is dedicated to a systematic literature review about vision-based serious games and virtual reality systems used for motor rehabilitation. In this chapter, research questions were defined, included articles were assessed using Downs and Black checklist, and data were collected and analyzed. At the end, a research methodology was proposed to tackle the issues related to the design and report of clinical trials that engineers usually dismiss or forget to address. The third chapter discusses the design and development process that we followed to obtain a set of interactive prototype games for balance rehabilitation. A clinical case study to investigate the effectiveness of these games is conducted in a Tunisian elderly house where participants' recruitment, procedure, and main outcomes are also described. The chapter four aims to validate Microsoft Kinect for measuring the Functional Reach Test (FRT). The mentioned balance test and its corresponding developed system were first explained in the chapter and then the experiments done for validation were presented. Finally, it is worth noting that some of the chapters are based on published articles.

Chapter 2

Vision-based interactive systems for motor rehabilitation

"Indeed, one of my major complaints about the computer field is that whereas Newton could say, "If I have seen a little farther than others, it is because I have stood on the shoulders of giants," I am forced to say, "Today we stand on each others' feet." Perhaps the central problem we face in all of computer science is how we are to get to the situation where we build on top of the work of others rather than redoing so much of it in a trivially different way. Science is supposed to be cumulative, not almost endless duplication of the same kind of things"

Richard Hamming, 1968 Turning Award Lecture

Vision-Based Interaction sensors (VBI) [182] can visually capture information on the performance of users' actions. Different studies have validated their effectiveness in rehabilitation purposes such as postural control [37], clinical functional analysis and rehabilitation [19], gait retraining [36], activities of daily living rehabilitation [39], and coaching of elderly population [123].Visual information on the performance of patients' actions is the preferred data collection method for two reasons: first, because motor rehabilitation consists of body movements that can be recorded; and second, because vision capture technology is non-invasive and can be used by patients who have difficulty holding physical devices. VBI systems aim to provide reliable computer methods to detect and analyze human movements. As new vision based technologies emerged, diverse disciplines' interest in this area of research grew rapidly. This growth of interest has made the interpretation of results and the extraction of broader principles from existing work more challenging. One possible solution to this challenge is to adopt an evidence-based paradigm. To understand the role of evidence, we need to recognize that across diverse study disciplines, there is a common need for methods that allow objective and consistent aggregation of outcomes in multiple empirical studies [24]. In this context, evidence is defined as the synthesis of the best scientific studies on a specific topic or research question. The primary method of synthesis is a Systematic Literature Review (SLR) [81]. In contrast to an expert review based on ad hoc literature selection, an SLR is a methodologically rigorous review of research findings. The aim of an SLR is not merely to aggregate all available evidence on a research question but to also enable the development of evidence-based guidelines for practitioners.

Thus, in this chapter, we present an SLR of the current direction in the field of motor rehabilitation using vision-based serious games and virtual reality systems. Based on an overview of the existing scientific evidence, we discuss the main limitations, future directions, and the institutions and influential figures in this field. We present the related work in section 2.1. We describe our methodology in section 2.2 and results in section 2.3. In sections 2.4 and 2.5, we discuss our seven primary research questions and propose a research methodology for engineers. Our conclusions are presented in last section.

2.1 Previous reviews

In recent years, several reviews have been conducted regarding the use of virtual reality in motor rehabilitation. On the one hand, in 2004, Sveistrup et al. [176] reviewed virtual environments and virtual reality applications deployed for motor rehabilitation, comparing them to real-world applications. The review covered different virtual reality systems and illustrated their different uses such as intervention, assessment, and rehabilitation therapy by referring to some sample studies. However, no research protocol was applied in covering all related research studies. In 2007, Henderson et al. [65] studied the effectiveness of virtual reality on the functioning of upper limbs for stroke rehabilitation by distinguishing between immersive and non-immersive virtual reality. In the same way, Lohse et al. [94] solely studied stroke rehabilitation where they conducted a review and meta-analysis about the effectiveness of virtual reality when used on post-stroke adults and quantitatively studied the effectiveness of the virtual environment and commercial gaming interventions compared to control therapies. For the purpose of conducting a meta-analysis, only randomized controlled trials were used, and other study design types were excluded. Unlike Henderson et al. [65] and Lohse et al. [94] who focused only on stroke patients, Rahman et al. [139] studied the effectiveness of virtual reality on motor rehabilitation in patients with neurological disorders other than stroke including cerebral palsy. Though these studies reported positive or no improvements following the use of virtual reality, they were all cautious when drawing a definite conclusion about the impact of virtual reality on motor rehabilitation due to the wide variability and small sample sizes of the studies.

On the other hand, Hondori et al. [116] explored the use of Kinect in motor rehabilitation by classifying the studies into three main areas: accuracy and reliability of Kinect, its use in rehabilitation with clinical validation, and its use in rehabilitation without clinical validation. Moreover, Webster et al. [193] reviewed the use of Kinect in elderly care including fall detection and fall risk reduction, in addition to stroke rehabilitation using Kinect's accuracy evaluation and Kinect's applications. Likewise, Da Gama et al. [41] divided the use of Kinect in rehabilitation into five subsections namely assistive systems for rehabilitation, evaluation, applicability, validation of Kinect anatomic and clinical evaluation, and improvement techniques. Though these studies were not restricted in terms of pathology or target group, research was narrowed down to the study of one technology called Microsoft Kinect. Finally, Rego et al. [144] addressed through a survey, a serious game design for rehabilitation and proposed a taxonomy to adequately distinguish and compare serious games for rehabilitation systems based on their fundamental characteristics, seeing as serious games are increasingly being deployed in rehabilitation.

In this chapter, we reviewed the use of vision-based serious games and virtual reality systems in clinical interventions for motor rehabilitation. Unlike Sveistrup et al. [176], we followed a rigorous research methodology using the Kitchenham guidelines [81] to conduct the review and the White and Black checklist to assess the quality of the studies used. In addition, restrictions were neither applied in terms of the study design as indicated in [94], nor in target population such as limiting the search to stroke, cerebral palsy, or elderly people [94, 139, 193]. In spite of this, patients suffering from stroke or cerebral palsy, and elderly people made up the largest target groups and due to their functional capabilities, rehabilitation programs were not exclusively addressed to them. We sought to comprehensively show possible trends and limitations by eliminating these restrictions. Our choice to focus on vision-based serious games and virtual reality systems was justified by the fact that visions based serious games and virtual reality systems produce promising results and are becoming more robust and efficient. Additionally, they offer important benefits over other systems, are free controllers which could be a great option for patients that have difficulty holding devices, and offer intuitive interaction with real time feedback and affordable prices. Furthermore, they are easy to use and apply since they do not need complicated settings or calibrations and do not experience drift or occlusion.

2.2 Systematic literature review methodology

An SLR was conducted based on the guidelines proposed by Kitchenham [81]. These guidelines have been adapted to adequately address software engineering research problems; they are based on existing guidelines used in medical research, books of authors having social science backgrounds, and discussions held with researchers of other disciplines. For a fair evaluation of a research topic, a rigorous methodology is followed where a review is planned, conducted, and reported. The goal of this review is to articulate themes from existing scientific evidence and to address their main limitations. A detailed protocol of the SLR can be found in Appendix A.

2.2.1 Research Questions

This study addressed the following research questions:

- RQ1: Has the number of investigations increased over the years?
- RQ2: Who are the investigators directing the research?
- RQ3: Who are the main target participants of the therapy?
- RQ4: What are the most repetitive tasks used in therapy in the different experiments?
- RQ5: What are the top technologies and frameworks used in the interventions?
- RQ6: What are the most common measurements used for assessment?
- RQ7: What are the important features in this area?

In RQ1, we address the recent growth in interest for this area of investigation. In RQ2, we identify key institutions and groups of researchers involved in the research. In RQ3, we specify which category of patients the research studies are focusing on. In RQ4 and RQ5, we mention the most repetitive tasks and list the top technologies utilized in the different experiments. In RQ6, we provide the most common measurements used to assess the effects of the therapy suggested. Eventually, in RQ7, we develop a simple research methodology spotting the most important features in this area of research. Our final goal is to make some unified and general recommendations addressed specifically for engineers.

2.2.2 Search Process

The search process was performed by querying the *Web of Science* electronic database, because it is the citation indexing service for references on databases that reference cross-disciplinary research, and *Medline (PubMed)* because it is the citation indexing service for reference on databases regarding life sciences and biomedical information. To ensure we did not overlook any important material, we conducted secondary searches based on references and citations found in our primary search results. We also checked the first author's publications for related or recent works.

2.2.3 Search Terms

The keywords selected for the search were "serious games," "motor rehabilitation," "Kinect," "vision-based," and "virtual reality." The string search wording used was "(serious games OR virtual reality) AND (Kinect OR vision based) AND motor rehabilitation." Moreover, we classified the keywords of the papers that we used most frequently as new search terms. All the research studies were extracted by one researcher and then reviewed by another.

2.2.4 Contingency bias

We assessed the studies' quality using the Downs and Black checklist [47]. This scale assesses both randomized and non-randomized studies. It contains 27 items that assess the quality of reporting (10 items), internal quality (13 items), external quality (3 items), and validity and power (1 item). Since this research area is relatively new, many studies did not include many participants. For this reason, we customized the checklist in order to do not exclude any study for quality reasons. Therefore, we modified the power item 27 by assigning 1 point to the studies that used more than one group for the experiments and 0 points to studies with only one group or where we were unable to determine the number of groups. At the end, the total score for every study was out of 28 instead of 32.

2.2.5 Inclusion Criteria

Studies were selected if they involved a clinical study where at least one VBI system was used for motor rehabilitation as a primary focus. Moreover, they needed to directly answer one or more of our research questions. Further, selected studies had to have been published on or after the year 2007. A previous review [201] covered studies published before 2007; vision-based system technology and techniques were described and their strengths and weaknesses were presented along with their existing or potential applications for rehabilitation. The study by Zhou et al. [201] was our starting point as the authors summarized human motion tracking systems used for rehabilitation with a particular focus on markerless visual systems owing to their positive features such as reduced restriction, robust performance, and low cost.

2.2.6 Exclusion Criteria

We excluded articles if they were primarily intended for cognitive rehabilitation, presented a simple comparison between different technologies for rehabilitation with no use of clinical experiments, or did not use VBI technology. For feasibility reasons, studies in languages other than English and studies whose corresponding abstract or full article was not found were excluded as well. When the same research article was published in more than one journal or conference, the most comprehensive version was used. However, in case the two articles used different measurements for the same experiment we kept both of them since they answered one of our research questions differently.

2.2.7 Data Collection

The data extracted from each study included the following:

1. Source (journal or conference) and full reference
2. Year in which the paper was published
3. Institutions and countries represented by the authors
4. Summary of the study, including the key research questions and conclusions
5. Quality evaluation
6. Therapy exercises and technologies utilized in the therapy
7. Measurements used to assess the effects of the therapy

2.2.8 Data Analysis

Data were tabulated to present the basic information for each study. Tables were checked to answer the research questions and to identify any interesting trends or limitations in the investigation related to vision-based serious games and virtual reality systems used for motor rehabilitation:

- RQ1: We analysed the number of articles published every year since 2007 to observe whether this number has been increasing over time
- RQ2: We explored the specific organizations and authors that carried out investigations with large number of studies
- RQ3: We specified the different categories of participants in the experiments according to pathology and age
- RQ4: We focused on the treatments that the participants received in order to identify the most repetitive tasks
- RQ5: We listed the top technologies utilized in the different interventions
- RQ6: We determined the most common measurements used to assess the effects of each intervention
- RQ7: We studied the main features of an intervention to provide a simple research methodology specifically addressed for engineers

2.3 Results

2.3.1 Search Result

The first selection based on keywords yielded a pool of 184 papers. We refined our selection by examining both the abstract and title initially, and later by reading the full text. Consequently, the number of selected articles decreased to 55. We conducted a second search based on the most frequent keywords obtained from the primary studies already selected. Additionally, we examined their citations and references. We then added 31 articles, obtaining a final set of 86 papers. These papers are summarized in Appendix A. Figure 2.1 summarizes the study selection procedure.

2.3.2 Data Source

Around 80% of the selected papers were published in journals indexed by Journal Citation Reports (JCR), which demonstrates the scientific community's growing interest in this topic. Table 2.1 lists the first 15 journals and conferences in which the selected papers were published.

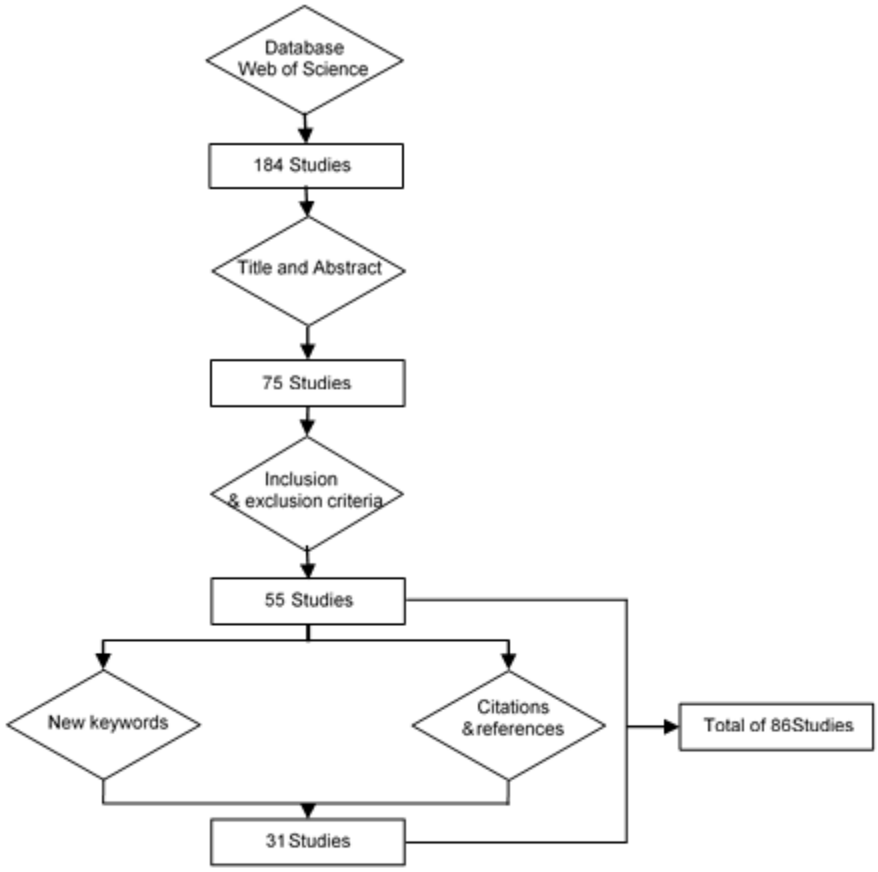


Fig. 2.1 Research process.

2.3.3 Quality Assessment

The average rating for the quality of selected studies using the Downs and Black checklist was 13.44 (maximum scale value = 28), with 46.51% of the papers yielding a score that was equal or higher than 14 (see Appendix A). Although the study's aim and the intervention procedure were well described in most of the studies, some of the studies' main findings were poorly described [44, 29, 133, 96, 68, 17, 88, 173], while others failed to use standard and valid outcome measures [175, 44, 104, 132, 54, 181, 29, 58, 91, 31, 140, 135, 154, 92, 145]. Additionally, as this field of research is relatively new, many studies' study subjects' recruitment (source population, number of participants that were asked to participate and accepted, and time of recruitment among others), randomization procedures, assignment concealment and blinding; especially given that it is very difficult to blind the patients in this kind of interventions; were done poorly. Therefore, we recommend that the researchers read the Downs and Black checklist before starting their clinical studies.

Table 2.1 Publication sources of our included studies.

Journals and conferences	Number of papers
Journal of physical therapy science	5
Journal of neuroengineering and rehabilitation	5
American journal of physical medicine & rehabilitation	4
Games for health journal	4
Journal of neurologic physical therapy	3
IEEE Transactions on neural systems and rehabilitation engineering	3
Research in developmental disabilities	3
Cyberpsychology & Behavior	2
Developmental neurorehabilitation	2
BMC Neurology	2
European journal of physical and rehabilitation medicine	2
2009 Virtual rehabilitation international conference	3
Neurorehabilitation	2
Pediatric physical therapy	2
Stroke	2

2.3.4 Data collected

We summarized the data collected in tables for a better visualization and understanding of the findings. Five tables (Table 2.2 - Table 2.6) were then generated according to the main tasks addressed in the research studies. Another table (Table 2.7) was made to show the most used measurements in these studies. We believe that these data are important in the discussion of the next sections so we included them here instead of putting them as an appendix.

Table 2.2 Balance

Technology	Pathology	Study (first author, ref)	Type	Age group	Type of games	Therapy exercises
Microsoft Kinect	Stroke	Singh et al. [168]	CT	Elderly	Commercial	- Whole body coordination - Whole body movement (body sideways or up/down) - Upper or lower limbs movements - Reaching (laterally, away from the centre of gravity) - Leaning sideways - Bending
		Song et al. [16]	RCT	Mixed	Commercial	
		Llorens et al. [93]	UCT	Mixed	Prototype	
		Lee et al. [87]	RCT	Mixed	Commercial	
	Parkinson	Galna et al. [54]	UCT	Elderly	Prototype	
		Pompeu et al. [137]	UCT	Elderly	Commercial	
		Shih et al.[163]	RCT	Elderly	Prototype	
		Nuic et al. [122]	UCT	Elderly	Prototype	

Table 2.2 continued from previous page

	CP	Jaume Capo et al. [73]	UCT	Adults	Prototype	
		Luna-Oliva et al. [101]	UCT	Children	Commercial	
		Pavao et al. [134]	UCT	Children	Prototype	
		Camara et al. [25]	UCT	Children	Commercial	- Stepping (lateral steps, duck step to the right or left, alternating steps without going forward) - Weight shifting - One-leg standing - Squatting (squats and side-lunges, and gallops) - Jumping - Stretching - Crouching - Running on the spot - Trunk movements (forward, backward, left and right, lateral
		Jung et al. [75]	UCT	Children	Commercial	
	MS	Ortiz Gutierrez et al. [128]	CT	Adults	Commercial	
		Lozano-Quilis et al. [100]	RCT	Adults	Prototype	
	Degenerative Ataxia	Ilg et al. [68]	UCT	Children	Commercial	
	MLD	Ulasli et al.[184]	UCT	Adults	Commercial	
	PSP	Seamon et al.[159]	UCT	Elderly	Commercial	
	Previously injured athletes	Vernadakis et al. [189]	RCT	Adults	Commercial	
	Healthy	Ofli et al. [125]	UCT	Elderly	Prototype	
		Sato et al. [156]	RCT	Elderly	Prototype	
		Bronner et al. [23]	UCT	Adults	Commercial	
		Karahan et al. [77]	RCT	Elderly	Commercial	
		Bacha et al. [11]	RCT	Elderly	Commercial	
	Fibrimiyalogia	Collado et al. [40]	RCT	Mixed	Prototype	
	TBI	Ustinova et al. [185]	UCT	Adults	Prototype	
Gesture Tek IREX	Stroke	McEwen et al. [109]	RCT	Elderly	Commercial	
		Kim et al. [80]	RCT	Mixed	Commercial	
	CP	Brien & Sveistrup [22]	UCT	Children	Commercial	
	Healthy	Bisson et al. [17]	UCT	Elderly	Commercial	
	Dementia	McEwen et al. [108]	UCT	Elderly	Commercial	
PrimeSense	Stroke	Bower et al. [21]	RCT	Elderly	Prototype	
Webcam	CP	Bilde et al. [15]	UCT	Children	Prototype	
EyeToy	Stroke	Flynn et al. [51]	UCT	Elderly	Commercial	
		Rand et al. [141]	UCT	Elderly	Commercial	

Table 2.2 continued from previous page

	Diabetes	Lee and Song [90]	RCT	Elderly	Commercial	
		Lee and Shin [89]	RCT	Elderly	Commercial	

CP: Cerebral Palsy; MS: Multiple Sclerosis; MLD: Metachromatic leukodystrophy; TBI: Traumatic Brain Injury; Progressive Supranuclear Palsy: PSP; UCT: Uncontrolled trial (without a control group); CT: Controlled trial (with a control group); RCT: Randomized Controlled Trial; Mixed: adults+ elderly.

Table 2.3 Upper Extremities

Technology	**Pathology**	**Study (first author, ref)**	**Type**	**Age group**	**Type of games**	**Therapy exercises**
Microsoft Kinect	Motor impairment	Chang et al. [29]	UCT	Children	Prototype	- Lifting both arms in different directions - Reaching, punching and swinging with upper extremities - Stepping, kicking, and weight shifting of the lower extremitie -Waving, hitting - Shoulder flexion, extension, abduction, adduction, external rotation, and internal rotation - Flexing fingers - Elbow flexion and extension - Forearm supination and pronation - Wrist flexion and extension - Grasp ad release - Affected arm abduction, adduction, elevation, and depression, with power gripping -Fine and gross elbow, shoulder and arms movements - Increasing the range of the affected upper limb and hand separation movements
	Stroke	Pastor et al. [133]	UCT	Adults	Prototype	
		Rand et al. [140]	RCT	Mixed	Commercial	
		Hoda et al. [67]	CT	Elderly	Prototype	
		Turkbey et al. [183]	RCT	Mixed	Commercial	
		Sin and Lee. [167]	RCT	Elderly	Commercial	
		Bao et al. [13]	UCT	Elderly	Commercial	
		Chen et al. [30]	UCT	Elderly	Prototype	
		Aşkın et al. [9]	RCT	Mixed	Prototype	
		Adams et al. [4]	UCT	Mixed	Commercial	
	Healthy	Ren et al. [145]	RCT	Adults	Prototype	
	CP	Zocolillo et al. [202]	RCT	Children	Commercial	
		Sevick et al. [160]	UCT	Children	Commercial	
		Ni et al. [121]	UCT	Children	Prototype	
	DCD	Gonsalves et al.[55]	CT	Children	Commercial	
GestureTek IREX	Stroke	Lee [88]	UCT	Elderly	Commercial	
		Kwon et al. [83]	RCT	Mixed	Commercial	
		Cho et al. [33]	RCT	Elderly	Commercial	
	CP	Guberek et al. [58]	UCT	Children	Commercial	
	Brain tumor	Yoon et al. [198]	RCT	Adults	Commercial	
Optotrak	stroke	Subramanian et al. [173]	RCT	Elderly	Commercial	

Table 2.3 continued from previous page

EyeToy	Stroke	Peters et al. [135]	RCT	Elderly	Commercial	
		Yavuzer et al. [196]	RCT	Elderly	Commercial	
		Rand et al. [142] (Kinect)	RCT	Elderly	Commercial	
	CP	Sandlund et al. [154]	UCT	Children	Commercial	
		Chen et al. [32]	UCT	Children	Commercial + protototype	
		Jannink et al. [71]	RCT	Children	Commercial	
RGS	Stroke	Cameirao et al. [26]	RCT	Mixed	Prototype	- Balance and coordination movement by both hands -Full forehand/backhand strokes - Fine manual dexterity
		Cameirao et al. [27]	RCT	Elderly	Prototype	
PrimeSense	Stroke	Shin et al. [164]	RCT	Mixed	Prototype	
		Shin et al. [165]	RCT	Adults	Prototype	
GTP	Stroke	Sucar et al. [175]	UCT	Mixed	Prototype	
		Sucar et al. [174]	RCT	Adults	Prototype	
Leap motion controller	Parkinson	Oña et al. [126]	UCT	Mixed	Prototype	
	Stroke	Vanbellingen et al. [187]	UCT	Mixed	Commercial	
		Wang et al. [191]	RCT	Mixed	Commercial	
		Iosa et al. [69]	UCT	Elderly	Prototype	

RGS: Rehabilitation Gaming System; GTP: Gesture Therapy platform; HMD: Head Mounted Display; CP: Cerebral Palsy; DCD: Developmental Coordination Disorder; UCT: Uncontrolled trial (without a control group); CT: Controlled trial (with a control group); RCT: Randomized Controlled Trial; Mixed: adults + elderly.

Table 2.4 Lower extremities

Technology	**Pathology**	**Source**	**Type**	**Age group**	**Type of games**	**Therapy exercises**
Microsoft Kinect	Parkinson	Palacios-Navarro et al. [130]	UCT	Elderly	Prototype	- Lateral leg movements - Stepping, kicking, and weight shifting - Reaching, punching, and swinging
	CP	Ni et al. [121]	UCT	Children	Prototype	
	Stroke	Park et al. [131]	RCT	Mixed	Commercial	
EyeToy	Stroke	Peters et al. [135]	RCT	Elderly	Commercial	

CP: Cerebral Palsy; UCT: Uncontrolled trial (without a control group); RCT: Randomized Controlled Trial.

Table 2.5 Physical fitness and muscle strength

Technology	Pathology	Source	Type	Age group	Type of games	Therapy exercises
Microsoft Kinect	With disabilities	Chen et al. [31]	CT	Elderly	Commercial	- Using all body parts - Gross movements of the upper extremities and changes in trunk movements
	Healthy	Kim et al. [79]	RCT	Elderly	Commercial	
	Stroke	Lee [86]	RCT	Elderly	Commercial	
GestureTek IREX	IDD	Lotan et al. [96] (EyeToy)	RCT	Mixed	Commercial	- Stepping and feet lifting - Leg standing with hip and knee flexion - Weight shifting
		Lotan et al. [97]	RCT	Adults	Commercial	
EyeToy	CP	Sandlund et al. [155]	UCT	Children	Commercial	
Webcam	Development disabilities	Lin and Chang [92]	UCT	Children	Revised and remixed game	

IDD: Intellectual and Developmental Disabilities; CP: Cerebral Palsy; UCT: Uncontrolled trial (without a control group); CT: Controlled trial (with a control group); RCT: Randomized Controlled Trial; Mixed: adults + elderly.

Table 2.6 Sight movement coordination and visual perception

Technology	Pathology	Source	Type	Age group	Type of games	Therapy exercises
Gesture Tek IREX	Stroke	Cho et al. [33]	RCT	Elderly	Commercial	- Upper extremity function and visual perception - Improving timing accuracy - Fine and gross motor skills
- EyeToy - Kinect	DCD	Straker et al. [172]	RCT	Children	Commercial	
EyeToy	DCD	Ashkenazi et al. [8]	UCT	Children	Commercial	
Webcam	CP	Manresa-Yee et al. [104]	UCT	Children + adults	Prototype	- Upper and lower limb movements - Head movements - Flexion–extension and diagonal neck movements

CP: Cerebral Palsy; DCD: Developmental Coordination Disorder; UCT: Uncontrolled trial (without a control group); CT: Controlled trial (with a control group); RCT: Randomized Controlled Trial.

Table 2.7 Measurements

Outcome measure	**Type**	**General use**	**Tasks**	**N**	**References**
FMA	standard	evaluation of upper limb motor function	- Balance - Upper extremities	18	[133] [88] [173] [51] [167] [26] [27] [174] [13] [83] [30] [164] [198] [165] [9] [4] [131] [187]
BBS	standard	static and dynamic balance	- Balance - Upper extremities	16	[184] [51] [159] [73] [93] [80] [100] [185] [89] [156] [163] [125] [77] [87] [131] [23]
TUG	standard	time it takes a subject to stand up from an armchair, walk a distance of 3 m, turn, walk back to the chair, and sit down	- Balance	14	[108] [51] [159] [100] [89] [168] [163] [16] [40] [77] [87] [131] [75] [109]
FRT, modified FRT	standard	reaching	- Balance - Upper extremities	10	[51] [73] [185] [156] [21] [40] [160] [142] [87] [89]
Number of correct movements	not standard	counting number of movements done correctly by the user	-Balance - Upper extremities - Physical fitness	7	[29] [140] [175] [141] [137] [92] [160]
x-MWT	standard	assess walking speed in meters per second over a short distance	- Balance - Sight movement coordination - Lower extremities - Physical fitness	18	[22] [184] [51] [137] [168] [21] [8] [15] [159] [101] [80] [100] [40] [130] [109] [108] [155] [131]
BI	standard	overall independence in activities of daily living	- Upper extremities - Balance	8	[88] [168] [71] [27] [83] [198] [165] [87]
FIM	standard	physical and cognitive disability: focuses on the burden of care	- Balance - Upper extremities - Physical fitness	7	[184] [86] [26] [196] [30] [21] [183]
BBT	standard	manual dexterity	-Upper extremities	8	[27] [30] [83] [183] [167] [142] [126] [87]
Adverse effects	not standard	undesired harmful effect	- Balance - Upper extremities	13	[165] [137] [54] [21] [183] [87] [122] [9] [4] [25] [187] [191] [69]

N: Number of papers that used the mentioned outcome measure; FMA: Fugl-Meyer Assessment; BBS : Berg Balance Scale; TUG: Time Up and Go Test; FRT: Functional Reach Test; NCM: Number of correct movements; x-MWT: x-Minute Walking Test; BI: Barthel index; FIM: Functional Independence Measure; BBT: Box and Block Test; AE: Adverse effects.

2.3.5 Trends

Figure 2.2 shows an increasing number of studies in this area between 2007 and 2018, with maximum publications in 2014 and 2015.

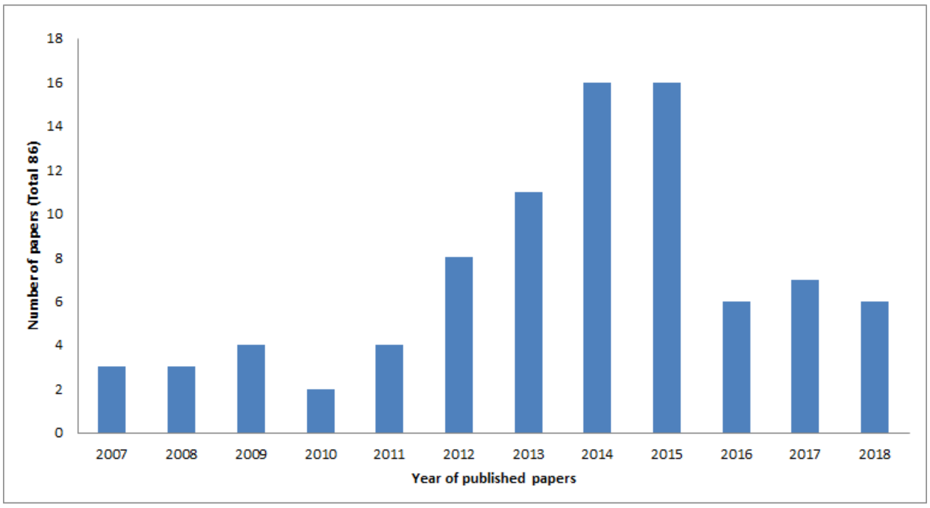


Fig. 2.2 Number of papers according to the time they were published.

In addition, as depicted in Figure 2.3, the majority of the selected studies were carried out mainly in Asia (36%), Europe (31%), and North America (24%), with Korea (15 studies) and USA (14 studies) in the lead, followed by Spain, Canada, and Taiwan respectively.

2.3.6 Target population

To identify the target population of the studies selected, we examined the profile of the participants in terms of pathologies and age categories. Motor impairments were secondary effects of diseases and accidents such as stroke, Parkinson's disease, cerebral palsy, and multiple sclerosis among others. As illustrated in Figure 2.4, 42% of the studies used stroke patients as study subjects, 20% focused on individuals with cerebral palsy, and 7% recruited participants with Parkinson's disease. Moreover, more than 50% of the studies recruited elderly participants while 24% of the studies had children participating. We considered participants who were less than 18 years old to be children, participants aged more than 55

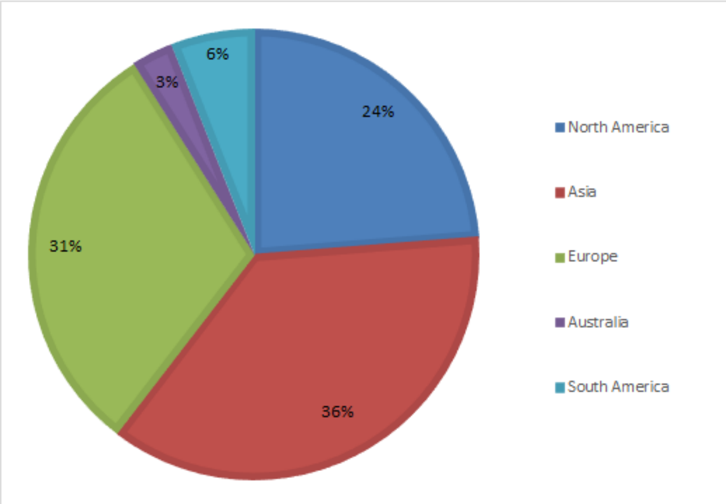


Fig. 2.3 Number of publications per continent.

years to be elderly, and those whose ages were between 18 and 55 to be adults (see Table 2.2-Table 2.6 for more detailed data).

2.3.7 Tasks

To get a clearer idea of the data gathered in terms of tasks provided, we categorized the studies into five categories according to their finalities; (1) balance (N=37), (2) upper extremities rehabilitation (N=37), (3) lower extremities rehabilitation (N=4), (4) physical fitness and muscle strength (N=7), and (5) sight movement coordination and visual perception (N=4). Many researchers addressed the general balance and postural control of participants. Games involved tasks that challenged balance like reaching in different directions, leaning sideways, lateral weight shifting, and stepping among others (see Table 2.2 for more detailed data). However, the studies more focused on rehabilitation exercises for upper extremities (shoulder, arm, elbow, hand, and wrist), participants performed movements such as abduction, adduction, arm extension and flexion, and lifting arms in different directions, in addition to exercises for impaired upper extremity, hand movement, grasp and release, waving, and hitting (see Table 2.3 for more detailed data). Other games provided exercises for trunk and lower extremities as they required stepping, weight shifting, and knee flexion movements (see Table 2.4 for more detailed data). Improving physical fitness and muscle strength was the aim of studies which promoted whole body movements, stepping, and feet lifting (see Table 2.5 for more detailed data). At the end, arm and leg coordination, eye–hand coordination, and improving accuracy of movements, were included in the main tasks and aimed at improving sight movement coordination and visual perception as shown in Table 2.6. All these tasks and

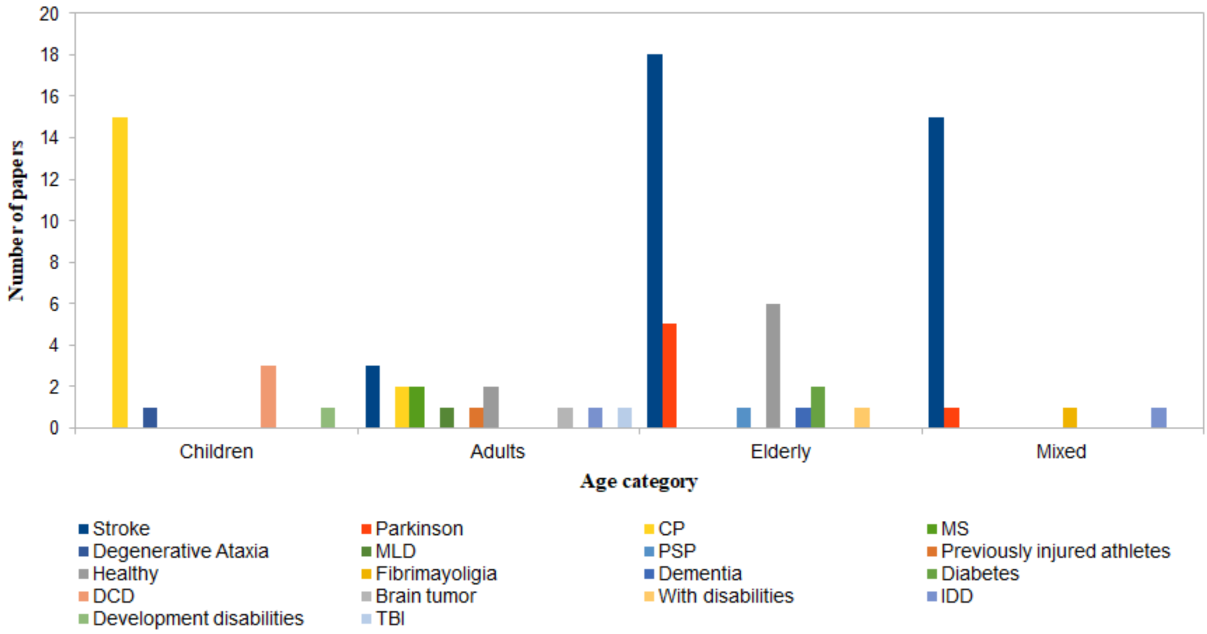
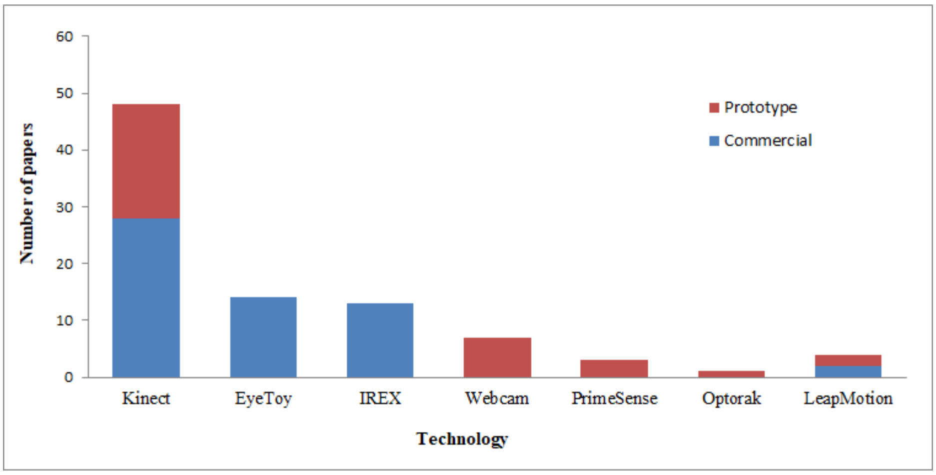


Fig. 2.4 Number of studies in function of target population.

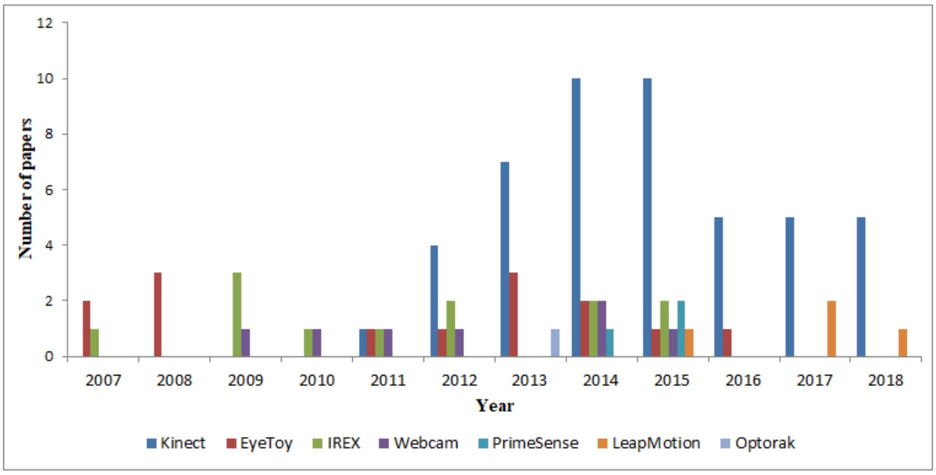
activities were elaborated in a fun and encouraging environment where motivation was a priority.

2.3.8 Technologies

We were exclusively interested in vision-based technologies; however, several interfaces were deployed. Over the last five years, there has been an increase in the use of Kinect^{TM} for rehabilitation programs. Figure 2.5 shows that out of 86 studies, 48 used Kinect^{TM} as a tool for motor rehabilitation; 58% of them chose to work with commercial games while the other 42% preferred developed games and systems based on Kinect^{TM} such as Biotrak [93] and RemoviEm [100]. Concurrently, EyeToy^{TM} system and GestureTek IREX^{TM} have been used widely. Commercial EyeToy^{TM} games were carefully chosen to meet the requirements of the therapy and promote rehabilitation programs. GestureTek IREX^{TM} is specifically customized for rehabilitation: its activities are tailored to provide an immersive virtual reality environment for patients with physical and cognitive disabilities. Some studies introduced new vision-based systems for rehabilitation like Gesture Therapy System [174, 175] and Rehabilitation Gaming System [26, 27] that used the webcam. Unfortunately, some of these systems and games were poorly described. A good description of the system functionalities and characteristics is necessary to advance in this field of knowledge.



(a)

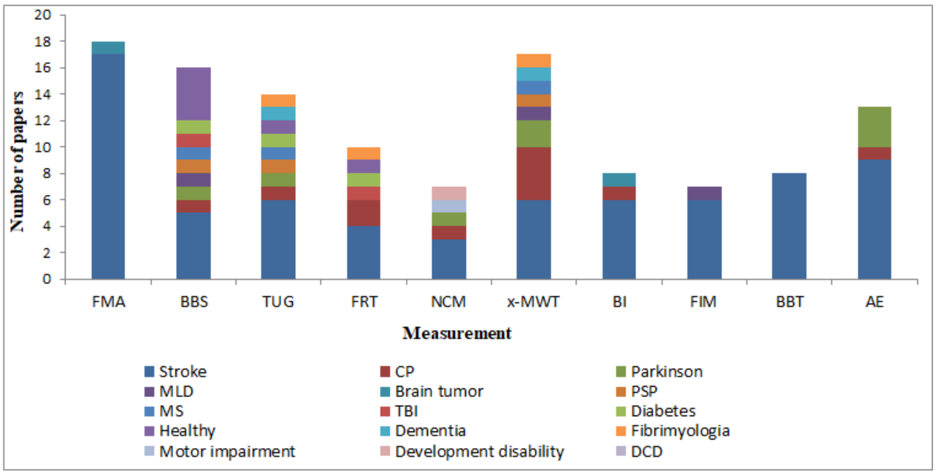


(b)

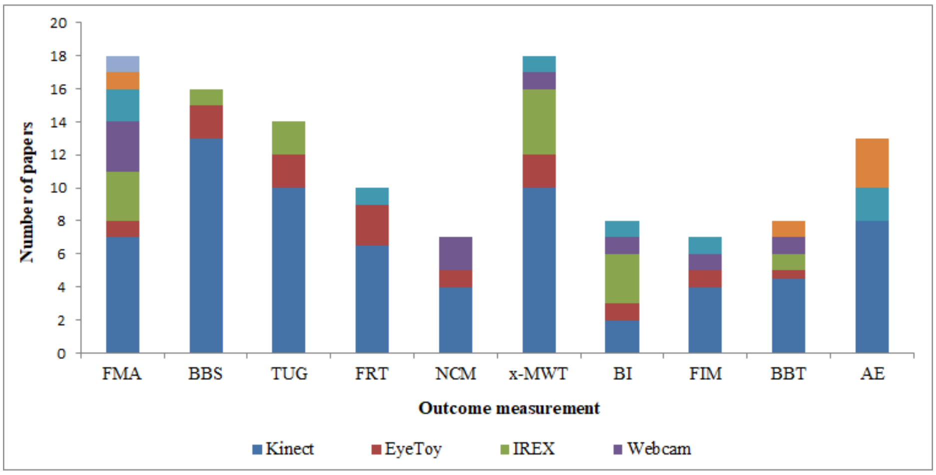
Fig. 2.5 Technologies used in treatment: (a) Type of games for each technology and (b) Technologies per year.

2.3.9 Measurements

Around 180 different measurements have been used in the selected studies to detect the effects of the therapies suggested. Nevertheless, the number of studies jointly using standard measurements is relatively small. Most of the study results were reported using different clinical tests like Fugl-Meyer Assessment, Berg Balance Scale, Time Up and Go Test, and Functional Reach Test, among others. Other measurements related to kinematics parameters were registered during the playing of games in order to quantify the user's movements like movement time, movement length, and velocity. User game performance was also used frequently. Generally, the user's performance improved with game practice, but it was not clear if this was a result of the game's effect or the effect of learning. Finally, in order to apply the participants' feedback to the system used for therapy, subjective questionnaires and usability surveys were administered. These questionnaires sought to determine the level of satisfaction, fatigue, enjoyment and interest in the game, and motivation. Figure 2.6 illustrates the 10 most used measurements in the articles reviewed.



(a)



(b)

Fig. 2.6 Top 10 outcome measurements used in selected studies: (a) Measurements per pathology and (b) Measurements per technology.

2.4 Discussion

In recent years, vision-based serious games and virtual reality systems have been increasingly used for motor rehabilitation and improvement of functional abilities. Users can interact intuitively with vision-based serious games and virtual reality systems by means of body gestures and movements and need not to place any markers on their bodies or hold any device. This natural interaction facilitates their engagement in the task being performed and increases their motivation and interest in the activity. VBI systems also offer real time feedback that can be adapted to users' needs and capabilities. In the beginning, the cost was a significant challenge but nowadays it is affordable and effective for rehabilitation use.

The growth of the research community's interest in studying the effects of vision-based serious games and virtual reality systems in motor rehabilitation can be seen in both the total number of investigations (RQ1) and continents represented (RQ2). As it is a multidisciplinary research area, both engineers and clinicians should be involved. However, we perceived that many articles focused on the clinical part and neglected the technological one or on the contrary, resulting in works of lesser quality. Teams of engineers, clinicians, ergonomics and human factors experts, and psychologists could tackle the different challenges raised in the development of vision-based serious games and virtual reality systems in motor rehabilitation.

As shown in Figure 2.2, the number of studies has increased since 2007, which can be related to the advent of Kinect^{TM} by late 2010. Since 2016, there has been a decrease in the number of studies which can be attributed to the discontinuation of the Microsoft Kinect^{TM} device in 2015 and the shutdown of the original OpenNI project in 2013, this can also be noted in Figure 2.5b where the number of Kinect based studies has decreased after 2015. In fact, among the top three tools for low-cost virtual reality mentioned by Tanaka et al. [178] in their comparison study of exergaming interfaces for use in rehabilitation programs and research, Kinect^{TM} comes first providing the most natural human computer interaction method. In addition to its low cost, it is a free-controller and easy to access and to develop. Ultimately, we believe that this area will continue growing thanks to the competitive features of low cost of depth cameras and the reported promising results for healthcare applications in spite of some current limitations that they have such as minimum distance required between the user and the sensor for optimal tracking, occlusion by body parts, and data acquirement conditions like lightening, etc. Though Kinect^{TM} is no longer in sale, we want to remark that nowadays different companies offer different depth devices (Intel^{TM}, Orbbec^{TM}, Fujitsu^{TM}, and Apple^{TM} among others).

In addition, the distribution of studies per continent shown in Figure 2.3 could be a reflection of the demographic change of the countries where the majority of the selected studies were carried out. For instance, the growth of an aging population has necessitated more research on health-care issues related to the elderly population which is the main target group, because this population faces a greater risk of suffering motor impairment and significant negative consequences for their quality of life and that of those who care for them. This, in addition, poses a risk for the sustainability of the health systems and quality assistance. Early detection of the risks associated with aging and treatment using Information and Communications technology (ICT) approaches may allow earlier intervention in order to alleviate their negative consequences [20, 107]. Furthermore, subjects that have suffered a stroke or cerebral palsy were the main focus of research as illustrated by RQ3. In fact, several reviews exclusively investigated the effectiveness of virtual reality on stroke patients [65, 94] or stroke and cerebral palsy [139]. Furthermore, stroke studies among the elderly and adults are often randomized controlled trials, indicating a large number of users in this category. Most of the studies involving children are CP, where the number of patients is relatively smaller since the population suffering CP is small. Hence, most studies involving children apply uncontrolled trials (see Figure 2.4). In summary, it is easier to recruit patients among elderly people and adults who have suffered a stroke than it is to find big groups of children suffering from CP. Nevertheless, the number of participants in many studies was not representative of the population they were selected from or it was too small to draw reliable clinical conclusions. For example, some studies had only one or two participants [133, 29, 109, 184, 51, 134, 159]. Rahman et al. [139] mentioned that their comparison was, to a certain extent, biased because of heterogeneous studies and small sample populations. Moreover, almost half of the interventions did not include a control group to compare the results with the experimental group. In addition, Lohse et al. [94] expressed concerns about differences in the types of control therapy provided to control groups. Consequently, we suggest that researchers conduct power analyses and sample size planning which are necessary for determining the number of participants required to draw statistically relevant results before starting any clinical intervention and to provide an elaborate description of the study's subjects and the control therapy applied. In fact, the low average of study quality is partially attributable to the details provided by the authors [94].

In order to answer RQ4, we identified five main areas targeted by researchers, namely, (1) balance, (2) upper extremities rehabilitation, (3) lower extremities rehabilitation, (4) physical fitness and muscle strength, and (5) sight movement coordination and visual perception. Likewise, Sveistrup et al. [176] identified several subdomains tackled by researchers in relation to the application of virtual reality in motor rehabilitation such as transfer of training, balance and posture, locomotion, upper and lower extremities function, exercise and pain, access to rehabilitation, and assessment. The largest share of articles covered general balance and upper extremities rehabilitation. Correspondingly, stroke and cerebral palsy patients mainly experience loss of balance, lack postural control, and upper extremities dysfunctions. Nonetheless, the activities offered to participants were characterized according to similarity as games typically involve whole body movements. In addition, the duration of intervention was so varied making it difficult to draw any comparisons between studies.

To answer RQ5, we extracted the VBI system used when interacting with the game or the exercise used. We found that both prototype and commercial games were proposed and interfaced by motion detection sensors, namely, Kinect, EyeToy system, and GestureTek IREX. As shown in Figure 2.5, commercial games were more widely used than prototype games because Kinect, EyeToy system, and GestureTek IREX are commercial interfaces. However, as Kinect and PrimeSense APIs were open, prototype games were developed mainly for stroke, cerebral palsy, and Parkinson's disease. EyeToy is based on optical flow and its system is not open like Kinect and PrimeSense. For this reason, researchers had to use commercial games, or implement optical flow in webcams, for example, GestureTek IREX comes also with a set of commercial games, but the user needs to wear a glove that is less attractive than that of other systems like Kinect. That said, some of these systems and games were poorly described. A good description of the system functionalities and characteristics is necessary to advance in this field of knowledge. Hence, systems should be accessible and well described in order to reproduce the investigation. Rego et al. [144], for instance, discussed fundamental concepts for the development of serious games like interaction technology, number of players, progress monitoring, and performance feedback among others.

Table 2.7 showed the measurements that were most frequently used by researchers to assess their interventions. A wide variety of measurements have been used to cover different aspects of a clinical trial. However, many of these measures were not previously validated which made it difficult to compare studies' findings or to identify any differences in the users' feedback between interventions. Therefore, we recommend that authors use more standard measurements in their future works. As argued in [74] and [6], a therapy is selected and then transferred into a serious game or an interactive system. So if a selected therapy was evaluated by measures such as BBS, TUG, FRT, x-MWT, FIM, or BBT, which are the outcome measures mentioned in more than 50% of the articles where Kinect was used as a technology interface; then results show that Kinect would be the most suitable device to capture the therapy (see Figure 2.6). Finally, we think that the best way to transmit authentic user experience of the system and its effects is by using both clinical and subjective measurements, during and after gameplay. Moreover, we recommend listing the reasons behind the therapy turned to a vision based serious game or a virtual reality system, and its purpose to facilitate the reproduction of the therapy and the comparison with other studies.

2.5 Research methodology

Upon answering our research questions defined earlier, we found that the description of the reviewed interventions is very different. This big variation in reporting and description makes comparison between studies difficult. In science, it is important to compare new results with previous ones or facts in order to appropriately position the new research work. Thus, to help non-clinicians to better design and report their interventions, we propose a simple research methodology that highlights the major features characterizing this area (RQ7). The development of this research methodology was partially based on the Downs and Black checklist: we moved from the questions that yielded high scores to the ones that yielded low scores. We also inspired some elements from the answers of our research questions to finally adopt a bottom-up strategy as follows:

1. Aim of the study: describes the primary aims of the intervention and its hypothesis if it exists. The aim can be the assessment of the effects of an exercise or game on activities (such as balance, upper and lower extremities functioning, physical fitness and muscle strength, and sight and movement coordination), body functions (cardiopulmonary aptitude), and participation (quality of life), investigation of safety and feasibility of a new game or a system used, or examination of transfer of learning, among others. The aim of a study is usually described briefly at the beginning and recalled at the end of a research article.

2. Target population: describes the participants recruited through:

    - Pathology information (for example cerebral palsy, stroke (time since stroke), and Parkinson's disease among others)
    - Demographics (age, and sex among others)
    - Inclusion and exclusion criteria applied for selection
    - Total population that was asked to participate, the number that agreed to participate, and those that actually participated in the study, in addition to dropout rates and corresponding reasons for dropping out
    - History of participants related to the use of vision-based serious games and virtual reality systems, and the therapy they are undergoing during the intervention

    Such information may help in minimizing confounding factors hence reducing the bias of the intervention. Other details about target population can be added depending on the intervention and its context.

3. Select the therapy: As discussed in [6], an existing therapy that can be captured with vision-based interaction for the task selected is recommended.

    - Outcome measures to validate therapy: describes the assessments and compares them to the existing systems used, including both quantitative and qualitative measurements. It could be clinical tests, interviews, and questionnaires among others. Once we have a list of measurements that we can measure we should check our list with figures (Figures 2.6a and 2.6b) in order to compare the study with previous articles. This is a good way to select measurements whenever possible.
    - Technology: describes the system used (platform or interface) and the type of game and exercise played (commercial or prototype in our case). The system should be accessible and well described in order to reproduce the investigation.

    As we focused only on vision-based technology, the systems used mostly are EyeToy, Kinect^{TM}, and GestureTek IREX^{TM} but we should ensure that we identify previous similar measures that used similar technology if possible. It is also commendable to mention if some existing therapy exercises were transferred to a serious game, the body parts involved and the movements and gestures required to perform these exercises especially when it comes to working with participants with impairments.

4. Study design: describes the study design adopted for the experiment and how the participants are grouped. In this paper, we followed the study types used in the review of Van Diest et al. [186] due to its simplicity.

    - Uncontrolled Trial (UCT): without a control group
    - Controlled Trial (CT): with a control group
    - Randomized Controlled Trial (RCT): a controlled trial where participants were randomly assigned to an experimental group or a control group

    The study types that we used are not exclusive and other study designs can be adopted. Randomization, assignment concealment, and blindness procedures used should be stated for further clarification in the article. In such interventions, double blindness is not possible since the users are aware of the treatment they receive hence only the assessor could be blinded. Finally, in case with enough users; it is better to conduct an RCT.

5. Vision-based interaction features: describes some specificities related to vision based systems such as:

- Type of interaction: natural interaction between the users and the technology through intuitive actions: intuitive in the sense that no previous knowledge is required to figure out how to interact with the system, response is real time (robustness and efficiency), and feedback is availed (visual, auditory).
- Interface design: since most of the participants have some kind of disability or impairment, an inclusive design should be envisaged depending on the target population, and a friendly and attractive interface could boost the motivation of the user to try the system and perform the exercises
- Environmental factors: place of intervention, space, distance from the device/screen, lighting, indoors/outdoors, whether the participant plays alone or within a group, and accompanied or supervised, among others.
- Accessibility: cost, use/application (for example how easy it is to calibrate the system)

In VBI there is no contact with the interface by means of an interaction device of reference. The user, therefore, should always know when the interaction is taking place using visual and audio feedback. Then, the input device is the user's own body; therefore, it makes sense that feedback should be related to the body of the user. An extended feedback related to user body is mirror feedback: giving patients the possibility of seeing themselves on a screen means that they remain constantly conscious of the actions they perform relative to the video game [72]. This research methodology is explicitly intended to help engineers during the development of interventions and in the reporting process. We believe that it can be helpful in data extraction for literature reviews and meta-analysis. In conclusion, the most important recommendation is to compare new systems to the ones used in previous studies, at least using the same measurements.

2.6 Strengths and limitations

As discussed above, the current review has three main characteristics. First, the systematic review was performed using defined research questions according to the Kitchenham guidelines. Second, the assessment of the selected studies was done according to the Downs and Black checklist for both randomized and non-randomized studies. Third, a simple research methodology was proposed and addressed specifically for engineers. However, the review has several limitations. We exclusively used web of science and PubMed databases for the search process. We could have included other databases but we were content to use these two databases since they are the most important databases in the engineering and health fields. Some of the studies used may look duplicated since the intervention method used was the same although the measurements were different. Another possible limitation of this work is the poor quality of some of the selected studies since reporting of clinical trials is relatively new for non-clinicians like engineers and computer scientists who design and develop games and systems for rehabilitation. However, since our goal is to assist non-clinicians in improving the design and reporting of their clinical interventions and give them an idea of the existing studies, we did not exclude any paper for quality reasons.

2.7 Summary of the chapter

We conducted a systematic literature review of studies that conducted trials that examined the effects of vision-based serious games and virtual reality systems in motor rehabilitation between 2007 and 2018. We defined and answered several research questions to investigate the state of research in this area according to Kitchenham guidelines [81]. The evaluation of studies by means of the Downs and Black checklist [47] gave rise to a bunch of recommendations for engineers to use when conducting clinical trials. First of all, reading this checklist in order to get informed about several aspects related to health care interventions is preferable. A second suggestion would be preparing the power analysis and sample size planning necessary to get accurate and reliable results. It is also very important to provide a good description of the participants, the systems and games used, and the procedure followed during the intervention. We noted that the activities and exercises proposed in the different studies are comparable. Nevertheless the duration of intervention and its outcomes' measurements are unrelated making comparison between studies difficult. Providing a rigid framework with a specific duration and outcomes measurements may not be possible but having an overview of the studies already achieved would be beneficial. Moreover, the use of both clinical and subjective outcomes could help reflect the system's user experience and its effects after intervention. Eventually, to further help the engineers in designing and reporting their clinical studies, we proposed a research methodology that contains the main basic components of better developing and reporting interventions.

As indicated by the findings of this chapter, Microsoft Kinect™ is one of the most popular vision-based technologies used by researchers and clinicians in rehabilitation programs due to its natural user interface and its low cost. Though it is no longer in sale, it exists other similar RGBD sensors that have comparable features and capabilities ensuring continuous growth of this area of research and validity of the results already obtained using the Kinect sensor. Therefore, despite we were interested in vision-based technologies in general, we chose Kinect to study and develop interactive therapeutic systems for the fall prevention of elderly people. So in next two chapters, we are going to dive into the details of these systems: a set of serious games for balance rehabilitation (Chapter 3) and a system for measuring the balance (Chapter 4). Key features of both versions of Kinect sensor that we used in the development process besides to some preliminaries related to the main functions provided by our work environment namely Unity^{TM} engine can be found in Appendix B.

Chapter 3

Serious games for balance rehabilitation

“*We do not stop playing because we grow old, we grow old because we stop playing.*”

George Bernard Shaw (1856-1950) Irish Author & Playwright

There is no better way to exercise than to exercise while playing. We are used to see our grandparents or the elderly population in general walk, run, play Tai chi or table games, but not playing video-games. Of course, this depends a lot on social and cultural contexts among others. In Tunisia or Spain for example, it is not very common that older adults stand in front of a screen and hold a console to play a video-game whether for entertainment or for rehabilitation. However, in last years we started to see some changes in this regard where video-games are introduced in healthcare centers, homes, and elderly houses. In fact, the emergence of commercial low cost depth cameras and motion sensing interfaces lead to an increased popularity of games in rehabilitation.

Several research studies were conducted to examine the effectiveness of commercial games on motor rehabilitation; however some studies reported negative effects since these commercial games are primarily intended for entertainment and not rehabilitation. Hence, tailored exercises and games should be proposed based on the target group and the purpose from the therapy selected.

So in this chapter, we aim to propose prototype games primarily addressed to older adults for balance rehabilitation and determine its feasibility and effectiveness with individuals attending an elderly house. We first introduce the motivation behind the deployment of serious games in the context of balance rehabilitation for elderly people, and mention subsequently the related work already published. Next, we go through the design and development process that we followed during the elaboration of our prototype games. Finally, we describe the clinical case study that we have conducted to evaluate the feasibility and effectiveness of these games.

3.1 Serious games for balance rehabilitation of elderly

Elderly individuals are more prone to instability and falls. Balance rehabilitation programs are then important to minimize their risk of falls. Nowadays, the use of video games are becoming popular in such programs for older adults to enhance their balance and postural control abilities.

3.1.1 Falls among elderly people

Aging population is constantly increasing due to the increased life expectancy span; nevertheless, age advancing entails some challenges. In particular, falls are considered one of the main issues related to aging. More than a third of population aged 65 years and more are experiencing a fall at least one time a year [28, 63]. In fact, the fall rate increases, among older adults, with age advancing [153]. Furthermore, an elderly individual has more probability to fall in an institutional residency than an individual living in a community dwelling older people [153, 151]. These falls lead to serious social, health, and economic consequences. On one hand, it affects the quality of life of the elderly individuals and their caregivers. On the other hand, it induces substantial medical and health-care costs [171]. To mitigate these negative consequences, many researchers have identified that improving or maintaining the functional abilities of older adults helps in minimizing the risk of falls [43, 110]. As a matter of fact, most of the fall prevention programs include motor rehabilitation exercises. A fall prevention meta-analysis showed that exercise programs that challenged balance were associated with significant reductions in fall rates [162]. In addition, older adults are recommended by World Health Organization to participate regularly in physical activities because participation in such activities contributes in building well-established physiological, psychological, and social benefits. Regarding fall prevention, regular physical activity prevents or diminishes an older person's risk for falling in community and home settings [199, 120].

3.1.2 Balance and falls

Balance and postural control deficit has been identified as one of the main factors of falls [152]. However, maintaining balance is affected by the interaction of musculoskeletal and sensory systems. The musculoskeletal system includes bones, muscles, and joints that permit the support and movement of the body. The sensory system provides vestibular, somatosensory, and visual information that help in knowing the position of the body and its movement. Together with some neurological functions, the body is then able to do a movement, react to instability, and maintain its balance. Unfortunately, these systems and functions deteriorate gradually with natural ageing [95]. Thus, elderly people are more prone to falls than young adults. Rehabilitation programs for fall prevention are then focused on balance and postural control. In fact, balance training has been proven to minimize the risk of falls. In addition, balance has been measured in many tests to predict falls [95].

3.1.3 Serious games and elderly target group

Serious games are games that are primarily designed for a purpose different than pure entertainment; this could be military, education, or rehabilitation, etc. With respect to rehabilitation, several studies have been investigating their effectiveness and demonstrated that serious games could lead to effective and promising results [144]. Video games usually require cognitive and motor activity that makes the user immersed and focused in the game and forgets that he is undertaking a therapy [106, 148]. Besides, these games are motivating and offer an engaging and entertaining experience to the user. As a matter of fact, most of long-term rehabilitation programs include intensive and repetitive exercises, patients then get bored and unmotivated. Ultimately, they decide to abandon the therapy; and when they do, the benefits acquired along the program are subsequently lost. Thus, motivation is really important in such long term programs, especially with chronic patients, to maintain the effectiveness of the therapy. At the end, these games can be deployed in rehabilitation programs for prevention, treatment, or recovery.

Elderly population was the target of many studies that examined the games' effectiveness in balance training [119, 186, 64]. Though much more research in this area is needed, published findings show that video games can be remedies for minimizing risk of falls [34, 12]. In addition, vision-based systems are proven to be suitable for elderly people as they are motivating and noninvasive [106, 170, 110, 148]. While exist many vision-based interfaces, Microsoft Kinect gained much interest in rehabilitation in recent years by offering a natural human computer interaction [193].

3.1.4 Related work

Several researchers have investigated the feasibility of Kinect based games to improve balance and gait of elderly people by using commercial games [137, 159]. However, usability tests conducted in [84] show that some commercially available games are not suitable for therapeutic purposes and provide negative auditory and visual feedback during game tasks. Thus, many research studies proposed prototype games specified for rehabilitation and addressed to defined target groups. For instance, Ofli et al. [125] suggested a set of exercises which included activities of upper and lower extremities for the improvement of balance, flexibility, strength, and endurance of elderly; and deployed their exercice system for six independently living older adults *in their homes (without a physiotherapist supervision)* who reported a positive attitude for using similar systems for longer term in the future. In addition, Galna et al. [54] investigated the feasibility of a rehabilitation game for dynamic postural control of people with Parkinson's disease (PD). Nine participants with PD (aged 54-78 years) played the game for 30 minutes *in a controlled laboratory setting* where they took the role of a farmer in a tractor that picks fruits by reaching out while the tractor is moving, the tractor can be driven by stepping to avoid obstacles. Similarly, Nuic et al. [59] developed a game where participants collect coins and avoid obstacles in three different environments ('The Garden', 'The Mine', and 'The River') by performing large amplitude and fast movements of upper and lower extremities, pelvis, and trunk. With the aim to treat gait and balance disorders for patients with PD, acceptability and feasibility of the game were assessed with ten older adults *in the authors' institute* under the supervision of a physiotherapist. Positive results were reported including high satisfaction and motivation scores to use the game, improved performance, and increased game duration.

Although there is evidence that serious games improve balance of elderly people in general, there is a lack of evidence about their effects, under the supervision of physiotherapists, on institutionalized older adults and their deployment in elderly houses and institutions.

3.2 Design and development of serious games

As mentioned earlier, commercial video games are generally not suitable for rehabilitation due to a certain cognitive or physical limitation that patients usually endure. The design of serious games is then customized to the target users in order to ensure effective and safe serious games. Rego et al. [144] for instance addressed through a survey a serious game design for rehabilitation, and proposed a taxonomy to adequately distinguish and compare serious games for rehabilitation systems based on their fundamental characteristics such as application area, technology and game interfaces, adaptability, and game portability among others. For this reason, during the design and development of our prototype games, we followed specific framework and guidelines for developing rehabilitative games.

3.2.1 PROGame framework

Given the interdisciplinary nature of serious games development, authors of [6] proposed a framework for the development of serious games for motor rehabilitation therapy called PROGame framework. Their work was inspired by Scrum model for agile project management [138], and based on similarities between serious game development requirements and web application requirements [76], and similarities between serious game for motor rehabilitation implementation and the clinical trial involving new drugs [52].

PROGame framework is a two-dimensional iterative process flow that can handle the different system development tasks. The first dimension includes three main activities:

- Project initiation activity: It is an entry point of the project where context, operational objectives, and restrictions for the serious game are identified by engineers and physiotherapists together. It is composed of four main tasks: determining the need for a serious game, identifying stakeholders and user categories, underlying game functionality and constraints, and selecting the corresponding therapy, which results in a detailed specification of the game's requirements and constraints.

- Iterative flow: It contains four basic development activities; planning and control, modelling, construction, and evaluation.

  1. Planning and control activity aims to achieve incremental project management for the development of serious games by determining the tasks to perform and identifying the end products during the increment (planning), allocating the estimated effort for specific tasks across the planned schedule for building an increment (scheduling), and measuring the development process (tracking).
  2. Modeling activity permits the development of models that enable the development team of a better understanding of the requirements and design of the serious game. It consists of refining the functional requirements, designing the application contents and the graphical user interface, and identifying and designing the different functional components of the system.
  3. Construction activity consists in producing executable software units mirroring the conceived design. This activity includes the production and testing of the software units that are part of an increment. For agility purposes, it is important to note that the software units to be constructed are designed during the construction activity, rather than in the previous modeling activity. Ultimately, construction consists in selecting reusable components, constructing executable components, and testing executable components.

4. The final goal of the evaluation activity is to find and correct the errors of the serious game before making it available to the patients. It can be done by playing the game, while considering some key aspects such as possible and safe interaction, effective therapy, and engaging game.

- A final clinical study: The objective of a clinical study is quantifying the improvement of rehabilitation based on types of functional exercises. As mentioned previously, a successful clinical study requires a definition of the experiment, participants, and measurements that should be aligned with the final goals and type of the therapy suggested. Use of pre and post assessments, inclusion of a control group, and maximization of the number of measurements are important factors that boost the quality of the clinical study.

The second dimension of the framework deals with the incremental development. Three core phases of a clinical trial are supported within this dimension. These phases have been included as three different increments: interaction mechanism, interaction elements, and serious game; where interaction mechanism aims to design an interaction mechanism to capture the selected therapy while considering existing technology, and interaction elements are designed in a way that force the patients to perform the therapy correctly. While the aim of the final increment (serious game) is to design a serious game that encourages the patient to perform the therapy regularly.

Eventually, PROGame is a framework that provides a coherent and systematic method that helped us in the design and development of our prototype games for balance rehabilitation. An example of the project initiation activity from the first dimension applied to our games may be the following:

- Identify the need for a serious game: improve balance and minimize risk of falls among elderly people.

- Identify stakeholders and user categories: elderly people are the direct beneficiary of the games; their role is to play the game, engineers design and develop the game, physiotherapists validate and supervise the elderly while playing.

- Identify the game functionality and constraints: For example, balls fall randomly within the same plan of the user. To play the game, the user must move laterally to hit the ball with his head. The game has to include motivating features to induce the elderly to move and play the game.

- Select the therapy for the serious game: By trying to hit the ball, the older adult makes lateral steps, neck flexion and extension, and trunk movements as therapy exercises. The therapy selected is further discussed in next section.

3.2.2 Therapy suggested

As highlighted in the framework, it is very important to select the therapy desired to be a video game since the beginning. Identifying the tasks and benefits from the therapy helps in keeping the design and development process aligned with the ultimate goal of the therapy. So in order to provide effective serious games, we had meetings with the physiotherapist before starting the design process and we skimmed the literature to define the exercises that help in minimizing the falls' risk of elderly individuals.

We determined that regular participation in moderate physical activity as stepping was highlighted as a remedial for balance recovery and fall prevention [149, 102]. In fact, falls often occur when stepping in response to loss of balance since older adults fail to control lateral stability which is linked to lateral falls and risk of hip fracture [102, 147]. Besides, stepping reaction strategies vary between younger and older adults; elderly adults tend to perform crossover stepping that induces lateral instability associated with falls [114].

Likewise, reaching movements help to improve balance and postural control [73]. They also require the control of center of mass (COM) in interaction with the changing of base of support (BOS).

Furthermore, the evidence suggests that trunk muscles fulfill a critical role in the dynamic control of posture [45]. A link between trunk muscle function and physical function in older adults has been reported [66]. It is clear that these muscles are key components that contribute to functional stability [45]. Additionally, it is shown that trunk lateral movements in a seated position indicate mobility impairments in frail elderly individuals [70].

Therefore, the serious games developed for this study try to imitate exercises included in traditional physical therapy, such as reaching in different directions, small and large lateral steps, weight shifting to both sides, neck movements (flexion, extension, lateral flexion, and rotation), shoulder movements (flexion, extension, adduction and abduction), trunk movements (flexion, extension, lateral flexion, and rotation), knee movements (flexion and extension), and hip movements (flexion, extension, rotation, adduction and abduction) [120, 199].

3.2.3 Prototype games

After identifying the therapy, we designed and developed a set of games focusing on the physical rehabilitation of the balance and postural control of elderly people with the final aim to prevent or minimize their risk of falls. In the design process, we followed the requirements and indications from physiotherapists. Besides, we followed the PROGame framework [6] described above and adopted the guidelines for developing vision-based rehabilitative games [74] with the intention to offer engaging exercises that predispose motivation, feedback, and game monitoring. Safety of the games was also a crucial element, thus game parameters were configured to allow the physiotherapist to adapt the exercises for each user according to his needs and preferences. At the end, we obtained the following games:

1. Reach game: In this game, the users had to move their centre of mass (COM) in order to reach with their hands one of the five elements located on their user plan. Once the user touches an element, it disappears and reappears after a determined time set by the physiotherapist according to the user's speed (See Figure 3.1). Two symmetric items are added on the level of hips to induce weight shifting movements, however in the clinical trial that we conducted, these two items were deleted because the participants found it very difficult to reach them. To further adapt the games for the participants recruited, the elements selected were balls; they were re-sized and their colours were set to black and red over a simple white background. Data like user id, session date, play duration, and distance from the sensor were automatically recorded and saved in an excel document for any later check or use.

2. HitIt: In this game, soccer balls fall randomly within the same plan of the user. To hit them, the user needs to make lateral steps, and touch them with his head when they are at his level (see figure 3.2a). The use of any other part of the body, except the head, goes unperceived during the game play in order to induce the player to move laterally. The game can be also played in a seated position (see figure 3.2b). The user has to make lateral movements of the trunk to be able to touch the elements with his head.

3. WatchOut: Here also subjects have to move laterally in order to escape falling eggs. When the user hits the egg with his head, it explodes, however when it is touched by anyother body part, the egg remains intact. Falling items fall randomly within the same plan of the user with adaptable falling rate and speed (see Figure 3.3).

During the clinical case study, a background with a solid colour has been defined for all games to keep the user focused on the game. Finally, to better assimilate the design

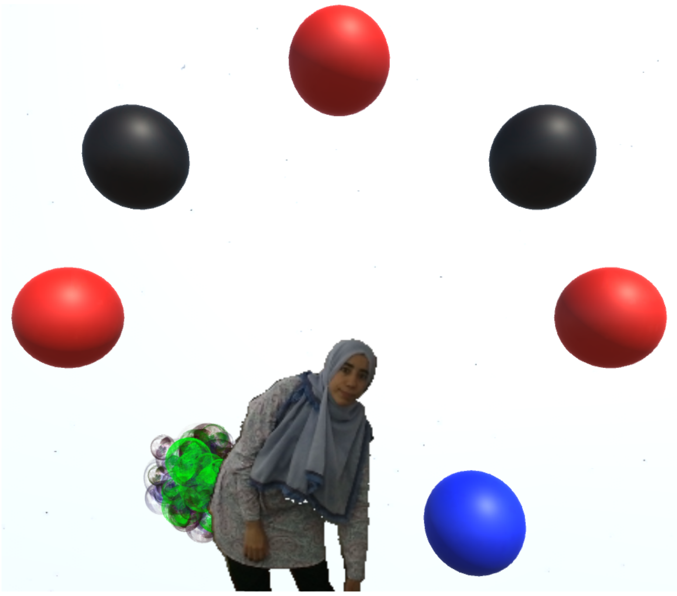


Fig. 3.1 Reach game.

(a) (b)

Fig. 3.2 HitIt game: (a) in a standing position and (b) in a seated position.

and development process of our games, we dedicate the next section to describe the design guidelines that we followed along with examples applied in our case.

3.2.4 Guidelines and features

PROGame framework supports the development of serious games for motor rehabilitation in general. In the specific case of vision-based games, authors of [74] identified 7 design issues related to the design of RGBD games for rehabilitation purposes. Thus, we considered the design guidelines provided by them as well. We cite below the issues as stated in their work, entailed by an example summarizing how we applied them in our case.

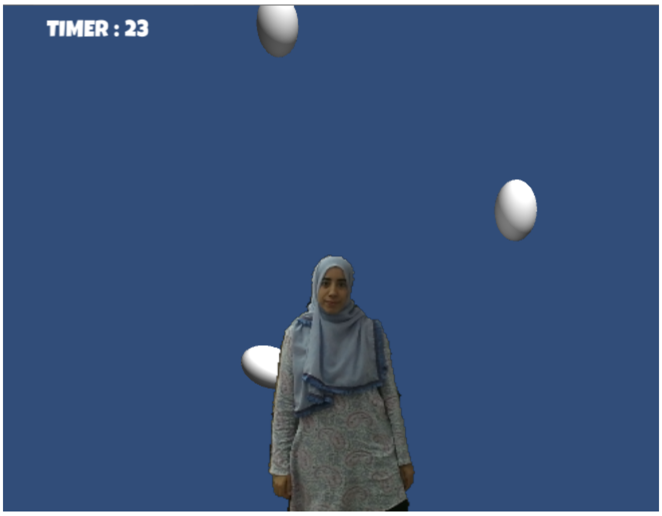


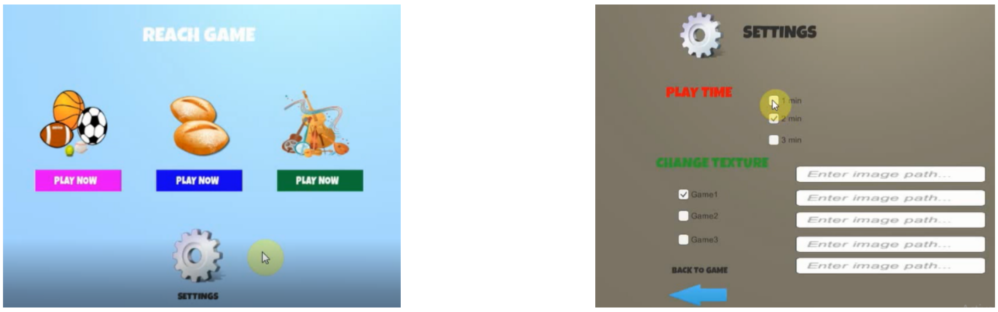
Fig. 3.3 WatchOut game.

1. Development paradigm: In a multidisciplinary team formed by engineers and clinicians usually there is some kind of challenge in the moment of defining the objectives of the serious games and the therapy proposed due to different educational background and different terminology used while communicating [129]. Thus, opting for a prototype development paradigm may ease this issue. In our work, we cooperated with a physiotherapist and an occupational therapist, so we adopted this paradigm to facilitate the communication between all the team members.

2. Interaction mechanism: Selecting an existing therapy and transfer it to a serious game is preferred over proposing a new therapy and then transfer it to a game in order to reduce the complexity of the work to do; in other terms, the validation does not need to be effected on the level of the therapy as well, researchers can exclusively focus on investigating the feasibility and effectiveness of the game and the technology applied. Subsequently, the user can interact with the game through the selected therapy. Additionally, holding a physical device represents a challenge for many patients, thus a vision based system like Microsoft Kinect can be used as an input device. Such interfaces help enormously to adapt the game to the users' capabilities and improve their perceptions to it [188]. In our case, interaction with the games can take place by hand or head motions, and mirror feedback i.e. the user can see himself on the screen (see Figure 3.4).

3. Interactive elements: The elements that the user is interacting with in the game should be carefully selected. Image themes influence on the motivation of the users. In fact, the time spent to perform a rehabilitation activity is less when the patterns used are

Fig. 3.4 Interaction by hand motion in Reach game.



(a) (b)

Fig. 3.5 Reach game: (a) themes and (b) settings.

related to the interest of the patient [73]. Three different themes are set by default in the reaching game; the user can choose playing with elements representing musical instruments, bread, or balls (see figure 3.5a). Changing to new patterns is also easy. The physiotherapist just has to download images that go with the preferences of the patient and print their locations in the settings interface (see figure 3.5b). Furthermore, the background images in all games are selected in a way that makes the user feel immersed in the virtual environment.

4. Feedback: Providing adequate feedback in serious games is fundamental in understanding the game as it provides the user with a sense of control and awareness about his state in the game environment. On receiving auditory and visual feedback, the user becomes animated which foment exercise adherence since most of rehabilitation programs are long and repetitive. For example, in Reach game we used stars and bubbles explosion effects when the item disappears and in HitIt game we used Soccer balls hit and audience applause sounds. The score is an optional parameter to display

it or not on the screen (see figure 3.6). In all games, the user can always see himself on the screen which facilitates the interaction with the virtual objects [72].

Fig. 3.6 The score displayed in HitIt game.

5. Adaptability: Individuals undergoing rehabilitation are of different range of capabilities and characteristics, hence serious games must be adapted to the abilities and progress of each user by defining a set of configuration parameters that can be customized and changed accordingly. For example, aging and disorders, among other factors, may alter significantly the movement and functioning capabilities of people. In particular, authors of [59] demonstrated that elderly women showed significantly smaller values of step length, stride length, ankle range of motion, pelvic obliquity, and velocity in comparison with the younger women. Thus, the physiotherapist must consider the characteristics of each user and adapt the rehabilitation to his needs. The configuration of the games that we designed allows to the physiotherapist to change the following parameters:

    - The maximum game playtime: It can be adjusted in each game according to the requirements of the therapy suggested, fatigue level, or the speed of the users.
    - Objects falling rate: In HitIt game, the time between two consecutive falling objects can be modified. It can be constant or randomly variable within a preset range. Seeing too many falling objects at the same time on the screen may confuse the patient and make him more vulnerable to falls.
    - Objects falling range: The position from where the balls fall is randomly assigned within a range that can be easily adjusted. Consequently, the physiotherapist can minimize this range if the user cannot move too much or prefers playing while sitting on a chair.

- Objects falling speed: The physiotherapist can change the speed that has a ball when falling in order to initiate the user to make lateral steps more quickly or slowly.

6. Monitoring: In rehabilitation programs, it is very important to observe the progress of the patients along the time. Our games offer the possibility to save user's information, configuration parameters, and patient's performance along the therapy sessions. The therapist can access to an XML file where several data are saved including user's profile, his preferences, date of the session, playing time duration, and the score. The file is easy to parse and analyze afterwards. An example of data from Reach game can be seen in Figure 3.7 where the user "Ines" is playing the game on 28/05/2019. The game duration was set to 5 min (300 s) and the player is playing for 13 s so far. She has a distance of 1.36 m from the sensor and she chose musical instruments as motivational objects. As a perspective, a real-time monitoring showing the motions of the user during the gameplay time can be added.

User	Date	Game_duration	Time_playing	Distance_from_came	Objects_number	Motivational_theme
Ines	05/28/2019	300.000	13.612	1.386	5.000	Musical instruments
Ines	05/28/2019	300.000	13.664	1.451	5.000	Musical instruments
Ines	05/28/2019	300.000	13.710	1.461	5.000	Musical instruments
Ines	05/28/2019	300.000	13.757	1.475	5.000	Musical instruments

Fig. 3.7 Example of data stored during Reach game.

7. Clinical evaluation: Evaluating the effectiveness of a rehabilitation system with real patients is very important to validate the system proposed. Optimally, a clinical evaluation comprises three main components: an experiment, participants, and measurements according to the goals and type of the therapy. Including pre-assessment and post-assessment of every measurement, recruiting a control group, and deploying a larger number of measurements are also highly recommended to ensure a clinical evaluation of a higher quality. Regarding our developed games, we conducted a case study to examine their feasibility and effectiveness on postural control and balance rehabilitation of older adults attending an elderly house, the clinical evaluation is described in detail in section 3.3.

3.2.5 Implementation details

Besides to its low cost, Microsoft Kinect offers intuitive interaction for users without the necessity to hold any kind of remote controllers. Its use is beneficial in rehabilitation programs with computer games since some patients have difficulty in carrying something in their hands. For these reasons, we used Kinect conjointly with Unity that is a flexible and powerful development platform for creating multiplatform 3D and 2D games and interactive experiences.

User Tracking

The Kinect Software Development Kit (SDK) processes raw data provided by the Kinect sensor (color image frames and depth image frames) to give, among other information, skeleton tracking information. In our games, we focused on tracking hands, head, and hips joints in both standing and seated positions. To achieve a good skeleton tracking, the user has to be detected first and move within the depth ranges of Kinect as indicated in Appendix B. Accordingly, the user stands in front of the sensor and the objects falling range is set within Kinect depth ranges.

Interaction within the game

Interaction with the objects in the games' scenes is accomplished by implementing collision events in Unity as described in Appendix B. We assigned a collider and a rigidbody to each joint that we need to track and use it in interaction. In response to collisions and forces applied, the objects disappear or take another direction. So when the user touches an item with his head or hand, the joint collides with the touched item and the item reacts upon the collision event. For example, the object reached disappears in Reach game whereas the ball bounces in HitIt game. Figure 3.8 shows an example from the reaching game where a collision takes place between hand joint and a ball by means of sphere colliders.

Tests

Most of tests were performed using a PC with the following settings:

- Intel^{R} Core ^{TM} i7-4510U CPU @2.00 GHz (4 CPUs)
- 8 GB RAM
- Graphic card Intel^{R} HD Graphics Family
- Windows 10 Home 64 bits
- Microsoft Kinect v1 and Microsoft Kinect v2

The system performance was 30 fps. This result ensured a real-time response [188]. Again, the serious games were developed using Unity 3D engine. The capture process, image processing and image visualization are performed by means of Microsoft Kinect SDK.

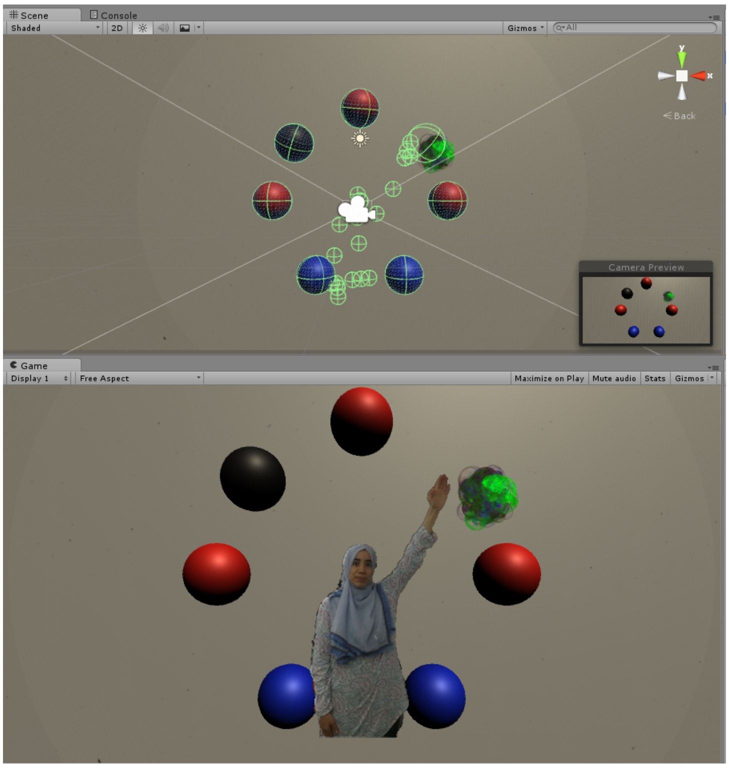


Fig. 3.8 Example of collision in Reach game in Unity.

Physiotherapist supervision

The physiotherapist was involved in the design and development process of our serious games since its early stages. Several meetings have been held between her and the research team to define the objectives of the therapy and test the games. Her role was of great importance in each phase of the work as shown below:

- Therapy selection: The first meetings with the physiotherapist were arranged to select the adequate therapy for the elderly target and define its objectives. The physical exercises found in literature along with the conventional therapies proposed for improving balance and postural control of elderly people were discussed. As an outcome, the physiotherapist validated a set of physical exercises to be transformed into serious games.
- Game design: In this phase, the physiotherapist checked if the sketched games translate the therapeutic exercises and suit the elderly target. The approval of the design allowed us to pass to the actual development of the games.

- Game validation: The physiotherapist tested the developed games by herself and validated that they contained the selected therapeutic exercises. In fact, she affirmed that the user can perform the following exercises while playing:
  - Small and large lateral steps
  - Weight shifting to both sides
  - Flexion, extension, lateral flexion, and rotation of the neck
  - Flexion, extension, and abduction of arms and shoulders
  - Flexion, extension, lateral flexion, and rotation of the trunk
  - Flexion and extension of lower extremities and knee
- Prototype tests: Different prototype tests were made to validate the games for the specific target group. The physiotherapist suggested different modifications to adapt the games to the elderly target. Further modifications were required in the clinical evaluation; the subject of the next section, since the physiotherapist has a better knowledge of the included subjects regarding vision problems and previous falls for example.
- Game play: In this phase, the physiotherapist supervised the users while playing the games and adjusted the settings according to their performance. In fact, the system allows the therapist to specify the difficulty level of exercises, frequency and number of repetitions, and distance from the sensor.

3.3 Clinical evaluation of the effectiveness of serious games

We conducted an exploratory and descriptive case study [197] about the impact that the games could have in the development of future rehabilitation games for the fall prevention programs for elderly people using vision-based technologies. Such works are preliminary studies that help in the design and preparation of randomized clinical trials [150]. They tend to describe the feasibility and potential effectiveness of the system proposed at a lower cost and shorter time. We aim to investigate the feasibility and effectiveness of prototype Kinect-based serious games that focus on postural control and balance rehabilitation in elderly people. For this reason, we used Microsoft Kinect as the vision-based interface, and we hypothesized that the games would have a positive impact on the participants attending the elderly house.

3.3.1 Study type

We present an intrinsic case study to investigate the feasibility and effectiveness of prototype Kinect-based serious games on postural control and balance rehabilitation in a group of elderly people. This was conducted into the specific context of an elderly house in Tunisia, where demographic changes have decreased fertility due to aging population. Persons aged more than 65 in the country constituted 8% of the total population in 2015; this percentage is considered the highest in Arab region. In 2050, it is predicted to reach 20 percent of the population [57].

3.3.2 Participants

Inclusion and exclusion criteria

Participants were chosen by a physiotherapist to participate in this study and were recruited in an elderly house. The inclusion criteria were as follows: (1) aged over 55 years; (2) ability to understand, learn, and follow simple instructions; and (3) voluntary agreement to participate in the clinical study. The exclusion criteria were as follows: (1) severe cognitive deterioration; (2) profound bilateral hearing loss with the use of hearing aids; (3) hemiplegia, dementia, or Parkinson; (4) serious or uncontrolled epilepsy; and (5) serious or recurring medical complications.

Recruitment process

Total population was screened for eligibility in the elderly house of Manouba in Tunisia which constituted 120 older adults. Among them, only 32 met the inclusion and exclusion criteria. The research team made a request to participate in the intervention to all adults who met the inclusion criteria. 15 subjects accepted to participate in the study but only 8 showed up for a trial session that lasted between 10 and 15 min to explain and show them the games. Those who joined the trial session liked the games, but for different reasons, some of them could not adhere to the trial sessions (one got a job and others had time incompatibility with doctor visit or their time of hanging out of the elderly house), so the final case study sample included only 3 subjects. One of the participants dropped in the middle of the intervention as she left the elderly house, and 2 completed the intervention and the pre- and post assessments.

Final participants characteristics

Subjects who accepted to participate were illiterate and were screened for cognitive impairment using Arabic-Mini Mental State Examination (A-MMSE) [5]. An A-MMSE score

Table 3.1 Participants' characteristics.

	Participant 1	Participant 2
Age (years)	78	72
Sex	Female	Female
History of falls	2	0
Walking aids	Yes	Yes
A-MMSE	22/30	28/30

higher than 20 suggested that both participants had no severe cognitive impairment as defined in the exclusion criteria.

For accessibility reasons, the serious game program was provided to users with different conditions (education, history of falls, cognitive impairment level, and balance problems). The two subjects included in this case study [85] met also the following criteria:

1. Subjects' capabilities were stable which means there would not be any progress in their capabilities during the study due to some pathology.

2. Users were attending intervention sessions according to the study schedule, so they were not exercising out of this time. This criterion provided homogeneity to the context of study.

The characteristics of the participants are presented in Table 3.1. An informed consent was signed before the intervention.

3.3.3 Procedure

The intervention was conducted along a period of 5 weeks. Each participant underwent one 30 min session per day at a rate of 3 days a week. The rehabilitation program was divided as follows: 20 min was devoted for Reach game, 10 min for HitIt game, and an extra 5 min was added for WatchOut game starting from session number 9. The duration of each game was set according to its understanding and its acceptability by the participants. A break time between 3 and 6 min was allowed each 5 min of play regarding the fatigue level.

Balance was assessed using the Tinetti balance test at the beginning (initial assessment) and at the end (final assessment) of the intervention. Adherence, game scores, and adverse events were noted along the intervention. The design of the clinical intervention is presented in Figure 3.9.

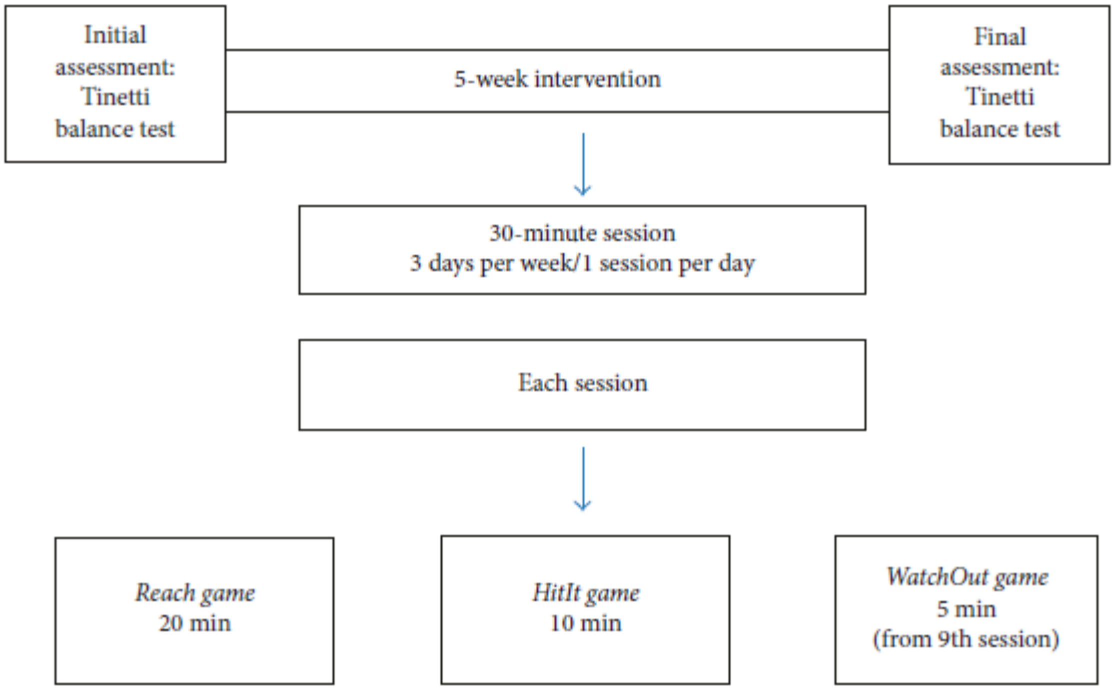


Fig. 3.9 Intervention scheme.

The system setting consisted of a personal computer and Microsoft Xbox Kinect sensor (see Figure 3.10a). In the literature, a vision-based system that processes higher than 19 fps its response is considered real time [188]. All games were designed to process at least 25 fps, and this ensures a realtime interaction. The participants stood in front of the camera which detected their presence and allowed them interacting with virtual objects appearing on the screen. The Kinect camera was placed at a fixed height of 1m and the average distance from the camera was 1.5 m. The games used were HitIt (see Figure 3.10c), Reach game (see Figure 3.10b), and WatchOut (see Figure 3.10d).

3.3.4 Measurements

Gaming was assisted by an occupational therapist (OT) and monitored by the research team. As stated before, all subjects were clinically evaluated prior to the intervention program and again at the conclusion to assess their balance with the Tinetti balance test. The Tinetti test was performed by the OT who was not blinded to the intervention. Other measurements were registered in a case report form by the research team or saved automatically by the system.

To assess the feasibility of using vision-based rehabilitation games for balance and postural control in the elderly house, the following outcome measurements were used:

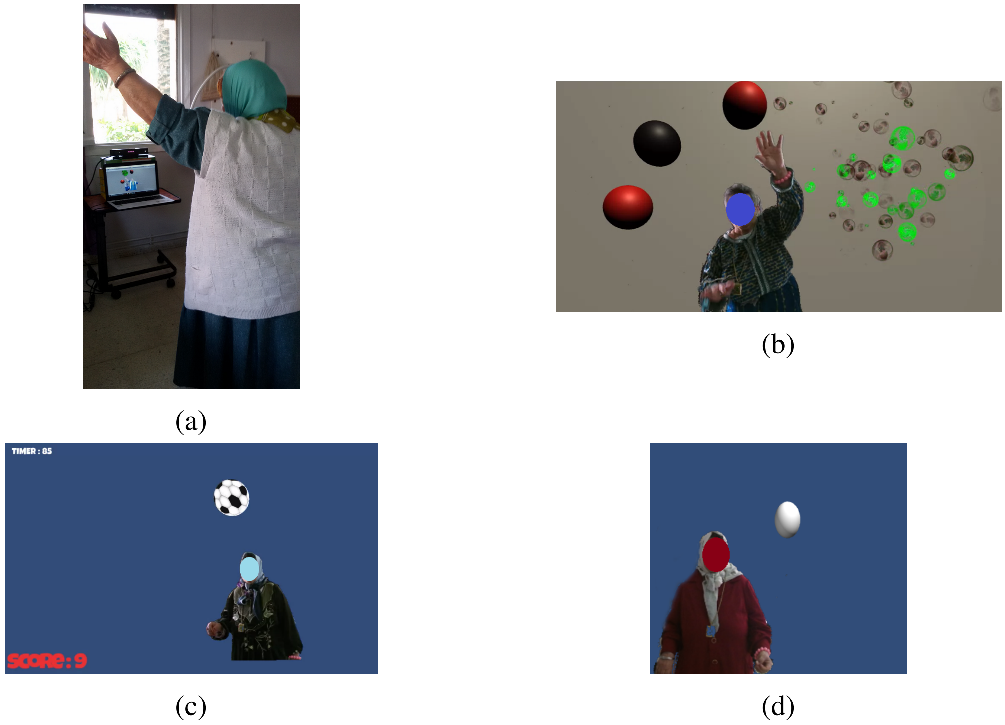


Fig. 3.10 Clinical trial games and settings: (a) System settings, (b) Reach game, (c) HitIt game, and (d) WatchOut game

- Tinetti balance test: The Tinetti assessment tool is a simple and easily administered test that measures a patient's gait and balance [179]. The test scoring is done on a three-point ordinal scale with a range of 0 to 2 where a score of 0 represents the most impairment, while 2 would represent independence of the patient. The individual scores are then combined to form three measures: an overall gait assessment score, an overall balance assessment score, and a gait and balance score. The maximum score for the gait component is 12 points. The maximum score for the balance component is 16 points. The maximum total score is 28 points. In general, patients who score below 19 are at a high risk for falls, while a score in the range of 19–24 indicates that the patient has a risk for falls [46].
- Adherence: The research team registered the number and length of sessions. Planned playing time and actual playing time were recorded by the system.
- Game score: The score of HitIt game was saved by the system at each session. Whenever the participant touched the ball with her head, one point was added to the score. The scores of the other games were not considered in this case since they did not

Table 3.2 Tinetti balance test scores.

	Participant 1		Participant 2	
	Pre	Post	Pre	Post
Total score	15	19	14	17
Balance score	7	11	6	10
Gait score	8	8	8	7

truly reflect the progress of the participant. Besides, the HitIt game score was used to motivate the patients and create a kind of competitiveness between them.

- Position of the patients and healthcare assistant: The position of the participants as seated or standing and the location of the therapist with respect to the participants were noted during intervention sessions.
- Adverse events: Events such as falls, fatigue, or any safety incidents requiring medical attention were also documented. Participants were orally asked for feedback during each session for any further improvements or suggestions.

3.3.5 Results

We are interested in reporting the results of the two participants who completed the intervention and performed the pre and post assessments.

- Balance: According to the Tinetti test scores, both participants showed a similar trend. As shown in Table 3.2, there was an improvement of 4 points in the balance section score, while almost no difference was noted between pre and post measures in the gait section. In the pre-assessment, Participant 1 had a total score of 15/28 (balance: 7/16; gait: 8/12) and Participant 2 had a total score of 14/28 (balance: 6/16; gait: 8/12). In the post-assessment, Participant 1 had a total score of 19/28 (balance: 11/16; gait: 8/12) and Participant 2 had a total score of 17/28 (balance: 10/16; gait: 7/12). There was improvement in balance section so we highlighted the elements of the Tinetti test that looked affected for both participants between pre and post assessments as shown in Table 3.3.
- Adherence. Participants attended 86.6% of the sessions with an average 30 min length each. As depicted in Figure 3.11, Participant 1 had 363 min of a total playing time divided between Reach game (245 min), HitIt (123 min), and WatchOut (15 min). Similarly, Participant 2 spent around 415 min of a total playing time divided between

Reach game (270 min), HitIt (125 min), and WatchOut (20 min). Details about the playing time for each session along with some notes can be found at Table 3.4.

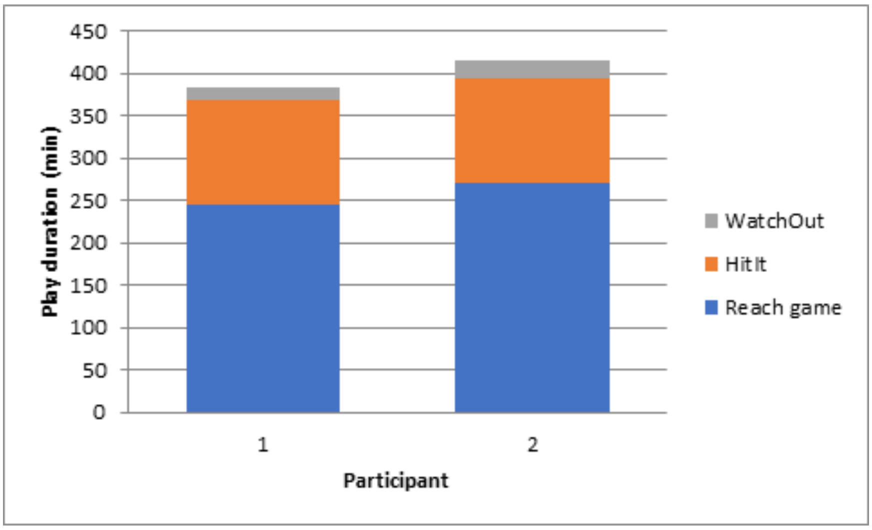


Fig. 3.11 Time spent by each participant in each game.

- Game Score: The game score improved over time, although there were no significant differences over time between the two participants as shown in Figure 3.12.

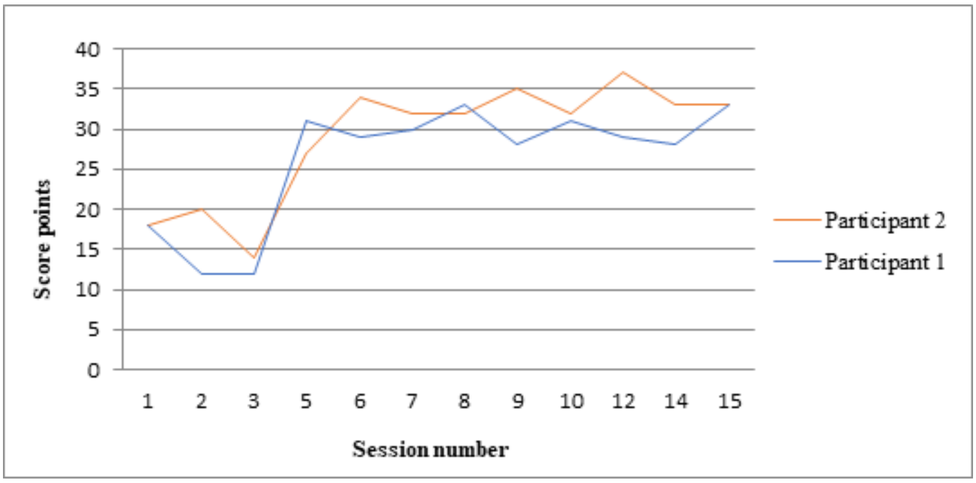


Fig. 3.12 HitIt game score for the two participants along the experiment.

- Position of the Participant and Healthcare Assistant: In all sessions, the participants were standing during playtime, and they sat on a chair during the breaks. As for the therapist, she stood behind the participants the first sessions as they expressed fear of fall and needed more help in doing lateral steps in HitIt and WatchOut games or reaching objects in Reach game. By the end, the participants could stand without any

Table 3.3 Elements of Balance section of Tinetti test that have been changed

Instructions	Score	Participant 1		Participant 2	
		Pre	Post	Pre	Post
Attempts to rise	Unable to without help = 0 Able, requires >1 attempt = 1 Able to rise, 1 attempt = 2	1	2	1	2
Immediate standing Balance (first 5 seconds)	Unsteady (staggers, moves feet, trunk sway) = 0 Steady but uses walker or other support = 1 Steady without walker or other support = 2	1	2	0	1
Nudged	Begins to fall = 0 Staggers, grabs, catches self = 1 Steady = 2	0	1	0	0
Eyes closed	Unsteady = 0 Steady = 1	1	1	0	1
Turning 360 degrees	Discontinuous steps = 0 Continuous = 1	0	0	0	0
	Unsteady (grabs, staggers) = 0 Steady = 1	0	1	0	1

support and the assistant stood on their left or right side, between one and three meters away, with the exception of Participant 1 who had a relapse after the fall accident and needed more support for restoring her confidence again.

- Adverse Events: Participant 1 fell during the intervention period; precisely after the ninth session, it was on a weekend day, not in the training day because she did not use her ambulatory aids that day. She returned to assist the training sessions just two days after the fall incident. At the beginning, she felt insecure and needed more assistance as someone had to stand behind her for reassurance, but sooner she started to gain confidence again. Besides, it is worth mentioning that she got tired easily in the post-fall period, usually both participants reported fatigue after 5 or 6 min of training, but she asked for a break after 2 or 3 min. No serious adverse events were reported from Participant 2.

Table 3.4 Play time per session in minutes

Date	Participant 1			Participant 2			Notes
	Reach	HitIt	WatchOut	Reach	HitIt	WatchOut	
08/02/2017	20	10	**	20	10	**	Physiotherapist is standing behind the participants to help them reaching objects.
10/02/2017	20	10	**	20	10	**	Reach game is played first and then HitIt game.
13/02/2017	15	8	**	20	10	**	
17/02/2017	20	10	**	20	10	**	Spawn rate of HitIt was increased.
20/02/2017	20	10	**	25	10	**	Participant 1 got little tired at the last 5 min of Reach game.
22/02/2017	20	15	**	20	15	**	Participant 1 got little tired since first 5 min of Reach game.
24/02/2017	20	10	**	20	10	**	
27/02/2017	20	10	5	20	10	5	The order of the games was changed: HitIt, Reach game, and then Eggs game to avoid confusion between games.
01/03/2017	20	10	**	20	10	5	Participant 1 needed more assistance (she fell on 28/02/2017).
03/03/2017	10	**	**	20	**	**	Session interrupted for external reasons.
06/03/2017	20	10	5	25	10	5	Participant 1 breathes a lot and she is tired. Participant 2 does reaching game by her own.
10/03/2017	20	10	5	20	10	5	
13/03/2017	20	10	**	20	10	**	Participant 1 got tired after 10 min of play.

**: No time was devoted to that game during the training session.

3.3.6 Discussion

As far as we reviewed, it is a first case study conducted in a Tunisian elderly house using Microsoft Kinect and serious games for balance rehabilitation and postural control. The findings show that the recruitment was very low, and this is due to the following. First, the recruitment period was short which partially explains the low participation between the elderly residents of the institution.

Second, exergaming was a new concept for many older adults. In fact, some refused to participate thinking it would be difficult for them to understand the games looking to the technology used, and others considered themselves too old to play. Consequently, we had to change the terminology used to stimulate them to participate at least to a trial session. We believe that using terms as “exercises” and “training” rather than “games” and “playing” may increment the recruitment rate.

Third, disliking exergames was also associated with low recruitment and high dropout rate as shown in another study suggesting that elderly people go for paper-based instructions to practice self-regulated conventional exercise instead of using computer-based exergames [124]. Nonetheless, the results related to the two participants were quite promising. Regarding the Tinetti balance test, both participants have shown an improvement of 4 points in the total score over the study period; the increase in the score was noticed especially in the balance section as highlighted in Table 3.3. The Tinetti test measures balance and gait, but our system focused particularly on balance; this justifies the absence of significant differences in the gait section as well. Besides, time allocation of the games may have had an effect on that as well. For instance, we can see in Table 3.4 that the time spent on HitIt and Eggs games that required stepping (lateral steps) was less than the time dedicated for Reach game which did not require stepping. However, with this improvement, Participant 1 moved from high risk for falls range to the risk for falls range, while participant 2 is still at high risk for falls [46, 103].

In addition, the adherence rate was very high and participants reported enjoyment during play sessions. We assume that the prototype games provided engagement, fun, and motivation for the participants. Interest and enjoyment provided in a game-based environment was pointed out by many researchers [54, 133, 183]. Regarding to play duration, the time dedicated to play WatchOut game was much less than the playtime of HitIt game because they both implicated doing the same movements nevertheless it was sometimes confusing for participants whether to hit or to avoid falling objects. The game score in HitIt game was motivating and created competitiveness between the two participants as they were performing the exercises alternately at the same period of time. They were both eager to score more points by hitting more balls. Social interaction between the two participants had an impact on motivation as well. In this respect, the findings of Wu et al. highlighted the importance of social presence for motivating elderly people while exergaming [34, 194].

Though fatigue was daily reported every five or six minutes of play, the games were safe especially with the presence of the physiotherapist around. The fall of one participant occurred out of the training sessions, and her return to the intervention program had implied two main points. The first point is that games were engaging and interesting. The second point is that games could be used to restore confidence after falls. Older adults minimize their activities and close up on themselves after fall, besides they express fear of falling again [49]. They usually develop "postfall syndrome" when they fall; in other terms, they become very anxious and cannot stand and walk without support [50]. For that reason, the participant needed more support and reassurance. Games may soften the impact of postfall syndrome and help in the reintegration of the faller into her community [105, 192].

The two subjects included in this case study met the criteria that would be accomplished by the future subjects. Conducting this study, we proved that for subjects that meet these criteria, the system and rehabilitative activities facilitated by the prototype games may be suitable and have allowed closely spotting and improving the issues that elderly subjects may face when interacting with the system providing more effective rehabilitation training for fall prevention.

The use of materials that were relatively small in size recommends a wider screen to facilitate the accessibility to elderly people. Besides, expanding the games repertoire by adding games that require movement and gait to work on static and dynamic balance was highly recommended by the physiotherapist for any future work.

3.3.7 Lessons learned

Usually the whole process of designing, developing, and evaluating serious games for its use by elderly individuals suppose different challenges to overcome and considerations to take into account. So in this section, we would like to share few recommendations and insights that we gained from our experience.

- Working with physiotherapists: It is extremely important collaborating with physiotherapists when the target group has special needs as elderly people do. In fact, certain exercises and movements that sound acceptable to us may result inadequate and harmful to them either in the short or long term. In such cases, the physiotherapist could easily tell which the right physical exercises are as she usually has more knowledge of the patients and their limitations. It is also important to note that in some circumstances, some research evaluations in clinical settings suppose an extra work for the physiotherapist. Thus, it is appreciated that the research team takes that into consideration and, in case needed, proposes some initiatives such as offering the help with the supervision of the participants during the intervention.

- Adequate games and adaptable settings: For elderly target, it is important to create interactive scenarios that are intuitive, simple, and inclusive. For instance, we had to change the background and emphasize the color contrast of the game elements as the included participants had some vision problems. The possibility to configure the settings for the games was also very helpful during the intervention as it allowed the physiotherapist to easily adapt the games to the performance of the patients and their state (level of fatigue for example).

- Clinical settings: Here, some of the things that can be checked are the existence of similar systems in deployment at the same period of the intervention or before, the equipment that they dispose and its adequacy to conduct the intervention, the space offered, and opening hours, among others.

- Bureaucracy: Conducting an evaluation with elderly users in institutionalized settings requires certain permissions. Such procedures usually take time so it better to plan that in advance.

- Length of the evaluation: Theoretically, together with the physiotherapist an optimal period can be set according to the objectives of the intervention, however this period may be affected by other factors such as the availability of the people involved (physiotherapists, participants, and research team), opening hours and the internal schedule of the clinical setting (doctor visit, lunch time, etc.).

- Recruitment: It is one of the delicate phases in the project as it depends a lot in culture, acceptance of technology, and willingness to participate, among others. We had many rejections from participants who thought that they are old for playing video games, in this case we had to change the terminology used (games vs training exercises) and provide them with further explanations about the study and the effects of the games. It is also noteworthy that many participants will refuse to participate in the study for one reason or another, so it is advisable not to take personally those rejections.

- Dealing with biases: There are many sources of bias when conducting an evaluation of the games. One should preferably identify these biases and minimize them if possible. For instance, number of participants, gender bias, the fact that in some studies the participants are paid to attend the intervention, etc.

3.4 Summary of the chapter

We described in this chapter the design and development process that we undertook to develop a set of Kinect-based prototype games for balance rehabilitation. In order to investigate the feasibility of these games and study its effectiveness on balance and postural control of elderly people, we conducted a first case study in a Tunisian elderly house where two participants underwent a 5-week intervention. During the training sessions, the included participants played three prototype games using Microsoft Kinect. Consequently, aspects such as enjoyment, adherence, and adverse events were monitored. In addition, balance impact was assessed by the Tinetti balance test. In general, the participants reported enjoyment. They attended the majority of the training sessions and no adverse events were noted. Furthermore, there was an improvement in Tinetti balance test scores.

In conclusion, despite that the study sample size was very small, the findings suggest that the use of Kinect-based prototype games for improving balance and postural control of elderly people living in a Tunisian elderly house is feasible and safe and can be integrated in fall prevention programs. In future work, it is intended to conduct a randomized controlled study with a larger sample size to further study the effectiveness of these games.

Ultimately, selecting an adequate therapy or adapting an existing therapy for balance rehabilitation based on the capabilities of an elderly individual is very important to get effective results. However, this may not be possible without objectively assessing balance abilities using reliable clinical tests. Hence, in next chapter, we will describe one of the most used balance tests and we will present a vision-based interactive system for measuring the outcome of this test.

Chapter 4

Balance measurement using vision-based systems: Case study of FRT

"*Subjectivity measures nothing consistently.*"

Toba Beta, My Ancestor Was an Ancient Astronaut

As discussed earlier, physical activity is very important in minimizing risk of falls and fall related injuries. In fact, different studies have investigated the effectiveness of fall prevention interventions and its subsequent effect on the quality of life of older people when specific programs of physiotherapy are used to improve balance [50, 113, 152]. Furthermore, several studies have demonstrated the promising results of the clinical deployment of vision-based systems in fall risk reduction as they facilitate the capture of human movements and are cheap to acquire [193, 17, 31]. Besides, these systems can be easily set up at the patients' homes. Consequently, patients can perform their rehabilitation program at home unhindered by the encumbrances of the displacement to a hospital or a rehabilitation center. As a matter of fact, it is common for a patient to do rehabilitation exercises independently at home, and then a physiotherapist visits him from time to time to assess his performance and measure the effectiveness of the treatment [98, 111, 78]. For determining the effectiveness of a therapy, reliable and valid tests are usually used to measure its clinical outcomes. Among the tests used for clinically measuring balance and postural control of older adults in rehabilitation programs, we identified the Functional Reach Test (FRT) [48] as one of the most used tests in elderly population since it is easy to administer and it measures their limits of stability while standing. In addition, it can detect limitations in activities of daily living and indicates risk of falls.

Thus, this chapter presents another focus of the thesis work. We aimed to validate the calculation of the FRT using a vision-based technology. Since the user uses interactive applications for balance rehabilitation using an RGBD device, the physiotherapist could use the same device to measure the FRT of the patient at home without having to carry any additional material. Therefore, the calculation of the FRT manually and with an experimental system that uses an RGBD device, namely the Microsoft Kinect, was compared. In next section, we cite the main balance tests for elderly people, describe the Functional reach test in detail, and present subsequently the related work. Then, we present the experimental system which allows assessing the FRT automatically using an RGBD device. Afterwards, we explain the evaluation conducted to preliminarily validate the experimental system. Finally, we dedicate last section for discussion.

4.1 The Functional Reach Test (FRT)

It is important to measure the balance abilities of an older adult using clinical and reliable tests in order to determine the right rehabilitation program in an objective way. The progress of each individual can then be monitored and the therapy can therefore be adapted according to his capabilities.

4.1.1 Clinical measurements in rehabilitation

Balance deterioration in older adults may increase their falling rate. Being able to measure this decline helps identifying the individuals with higher risk of falls and taking subsequently the necessary preventive measures such as specific rehabilitation programs to minimize this risk. Moreover, assessing balance permits measuring the effects of the exercises proposed in a certain therapy. Various clinical tests have been developed to help assessing balance, gait, and postural control of elderly subjects and predict therefore fall risks [158]. These tests include Tinetti Balance test [180], Berg Balance Scale [14, 18], Timed Up and Go test [136], and Functional Reach test [48]. The latter was one of three tools having strong predictive validity to assess fall risk in a community setting besides the 5 min walk and the five-step test [158]. The functional reach test is also easy to administer and takes only few minutes to conduct. In fact, time is reported as one of the barriers considered by physicians for routinely assessing fall risks [35]. Thus, easy and simple tests must be provided for screening periodically balance and gait disorders. In addition, it is demonstrated that rehabilitation has

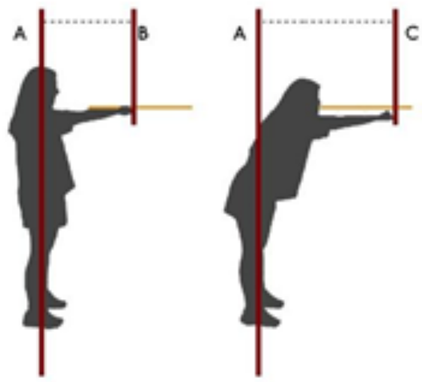


Fig. 4.1 Measurement of the Functional Reach Test

more efficiency when done in a familiar environment like at the home of the patient [7]. As mentioned earlier, this is possible thanks to RGBD devices like Microsoft Kinect which can be used also for providing an easier and simpler way to conduct the test.

4.1.2 FRT performance

In this test, the patient is first instructed to stand close to a wall. While standing in a comfortable position and looking straight ahead, the patient is asked to raise the arm that is closer to the wall at 90 degrees of shoulder flexion with a closed fist: here the position of the head of the 3rd metacarpal is marked on the wall (this is the initial position, B). From this position, the patient is asked to flex the trunk and reach forward as far as he can without taking a step or touching the wall: here the physiotherapist marks on the wall the end position of the 3rd metacarpal (this is the final position, C) (See Figure 4.1).

The final score of FRT is the distance between the start and end positions. Three trials are done and the average of the last two is noted. Results of less than 25 cm indicate a limitation in activities of daily living (ADL) and a risk of falls [146, 99].

4.1.3 Related work

Several studies have examined the feasibility and validity of technology for measuring and parametrizing balance tests [169, 37, 37]. Regarding the FRT, some researchers opted for the use of inertial sensors. For instance, authors of [112] used InertiaCube3^{TM} sensor to record kinematic variables of stroke patients in order to analyze the reliability, sensitivity, and specificity of FRT. Likewise, Hasmann et al. [62] used wearable accelerometer data to differentiate participants with high risk of Parkinson disease from others since instrumenting FRT may improve diagnostic accuracy. Conversely, Moreno et al. [115] aimed to investigate to what degree inertial sensors can be replaced by depth cameras in the parametrization and kinematic analysis of Multi-Directional Reach Test (MDRT) besides Timed Up and Go test. Consequently, inertial sensor data were used as a benchmark for evaluating the data acquired using PrimeSense depth camera. In addition, with the increase of Microsoft Kinect popularity, Kinect v1 was used in the development of a standalone software to measure the FRT [53]. Concurrent validity of Kinect measures were assessed in comparison of measures obtained from 3D motion-capture system. Implementation feasibility was also examined in a clinical setting where patients' feedback was collected. Similarly, Clark et al. [37, 38] assessed the concurrent validity and reliability of reach test among other tests for evaluating standing balance and postural control. Firstly they used Kinect v1 and compared the data with a marker-based three dimensional motion analysis (3DMA) system [37]. Then with the release of Kinect v2, they updated the data with Kinect v2 measures in comparison with data obtained by a multiple-camera 3D motion analysis as a benchmark [38]. As it can be noticed, in all the studies proposed, they used another technology system as a gold standard, however in our work we use the standard manual test as it is performed by a physiotherapist as a benchmark. A summary of the studies that used vision-based technologies for measuring the functional reach distance is presented in Table 4.1.

Table 4.1 Previous works about FRT

Test Source	**Aim**	**Test execution**	**Technology Settings**	**Methodology**	**Validation**	**Measurements**
FRT: Computerized FRT (cFRT) [157]	- Provide additional functional reach parameters - Measure correlations between the cFRT, the MMSE and the Tinetti balance test	- The test was repeated 3 times - Order of tests (MMSE,Tinetti test, FRT, and cFRT) execution depends on the group - All tests were taken by an experienced physical therapist	- Logitech Express Quickcam - Camera is 1.5 m from the subject - The room is lit by a single 100 W bulb	- Video recording the test by camera - Check the recording if the test is executed correctly - Get wrist displacement from the recording	The system was calibrated by filming a measuring tape 1.5 m from the camera in order to calculate the displacement corresponding to each pixel and thus measure the value of the FR	Mean values of the FR, velocity, stop time and the lowering values for each subject

Table 4.1 continued from previous page

Interactive FRT (IFRT) [53]	Concurrent validity of IFRT among healthy adults	- All tests in a single session - 3 practice trials for each participant - Trial was repeated when performed wrongly	- Kinect v1 - Kinect sensor was mounted on a tripod (0.75 m) to the participant's left, at a distance of 2 m, 2.5 m, or 3 m from a reference line marking the position of the participant's right foot, offset in forward direction 0.75 m from lateral line	- A wireframe Skeleton avatar displayed the movements of the performer in real time - Based on the performer's initial shoulder height, visual constraints on vertical deviations of the reaching movement were added	- FRT was measured simultaneously by both the Kinect sensor using the I-FRT software and the Optotrak Certus_ 3D motion-capture system	- FR distance - NASA Task Load Index (NASA-TLX) questionnaire
Multi-Directional Reach Test (MDRT) [115]	Validate to what extent depth cameras can substitute inertial sensors for the parameterization and kinematic analysis of the TUG and MDRT tests	- 3 repetitions of each test - The trial in which the patient achieved the largest range (measured with a standard measuring tape) was selected as representative for the MDRT - Remain at a neutral, static position for 3 seconds at both the beginning and the end of the tests to clearly identify the movement in the later analysis	- Prime Sense - InertiaCube3^{TM} - The camera was placed with its optical axis perpendicular to the direction of the tested movements The distance between the camera and the participant was set to approximately 1.5 m	3D positions of the joints labelled Neck and Torso from PrimeSense were used to compute the angles between them for all tests	- InertiaCube3^{TM} sensor was used to measure inclination angles and angular rates and employed as a benchmark to evaluate those obtained from the depth camera - In order to record synchronized data from both sensors, their drivers were integrated into an open-source software library	Inclination angles, angular speed, time, displacement, and velocity

Table 4.1 continued from previous page

Static and Dynamic balance tests that involved forward and lateral reach [37] [38]	Assess the concurrent validity and reliability of kinematic data recorded using a marker-based 3DMA system and Kinect during a variety of static and dynamic balance assessments	The subject advised to: (1) abduct the shoulder until the arm was parallel to the floor while keeping the arm straight and hold this position for approximately two seconds, (2) reach as far out as possible in the respective axis of testing, while keeping both feet on the floor, and hold this position for approximately two seconds, and (3) return to the starting position [37]	- Kinect v1 [37] - Kinect v2 [38] - 3DMA system - Kinect camera located directly in front of the subject - Participants standing 2.5 m away from the camera	Participants attended two separate testing sessions approximately seven days apart (mean: 7 ± 2 days)	- Measures of forward and lateral trunk flexion angle relative to the ground were calculated - For the Kinect, the SDK quaternion angle output was converted to Euler angles, and for the 3DMA system by creating a trunk segment using anatomical and tracking markers modeled using Visual3D. Data from both systems were filtered using a low pass filter and synchronized using time stamps	- Forward and lateral trunk flexion angle - Trunk flex angle range

FRT: Functional Reach Test; MMSE: Mini Mental State Examination; 3DMA: 3 Dimensional Motion analysis.

4.2 Proposed system

RGBD devices are used in serious games for balance rehabilitation but they may be used to assess objectively the balance ability as well. In this section, we used Microsoft Kinect to measure the limits of stability of an individual through one of the most popular balance tests, namey the FRT. It is an easy to administer test that can be used in predicting falls among elderly people.

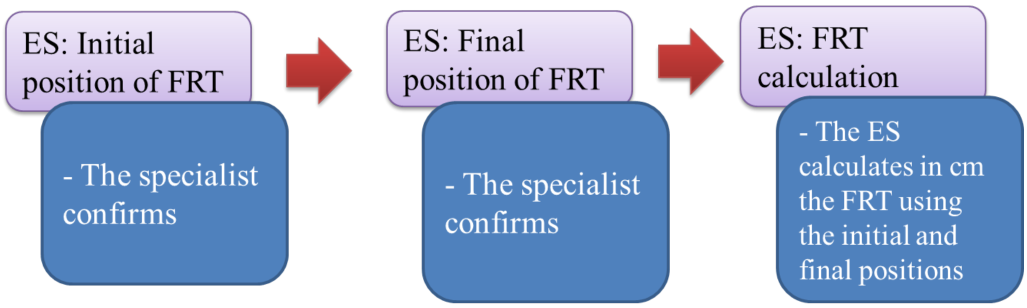


Fig. 4.2 Functioning sequence of the experimental system (ES).

4.2.1 Automatic FRT

The FRT was transferred to our experimental system as an interaction mechanism so that it can automatically measure the maximum distance that a user can reach forward. The system allows the physiotherapist to calculate the FR in three steps as shown in Figure 4.2.

We use an RGBD device namely Microsoft Kinect as an input method for our system. This capture device was chosen because it facilitates the capture of human movement and it has good capabilities besides to its low cost. As mentioned before, Kinect has a Software Development Kit (SDK) that allows access to the raw images of its sensors (depth and color images), and retrieve skeletal tracking information of the user situated in front of the sensor in order to implement gesture interactive applications. Therefore, the same interaction system used for rehabilitation can be also used for assessment, hence saving the elderly individual the hurdle of learning new interaction mechanism. An example of interaction with the system can be seen in Figure 4.3 where the user stands in front of the system and interacts with the objects shown on the screen. For computing the reach distance, we use the data provided by Kinect SDK and in particular the skeletal data. We were particularly interested in the hand joint to measure the distance travelled by the joint when performing the test. Finally, to ensure adequate feedback for the user, a text is displayed indicating whether the hand joint is tracked or not; if it is tracked, the color of the text is set to green, else it is red. In addition, “start” and “stop” instructions were shown on the screen to guide the user at the beginning and the end of the test. Furthermore, the user can see himself on the screen as it is demonstrated that mirror feedback provides motivation for the user [72].

4.2.2 Test performance

In order that the physiotherapist can calculate the FRT through our system, the user must stand in front of the RGBD device and a screen, as shown in Figure 4.3. This is the typical architecture of a video game in which the user’s movements are captured. The patient will

Fig. 4.3 An example of interaction with a vision-based system.

be familiar with the use of interactive applications for motor rehabilitation of balance with RGBD devices, thus he will know this architecture. First, the physiotherapist asks the user to perform the initial position of the FRT (position AB in Figure 4.1). When the physiotherapist thinks that the user does it correctly, the starting position is indicated to the system and the system stores the position of the user's hand. Then the user is asked to reach forward to the final position of the FRT (position AC in Figure 4.1). When the reaches the final position without losing balance, the final position is stored. At the end, the system calculates the FRT between the initial position and the end position.

4.2.3 Tests

All tests and experiments were conducted in laboratory settings using a desk computer with the following features:

- Intel^{R} Core^{TM} i5-4590 CPU @3.30 GHz (4 CPUs)
- 8 GB RAM
- Graphic card Intel(R) HD Graphics 4600
- Windows 8.1 Pro 64 bits

We used both Kinect versions, Kinect v1 was used for the first experiment and Kinect v2 was used in the second one. The system performance was then 30 fps. This result ensured a real-time response from the experimental system [188]. The interaction features of Kinect work better when the user is facing the sensor, for this reason the experimental system was designed to work in a frontal way and not laterally with respect to the user.

4.3 Validation of Microsoft Kinect for measuring the FRT

The experiments in this work were realized with the aim to validate the use of RGBD devices in measuring the Functional Reach Test (FRT), so these devices can be used for clinical teleassessment in the future. We used Microsoft Kinect v1 in Experiment 1 and Microsoft Kinect v2 in Experiment 2.

4.3.1 Experiment 1

The aim of this experiment was to validate whether the Kinect-based system can assess automatically the FRT with the same confidence as the standard mechanism, by a physiotherapist in a manual way. A case study was conducted with real users and using the first version of Kinect.

Participants

The experiment was performed on 14 healthy adults (11 men); aged between 22 and 48 years (mean 29.4, standard deviation 7.2). None of the subjects had cognitive and/or motor problems. All participants signed an informed consent form. The characteristics of the volunteers who participated in this experiment are presented in Table 4.2.

Process

On the one hand, all participants performed the FRT in the standard way. On the other hand, the participants used the experimental system in order to automatically calculate the FRT. We are interested in the differences between the experimental system and the standard application of the FRT. The standard procedure of FRT indicates that each user should repeat the test 3 times, that is why the participants also used the experimental system 3 times. To avoid the factor of pre-learning, the order in which the FRT is performed by the standard way (manually) and the experimental system (using Kinect) is decided randomly, as well as each repetition. An example of an experimental sequence for a user might be: Manual

Table 4.2 Participants' characteristics

User	Age	Gender
1	26	Male
2	48	Male
3	36	Male
4	24	Male
5	22	Male
6	24	Female
7	28	Male
8	33	Female
9	36	Male
10	26	Male
11	25	Male
12	25	Male
13	34	Male
14	24	Female

Fig. 4.4 Screenshot of the system during the FRT performance in Experiment 1.

(M_FRT_1), Experimental System using Kinect (K_FRT_1), K_FRT_2, M_FRT_2, K_FRT_3, and M_FRT_3. As it can be seen, a within-subjects design was used with the standard FRT as a control group. A demonstration was conducted before starting the experiment so that the users know how to use the experimental system.

Measurements

The measures used were the distance in cm between the initial position and the final one, for both the experimental system using Kinect (K_FRT) and the standard FRT (M_FRT). An independent statistical Student t-test for paired samples (paired t-test) was applied to these measures in order to determine whether there were significant statistical differences between them. The statistical analysis tool R was used.

Results

Table 4.3 shows the measurements made in our experiment. At first glance, the results of each measurement for each user are very similar. To get a more graphical view, Figure 4.5 shows for each user the mean of the three measurements obtained manually (M_{M_FRT}) and the mean of the three measurements computed by the system (M_{K_FRT}). We calculate the difference between the means for each user ($M_{M\_FRT} - M_{K\_FRT}$), and the results showed an average absolute difference of 2.84 cm (±2.62).

Table 4.3 FRT measurements obtained during Experiment 1.

User	M_FRT_1	M_FRT_2	M_FRT_3	M_{M_FRT}	K_FRT_1	K_FRT_2	K_FRT_3	M_{K_FRT}
1	35.5	36.5	42	38	37.06	38.13	31.57	35.58
2	42	44.5	48	44.83	36	40.5	37	37.83
3	48	47.5	45.7	47.06	49.16	51.28	41.97	47.47
4	47	42.2	46.6	45.26	39.79	53.94	46.11	46.61
5	55.2	56.2	52.9	54.76	60.94	50.75	56.38	56.02
6	33.5	35.5	38.9	35.96	30	28.44	37.08	31.84
7	49.5	45.5	51.5	48.83	50.75	57	50.51	52.75
8	45	43.5	40	42.83	46.23	37.34	40.6	41.39
9	45.5	42	42	43.16	50.03	45.3	36.41	43.91
10	34.5	44	43	40.5	44.83	38.93	38.91	40.89
11	38.5	44	45	42.5	34.45	36.66	43.28	38.13
12	36	33	34.5	34.5	37.4	32.59	43.6	37.86
13	33	36	41	36.66	46.1	43.05	47.54	45.56
14	42.5	41.5	41.5	41.83	40.1	41.9	42.7	41.56

To see if there were statistically significant differences on these averages, the paired t-test of the difference was applied, and as shown in Table 4.4, there are no statistical significant differences where $p = 0.973$, much higher than 0.05 the p value that is usually used to consider statistical significant difference. The alternative hypothesis was that the difference of measurements was not equal to zero. Also we applied Ad-hoc; an analysis of the statistical power of the test performed, and the result indicated that the lowest statistical difference that could be detected between the standard FRT and the experimental system with 14 subjects is 3.9 cm.

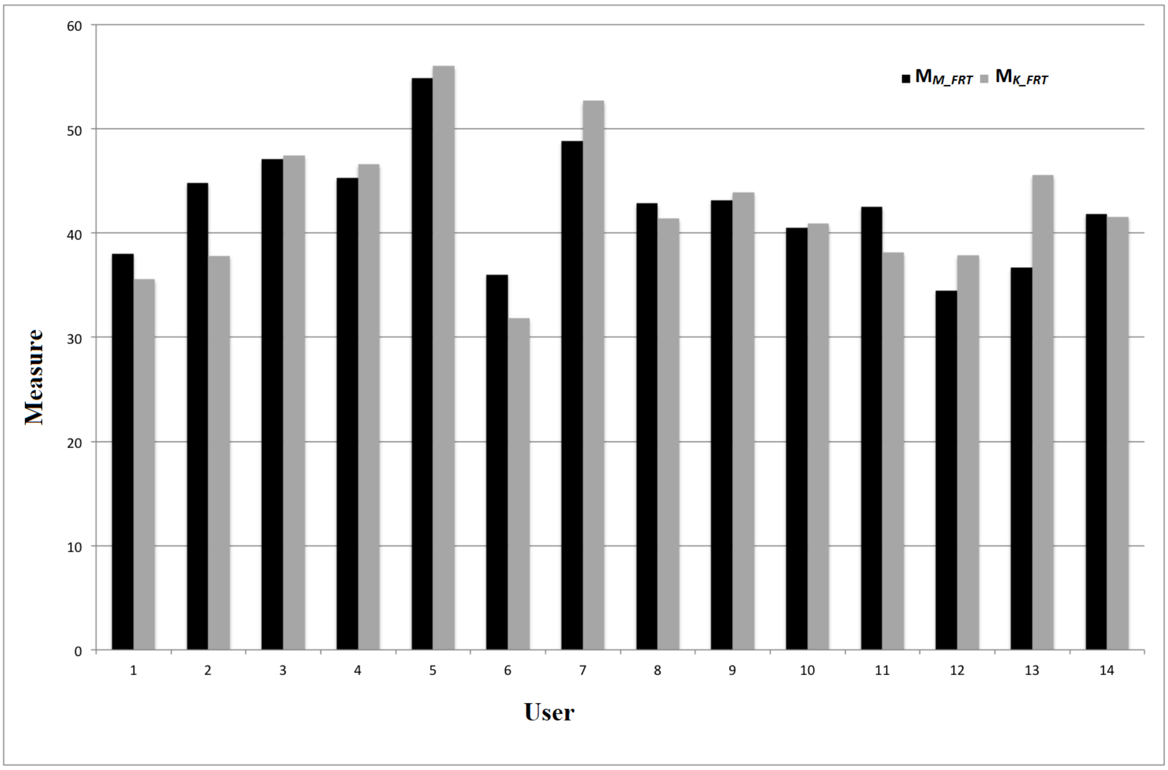


Fig. 4.5 Comparison Chart of the mean FRT and the mean of the experimental system for each user (in cm)

Table 4.4 Results of statistical test (paired t-test) applied to the results obtained

t(13) = -0.034
p-value = 0.973
Difference = -0.036

4.3.2 Experiment 2

The same system was improved in order to better validate the use of an RGBD device namely Microsoft Kinect for Xbox One (Kinect v2). In the previous experiment, we made the measurements separately for each method. In this time, the measurements were made at the same time for the standard way (manually) and for the experimental system using Kinect.

Participants

Nineteen healthy volunteers (9 men; aged between 18 and 37 years) participated in this experiment (see Table 4.5 for more details). None of them had cognitive and/or motor problems. All subjects signed an informed consent form before the experiment.

Table 4.5 Participants' characteristics

(a)

User	Age	Gender
1	37	Male
2	29	Male
3	25	Female
4	29	Female
5	33	Female
6	25	Male
7	30	Female
8	23	Female
9	32	Male
10	27	Male

(b)

User	Age	Gender
11	25	Male
12	23	Male
13	18	Male
14	22	Female
15	22	Female
16	35	Female
17	31	Male
18	35	Male
19	32	Male

Process

This experiment was done under the supervision of a physiotherapist. Firstly, each participant was instructed how to perform the test. Next, he or she was asked to stand close to a wall facing both the sensor and the screen where his or her image was displayed. The sensor was set at 1.5 m from the floor and 2 m away from the user. A white board was attached to the wall to help in the manual measurement of FRT as shown in Figure 4.6. The user's image is displayed on a computer screen. In order to minimize distractions, we applied a background subtraction algorithm provided by RF-Solutions in the wrapper that we used to link between Kinect and Unity (see Appendix B). The physiotherapist was standing close to the participant to supervise the test performance. The physiotherapist may intervene to correct the posture. Then, the participant was asked to hold a marker pen and mark the first

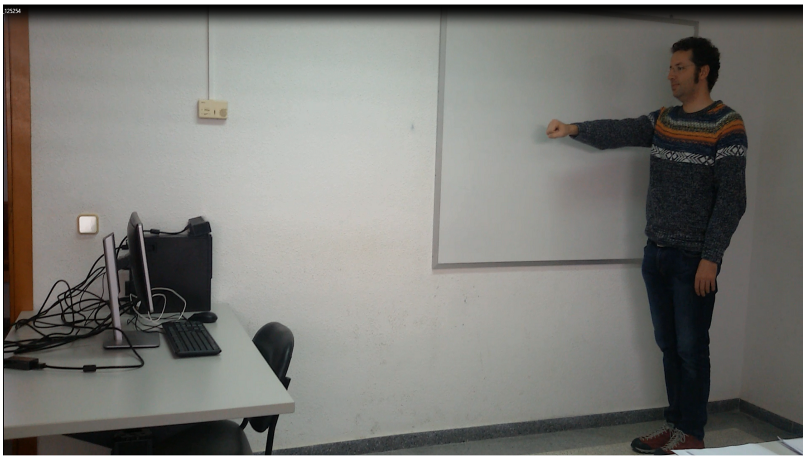


Fig. 4.6 Settings of experiment 2.

(a) (b)

Fig. 4.7 Screenshot of the system during the FRT performance in Experiment 2: (a) Initial position and (b) Last position.

point on the board while saying “Go”. The physiotherapist validates the initial posture and one of the research members hits the “G” key so the system can record the first position. After that, the participant is asked verbally to bend forward as maximum as he or she can. When he or she reaches the last position, he or she notes on the board the last point with the pen saying “Stop”. Again, the physiotherapist validates the posture and the last position was saved by hitting the “S” key. Eventually, the differences between the last position and the first one that are marked on the board and taken by the system were all noted. A screenshot of the performance of the test is shown in Figure 4.7.

Measurements

The participants performed the test 3 times as indicated in the standard test. The distance between the initial position and the last one was computed by the system. For each trial, we had the following measurements from both methods: manual FRT (M_FRT), the mean of the three measurements for each user (M_{M_FRT}), Kinect FRT (K_FRT), and mean of the three measurements for each user (M_{K_FRT}). Table 4.6 shows the measurements obtained for each user.

For statistical analysis, we applied Shapiro-Wilk normality test [161, 143] to the data to check its distribution. This test is widely recommended in the assessment of normality assumption which is necessary to run parametric statistical tests. The null hypothesis for this test of normality is that the data are normally distributed. The null hypothesis is then rejected if the p-value is below 0.05. We also applied the paired t-test to the mean of three measurements performed by each user and obtained by each method to determine whether there were significant statistical differences in the average. Moreover, we conducted power analysis to determine the number of subjects required for the mean difference between the two sets of data obtained by both methods. Furthermore, we run Pearson Correlation Test to see if there is any association between the measures obtained from the different methods (manual and Kinect). This test is also known as the “product moment correlation coefficient" and it measures the strength and direction of association that exists between two continuous variables [118]. Pearson’s correlation coefficient can range in value from -1 to +1 so the larger its absolute value, the stronger the relationship between the variables. In addition, in the presence of linearity and correlation between the measurements collected by the two methods, we applied a linear regression model in order to correct the data obtained by the experimental system using Kinect. The level of significance for all tests was set at $p < 0.05$. The statistical analysis tool R was used.

Table 4.6 FRT measurements obtained during Experiment 2.

User	**M_FRT$_1$**	**M_FRT$_2$**	**M_FRT$_3$**	**M_{M_FRT}**	**K_FRT$_1$**	**K_FRT$_2$**	**K_FRT$_3$**	**M_{K_FRT}**
1	48.5	47	47	47.5	49.5	49.3	49.2	49.33
2	42	47	49	46	47.3	46.9	49.2	47.8
3	34	36	33	34.33	33.7	35	35.1	34.6
4	40	40	41	40.33	41.5	40.8	42.4	41.56
5	33	35	30	32.66	29.1	35.5	33	32.53
6	48.5	43.5	46	46	54.5	49.2	51.4	51.7
7	40.5	38	35	37.83	42.9	39.9	34.9	39.23
8	23	26	28	25.66	24.1	29.7	31.7	28.5
9	30	25	27	27.33	30.5	26.1	28.5	28.36
10	46	45.5	38	43.16	48	48.6	41.3	45.96
11	32	35	32	33	33.4	37.4	33.5	34.76
12	52.5	52.5	55	53.33	54.2	54.9	57.6	55.56
13	41	44	45	43.33	45.3	50.1	45.9	47.1
14	44.5	32.5	37.3	38.1	45.9	39	43.7	42.86
15	36	41	38	38.33	42	44.5	43.5	43.33
16	42	43	43	42.66	47.6	49.1	45.7	47.46
17	33.5	34	45	37.5	40.6	32.6	49	40.73
18	38	40	42	40	43.8	46.5	46.4	45.56

Table 4.7 Results of paired t-test applied to data of Experiment 2.

t = -8.206
p-value = 3.538e-11
Difference = -2.36

Table 4.6 FRT measurements obtained during Experiment 2.

User	**M_FRT$_1$**	**M_FRT$_2$**	**M_FRT$_3$**	**M$_{M_FRT}$**	**K_FRT$_1$**	**K_FRT$_2$**	**K_FRT$_3$**	**M$_{K_FRT}$**
19	32	33	33	32.66	30.7	34.3	33.7	32.9

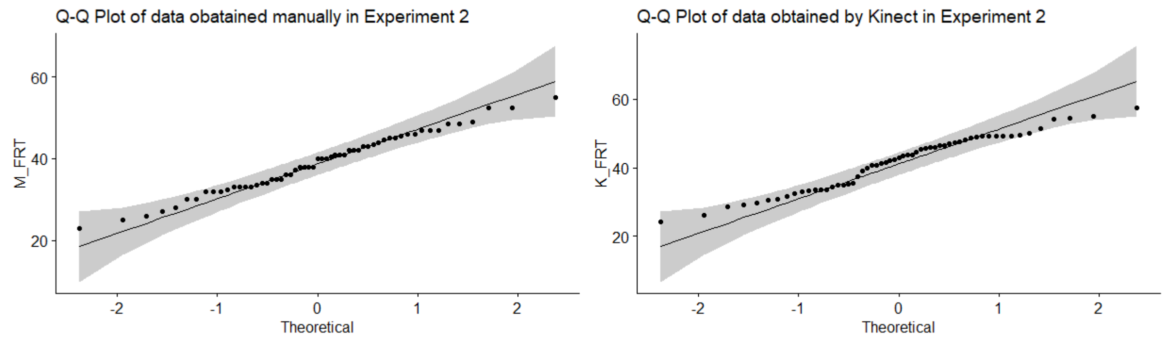
Results

To see the difference between the means of the two sets of data, we used the paired t-test. The null hypothesis is that true difference in means is equal to 0. As shown in Table 4.7, the p-value is much less than 0.05 so the null hypothesis is rejected and there is statistically significance difference in average means of the measures obtained by the two methods which is not correct since we know from Experiment 1 that there are no statistically significant differences in the average. Also we applied an analysis of the statistical power of the test performed, and the result indicated that we would need 9 subjects to detect an absolute mean difference of 2.63 cm ($\pm$2.4) between the standard FRT and the experimental system.

As the t-test yielded wrong results, we applied the other tests previously mentioned in order to correct the data. In terms of Shapiro-Wilk normality test, its outcomes (test statistic W and p-value) on the data obtained manually using the poster (M_FRT) and by the system using Kinect (K_FRT) are shown in Table 4.8. The null hypothesis for this test is that the data are normally distributed. The p-value of the data in both methods (M_FRT) and (K_FRT) is greater than 0.05 then the null hypothesis is maintained. Thus, we can assume that our data are approximately normally distributed. Visual inspection using normal Q-Q plots indicates also that the data obtained by both methods are approximately normally distributed as it can be seen in Figure 4.8 where the dots are approximately distributed along the line. To these data, we then applied Pearson Correlation Test to measure the strength of a linear relationship between the data obtained with the two methods: manually and using Kinect. The correlation coefficient obtained is equal to 0.95 with a p-value less than the significance level 0.05 (p-value < 2.2e-16). Hence, we can conclude that the FRT values obtained by Kinect and those measured manually are significantly correlated. This can also be shown visually in Figure 4.9 where the scatter plot shows linear correlation between the data.

Table 4.8 Shapiro-Wilk normality test applied to data of Experiment 2.

	M_FRT	K_FRT
W	0.98	0.96
p-value	0.83	0.10



(a) (b)

Fig. 4.8 Q-Q Plot of data of Experiment 2 (a) M_FRT and (b) K_FRT.

Given that we demonstrated that the data is linearly correlated, we made a linear model and corrected the K_FRT data. Regression results gave a slope coefficient of 0.86 and adjusted R-squared value of 0.91 which means that the regression model explains 91% of the variability in the observations. In order to inspect visually the linear regression assumptions, we examined the residual plots shown in Figure 4.10. The first is a constant variance plot, which checks for the homogeneity of the variance and the linear relation. There is no obvious pattern in this graph, then linearity assumption is met. The second plot in the graph is a Q-Q plot, which checks if residuals are normally distributed. The points fall on a line hence the normality assumption is also met. The third plot allows to detect heterogeneity of the variance while the fourth plot allows for the detection of points that have a large impact on the regression coefficients. Visual inspection to these plots show that the assumption of equal variance (homoscedasticity) is met and there is no influential cases. We can then say that the model works well for the data.

At the end, we re-applied the paired t-test using the corrected data and we found this time a p-value higher than the significance level 0.05 indicating that there are no statistical significant differences between the averages of measures obtained by both methods. Results of the t-test after data correction are shown in Table 4.9.

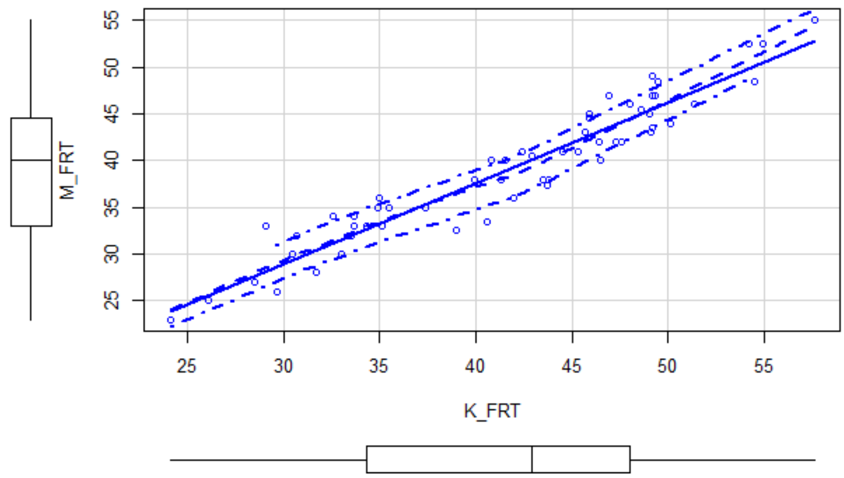


Fig. 4.9 Scatter plot of the data obtained by the experimental system and manually in Experiment 2.

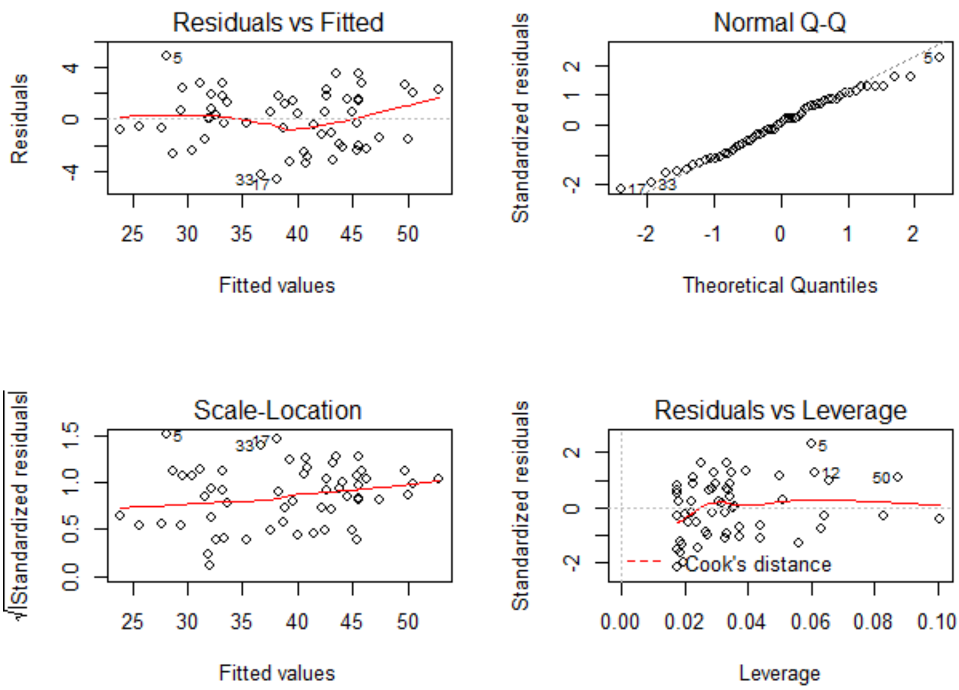


Fig. 4.10 Residual plots generated from the linear regression model in Experiment 2.

Table 4.9 Results of paired t-test applied to data of Experiment 2 after correction.

t = -0.00042
p-value = 0.99
Difference = -0.00012

4.4 Discussion

With the aim to validate the use of vision-based systems for measuring the Functional Reach Test (FRT), we compared FRT values measured using Microsoft Kinect with those measured manually. In Experiment 1, participants performed the FRT interchangeably between the manual way and using the system. Results showed an average absolute difference of 2.84 cm and no statistical significant difference was found applying a paired t-student test to the data. These results suggest that Microsoft Kinect can be used to measure the FRT. An Ad-hoc analysis of the statistical power of the test performed indicated that the smallest statistical difference that could be detected with 14 subjects was 3.9 cm, therefore as a future work it would be interesting to perform the experiment on a larger sample in order to detect minor differences between the FRT obtained by the standard way and the values obtained by the system and thus be able to validate more efficiently the RGBD devices for measuring this balance test. After the release of Kinect v2, a second experiment was conducted in order to improve and further validate the system with the aim to prepare for a clinical study with elderly people or people with balance problems in general. In Experiment 2, the data were acquired simultaneously by the standard way and the experimental system and we found that the measurements obtained by both methods are linearly correlated. Thus, we applied a linear regression model to correct the data acquired using Kinect. Examination of regression assumptions showed that the model explains well the data and applying the paired t-test to the data after correction indicated that there is no statistical significant difference between the measurements obtained by both methods. Consequently, the measurements obtained with Kinect v2 in this second experiment seemed valid but not correct, hence a correction has to be applied whereas the measurements obtained using Kinect v1 in the first experiment need not to be corrected.

Few studies used RGBD sensors for the measurement of the FRT. For instance, Clark et al. investigated the use of Kinect v1 [37] and then the use of Kinect v2 [38] in measuring the forward reach through Multi-Directional Reach Test (MDRT). In comparison with the FRT, MDRT measures the limits of stability in the anterior-posterior and medial-lateral directions.

In both their studies, they compared the results with those obtained by a marker-based three Dimensional Motion Analysis (3DMA) system. In the most recent study [38], the authors computed the reach distance through trunk flexion and concluded that Kinect could be used in instrumenting the reach test by providing excellent validity for trunk angle data. They also observed fixed biases in both reach tasks and noted that Kinect v2 results were lower than those returned by the 3DMA system. Similarly, Moreno et al. [115] also studied the validation of depth cameras for the parameterization of the MDRT. To do that, they used PrimeSense and compared it with inertial sensors intertiaCubre3^{TM}. Authors acquired kinematic data from both systems and comparisons revealed strong correlation in most of the evaluated variables of the MDRT. At the end, they concluded that depth cameras could be an alternative for the inertial sensors in instrumenting this test.

A similar work to our first experiment as a published work [10] may be the study conducted by Galen et al. [53] who sought the validity of an interactive function reach test. To achieve their aim, they used wrist joint data from Kinect v1 SDK with the camera set on the left of the user. They computed the reach distance and compared it with the outcomes obtained simultaneously by the Optotrak Certus 3D motion-capture system. They set the experiment with three different distances from the Kinect sensor: at 2 m, 2.5 m, and 3 m, with the best agreement was reported at 2.5 m. However, they noted that there was no optimal distance with minimal measurements errors. Even so, the mean measurement found at 2.5 m distance from the camera was 4.92 cm; a value that lays within the minimal detectable change values of the FRT in stroke and Parkison's disease populations as reported by the authors. As for our experiment, we used the hand joint data provided by Kinect v1 to compute the FRT with the user facing the camera at 2 m distance; the user is best tracked while he is facing the sensor. We compared the values returned by the system with those measured by the physiotherapist however not simultaneously as in [53]. An average absolute difference in our study was found smaller than the one reported in the other experiment; however this result must be treated with extreme cautiousness since the participants' characteristics, such as age and balance impairment, in the two studies are different. In fact, old people and young people apply different balance strategies when reaching forward, thus affecting the functional reach test performance [177]. In addition, a larger sample is required to detect minor differences between the standard FRT and the experimental system. As for display interface, we used mirror feedback where the user can see himself on the screen all time whereas Galen et al. employed a wireframe skeleton avatar to represent the user [53]. Both works have strengths and limitations, that's why we are constantly improving the system and the design of the experiments.

Finally, the experiments conducted in our work were held in laboratory settings and the volunteers were from university students and staff. The experiments came after the development of the system prototype for testing the validation of Kinect in measuring the functional reach test. These experiments were very important since they allowed us, in addition to compare the measurements of the system with those obtained manually, to test for the robustness of the system and the design of any future study with elderly people in terms of number of repetitions of the test, posture, etc. Some other limitations related to these experiments may include the variability within the trials of the same measurement performance as indicated in Table 4.6 for example, which can be due to the young age of participants and the fact that sometimes they are not reaching as far as they can comparing to other times.

In future work, it is intended to clinically validating these vision-based systems for measuring the Functional Reach Test with elderly population or participants with balance impairment, and certainly with larger sample size as balance deficits limit the variability of measuring the test and improve its reliability.

4.5 Lessons learned

A clinical test may differ from a serious game in several aspects, thus in this section we wanted to share some of the lessons that we have learned through the validation of Kinect in measuring the FRT.

- Know the test: It is very important to learn about the test to be transformed into an interactive system, see how it is performed, and identify the different elements that may affect the outcome result of the test, etc. For example, the standard FRT is performed close to a wall, however in some early tests with Kinect the performance of the test was done far from any support. In that case, some users did not reach forward as maximum as they can in comparison to the performance of the standard test, when asked why, they reported that the wall provided some sense of security.

- Technology used: Precision and accuracy are not that much required in games as in clinical tests, so it is recommended to see if the technology chosen for replacing the old way of measurement is capable of providing acceptable results. Kinect for example is well known to be used for gross movements in serious games; however the accuracy of its depth information has also been proven. Other considerations may include the position of the user with respect to the camera and the distance from the sensor, among others.

- Working with physiotherapists: As highlighted before, the coordination with the physiotherapist is very important. In our case, the physiotherapist helped us so much in correcting the posture of the user when performing and validating the test.
- Laboratory tests: They are very important in testing the robustness of the system, the design of the intervention (duration of the test, number of repetitions, etc.), and revealing possible issues related to the system or the performance of the test. Besides, a target group such as elderly or individuals with balance impairment is not easily accessible as in the case with healthy and young participants from the university.
- Comparison with other studies: In comparing with other studies, we have to be attentive to the differences related to the system, the measurement procedure, or the results. We should take into account things such as the test settings (laboratory, home, residence) and the target group (young, elderly, healthy, with or without balance impairments), among others.

4.6 Summary of the chapter

In this chapter, we presented an experimental system to assess the Functional Reach Test (FRT) with RGBD device, namely the Microsoft Kinect. The system, with the help of a specialist, indicates to the user what to do step by step, and internally measures its FRT. The system presented is preliminary validated, the results showed an average absolute difference of 2.84 cm ($\pm$2.62) and applying a paired t-student test for the data, where the hypothesis was there is no difference in the average, indicates that there are no statistically significant differences. Moreover, the analysis of statistical power test indicated that the lower statistical difference that could be detected with 14 subjects was 3.9 cm, therefore it would be appropriate to perform the experiment on a larger sample to detect minor differences between the FRT and the experimental system and thus to validate more efficiently the RGBD devices for measuring the FRT. A second experiment was done to further validate its use with Kinect v2. The measurements were obtained simultaneously by the experimental system and manually and results indicated that they had strong linear correlation. Hence, a linear regression model was applied to correct the Kinect measurements and results indicated that there are no statistical differences between the measurements computed using the two methods when a paired t-test was applied to these corrected data. These preliminary results suggest that the RGBD devices, namely Microsoft Kinect, are suitable for measuring the FRT.

Chapter 5

Conclusions and perspectives

With the constant growth of elderly population, some issues related to falls and fall-related injuries may arise in consequence of balance deterioration due to aging and inactivity, hence leading to high social, economic, and healthcare costs. To mitigate the effects of these falls, fall prevention strategies comprising physical activity and use of technology have been encouraged. In fact, vision-based technologies have been increasingly adopted for exercising for elderly individuals. However, the deployment of such technologies without previous investigation and validation may result unsafe for this category. Therefore in this thesis, we studied and proposed some interactive systems based on computer vision technologies with the aim to minimize the risk of falls among older adults.

First, we have conducted a systematic literature review about vision-based serious games and virtual reality systems used for motor rehabilitation. To do that, we followed Kitchenham guidelines to extract the relevant research studies and used Downs and Black checklist for randomized and non randomized clinical trials to evaluate the included articles. Then, we analyzed the data according specific research questions covering aspects addressed by researchers such as trends, technologies, tasks, and target groups, among others. Findings indicated that the number of studies in this field is increasing, with Korea and USA in the lead. We found that Kinect, EyeToy system, and GestureTek IREX are the most commonly used technologies and that cerebral palsy and stroke patients are the main target groups where elderly patients and exercises for postural control and upper extremity rehabilitation were of particular focus. On the light of the results of this review, we proposed a research methodology in the hope that it may assist engineers in better designing and reporting their clinical trials. The methodology was specifically elaborated for the context of vision-based systems as they are increasingly deployed for rehabilitation and healthcare applications.

That said, there are still few open questions and future research directions about this field. For instance, the studies often discuss the results of a clinical trial during a well-defined period of time however most of them do not conduct follow-ups. The lack of the long-term efficacy could avoid their use on real environments. In addition, there are systems that are used and deployed in hospitals but there are no reports or publications in that regard as the industrial companies that made such systems have no research interest. Hence, the number of publications is not always a true reflection to which extent these systems are used. Moreover, vision-based systems implicate free controller systems where people interact with body movements, however no monitoring done for these movements. For elderly targets who have limitations, forcing these movements could hurt them in long run.

Second, we designed and developed a set of prototype games for balance rehabilitation addressed to elderly target. The design and development process was done according to a framework and guidelines for development games for rehabilitation and administered by a physiotherapist. To study the effectiveness of these games, we conducted a case study in an elderly house in Tunisia. To the best of our knowledge, it was the first study conducted with elderly people and Kinect-based games. We assessed feasibility by examining recruitment, adherence, and safety. The Tinetti balance test was used as pretest and posttest assessments. Results showed that adherence was very high and no adverse effects were registered during the sessions. The included participants also reported enjoyment during the playtime and exhibited improvements in Tinetti scores. These preliminary results were promising and indicated that the games can be deployed in fall prevention programs.

A future work may include conducting a randomized controlled trial with a larger sample size of elderly participants. In addition, we have been recommended to design more games that can be used to improve both static and dynamic balance.

Third, we developed a system that measures the Functional Reach Test (FRT); a balance test that determines the limits of stability of an individual by computing the maximal distance he or she can reach forward. For an effective rehabilitation program, it is important to measure the balance ability of an individual. It serves as determining the right exercises to include in the therapy and monitoring the progress of the patients as well. In that regard, FRT test has the ability to detect falls among older adults. An experiment was performed on 14 healthy users to compare the FRT calculation manually and using an RGBD device. Results indicated an average absolute difference of 2.84cm ($\pm$2.62) and there are no statistically significant differences applying a paired t-student test to the data. Another experiment was conducted for the same purpose. In this experiment, a strong linear correlation was found between the measurements obtained by the standard way and the experimental system. Consequently, a linear regression model was applied to correct the data acquired using Kinect. Examining the regression assumptions showed that the model works well for the data and applying the paired t-test to the data after correction indicated that there is no statistical significant difference between the measurements obtained by both methods. This suggested that Kinect device is reliable and adequate to calculate the standard Functional Reach Rest (FRT).

A continuation of this work is by recruiting elderly participants to perform the test using our experimental system. At the end, Functional Reach test is just a case study of other possible therapeutic measures that could be studied since the thesis aim is more general. Thus, an extension of this work could be studying the validity of computer vision technologies in measuring other balance tests such as Berg Balance scale and Timed up and Go test.

Finally, it is worth noting that Kinect sensor has been discontinued but the technology itself is still existing in other commercial products. The algorithms and applications developed using Kinect remain effective and valid since new devices keep appearing on the market and replacing the old ones. Ultimately, we note again that vision-based systems implicate free controller systems and require body movements, if not monitored an older adult may perform movements that prove to be uncomfortable or harming in long term. RGBD sensors, Kinect for example, may fail in robust monitoring due to occlusions caused by body parts. Thus, wearable sensors can be a solution for this issue by defining some thresholds of the movement to be performed. In fact, combining wearable sensors with vision-based systems may lead to interesting results and more effective outcomes.

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Appendix A

Research protocol

In order to ensure a rigorous search process, we defined a research protocol that identifies both research questions to be addressed and methods to be used. Consequently, we extracted data related to our research questions as defined in Chapter 2. The data comprised the year and country of the included studies to understand the trends in this area of research. In addition, quality of each study was computed using the Downs and Black checklist for assessing randomized and non randomized studies. Besides, information about the participants recruited for the clinical study including their age and pathology, and the study design whether uncontrolled, controlled, or randomized controlled trial were also extracted. Other data included platform and technology used, and the tasks and game elements described in the studies.

Table A.1 Data extracted from the included studies

First author Year	**Country**	**Quality**	**Population**	**Study design**	**Platform or technology interface/ game type**	**Task and game elements**
Chen et al. [32] 2007	Taiwan USA	10	EG: 4 participants with spastic CP Age: 6.3 CG: none	UCT	- Sony PlayStation 2 EyeToy/ commercial games - VR-based hand rehabilitation training System using 5 digital data glove (haptic and auditory feedback) /prototype games	- EyeToy games: Bubbles, Seaworld, Wishi-Washi, Rocket Rumble, UFO Juggler, Slap Stream, KungFoo, and Boxing Chump - Prototype games: Reach and grasp a moving object (butterfly) or stationary objects in different directions (peg-board and pick-and-place blocks)

Table A.1 continued from previous page

Flynn et al. [51] 2007	USA	7	EG: 1 post stroke participant Age: 76 CG: none	UCT	Sony PlayStation 2 EyeToy/ commercial games	Eyetoy games: Air Guitar, Bubblepop, Colors, Do It Yourself (DIY), Drummin', Goal Attack, Homerun, Knockout, Kung 2, Monkey Bars, Mr. Chef, Pool, Secret Agent, Solar System, and Table Tennis
Bisson et al. [17] 2007	Canada	11	EG1: 14 healthy participants Age: 74.4 (3.65) EG2: 14 healthy participants Age: 74.4 (4.92) CG: none	UCT	- GestureTek IREX/ commercial games - Force platform/ prototype visual biofeedback exercise	- IREX game: Juggler - Biofeedback training: control the centre of pressure while reaching as far as possible to four different corners in a non-random manner
Rand et al. [141] 2008	Israel	11	EG: 12 participants with stroke: - 7 at chronic stage: Age: 63 (11) - 5 at subacute stage: Age: 73 (11) CG: none	UCT	Sony PlayStation 2 EyeToy/ commercial games	EyeToy games: Wishy-Washy and Kung-Foo
Jannink et al. [71] 2008	Netherlands	11	EG: 5 participants with CP Age: 11 years, 9 months (2,3) CG: 5 participants with CP Age: 12 years, 3 months (3,2)	RCT	Sony PlayStation 2 EyeToy/ commercial games	EyeToy games: Kung Foo, Wishy Washi, and Keep Ups
Yavuzer et al. [196] 2008	Turkey	16	EG: 10 participants with hemiparesis stroke Age: 58.1 (10.2) CG: 10 participants with hemiparesis stroke Age: 64.1 (5.8)	RCT	- Sony PlayStation 2 EyeToy/ commercial games	EyeToy games: Kung Foo, Goal Attack, MrChef, Dig and Home-Run

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Cameirao et al. [26] 2009	Spain	13	EG: 7 participants with stroke Age: ≤ 80 years CG1: 4 participants with stroke Age: ≤ 80 years CG2: 3 participants with stroke Age: ≤ 80 years	RCT	Rehabilitation Gaming System (RGS): arm movements are tracked by means of a vision based tracking system (AnTS) that detects color patches located on the wrists and elbows using a video camera. The finger flexion is captured by optic fiber data gloves that integrate seamlessly with the system via a USB connection/ prototype game	Prototype game: it consists of three tasks: -'Hitting' task: intercept approaching spheres that are flying towards the player -'Grasping' task: the intercepted spheres have to be simultaneously grasped through finger flexure -'Placing' task: the spheres have to be grasped and then released in a basket that matches their corresponding color
Guberek et al. [58] 2009	Canada	7	EG: 12 participants with CP Age: 9 (1.34) CG: none	UCT	GestureTek IREX/ commercial game	IREX game: Zebra Crossing: touch as many stars as possible while advancing along the crosswalks

Table A.1 continued from previous page

Lotan et al. [96] 2009	Israel	14	Study1: EG: 17 participants with mild to moderate levels of IDD and severe physical limitations Age: 28.1 (5.3) CG: 15 participants with mild to moderate levels of IDD and severe physical limitations Age: 28.1 (5.3) Study2: EG: 30 participants with moderate levels of IDD and different levels of physical limitations Age: 52.3 (5.8) CG: 30 participants with moderate levels of IDD and different levels of physical limitations Age: 54.3 (5.4) Study3: EG: 24 participants with severe levels of IDD Age: 52.3 (5.8) CG: 28 participants with severe levels of IDD Age: 54.3 (5.4)	RCT	Study1: GestureTek IREX/ commercial games Study2: Sony PlayStation 2 EyeToy/ commercial games Study3: GestureTek IREX/ commercial games	- IREX games :Birds and Balls, Soccer, Drums, Car racing, Juggler, Ocean, and Parachute - EyeToy games: Kung-Foo and washing windows
Kim et al. [80] 2009	Korea	16	EG: 12 participants with hemiparetic stroke Age: 52.42 (10.09) CG: 12 participants with hemiparetic stroke Age: 51.75 (7.09)	RCT	GestureTek IREX/ commercial games	IREX games: Stepping up/-down, Sharkbait, and Snowboard

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Sucar et al. [174] 2010	Mexico	13	EG: 22 participants with stroke Age: 47.9 CG: 20 participants with stroke Age: 51.9	RCT	Gesture therapy: a vision-based system using a low cost camera and a gripper/ prototype games	Prototype games: stove cleaning, window mopping, fish cashing, fruit shopping, flower watering, driving, etc.
Lotan et al. [96] 2010	Israel	16	EG: 20 participants with severe IDD Age: 47.9 (8.6) CG: 24 participants with severe IDD Age: 46.2 (9.3)	RCT	GestureTek IREX/ commercial games	IREX games: Birds and Balls, Soccer, Juggler, Ocean, and Parachute
Chang et al. [29] 2011	Taiwan	12	EG: 2 participants with motor impairments Age: 16 and 17 CG: none	UCT	Microsoft Kinect/ prototype game	Prototype game: the projector displayed animation of a singing whale with its tail flipping on the surface of the sea. The patients do rehabilitation movements: (1) lifting both arms to the front, (2) lifting both arms to the side and (3) lifting both arms upwards. The more accurate their movement is, the more the flipping is and the louder the whale singing is
Brien and Sveistrup [22] 2011	Canada	12	EG: 4 participants with CP Age: 16 (2.25) CG: none	UCT	GestureTek IREX/ commercial games	IREX games: Soccer, Snowboard, Sharkbait, Zebra Crossing, and Gravball
Sandlund et al. [155] 2011	Sweden	15	EG: 14 participants with CP Age: 10 years and 11 months CG: none	UCT	Sony PlayStation 2 EyeToy/ commercial games	20 different games of the EyeToy game Play3

Table A.1 continued from previous page

Bilde et al. [15] 2011	Denmark	13	EG: 9 participants with CP Age: 10.33 (2.39) CG: none	UCT	MiTii training system (Move It To Improve It) using web-camera/ prototype games	Prototype games: a number of training modules in which the child has to analyze visual information, solve a cognitive problem (i.e. mathematical question or similar) and respond with a motor act (i.e. bend to pick up needle and blow up balloon with the right answer)
Pastor et al. [133] 2012	USA	5	EG: 1 participant with stroke Age: 46 CG: none	UCT	Microsoft Kinect/ prototype game	Prototype game: control a cursor on the screen by moving their hand on top of a transparent support in order to select images that randomly appear in any cell of a 6X6 grid
Cameirao et al. [27] 2012	Spain Portugal Italy	13	EG1: 16 participants with chronic stroke Age: 68.7 (10.9) CG1: 14 participants with chronic stroke Age: 59.4 (9.7) CG2: 14 participants with chronic stroke Age: 59.9 (13.0)	RCT	Rehabilitation Gaming System (RGS)/ prototype game	Prototype game: a bimanual virtual task named Spheroids: the user intercepts and grasps spheres moving toward him
Llorens et al. [93] 2012	Spain	12	EG: 15 participants with chronic stroke Age: 51.87 (15.57) CG: none	UCT	BioTrak system integrating Microsoft Kinect/ prototype game	Prototype game: stepping on different items rising from the floor around a central circle

Table A.1 continued from previous page

Chen et al. [31] 2012	Taiwan	12	EG: 22 older adults with disabilities Age: 78.55 (6.70) CG: 39 older adults with disabilities Age: 79.52 (7.01)	CT	Microsoft Xbox 360 Kinect/ commercial games	Kinect games:three games in "Dr. Kawashima's Body and Brain Exercises": - Mouse mayhem: "touch" mice that will pop out from four different pipes located at four different corners on the TV screen - Follow the arrow: Red arrows pop out from five different directions and players have to point out those arrows within 5 seconds to get points - Matchmaker: Lots of colorful figures pop out on the screen and players have to match the same figures by using both hands to get points
Ilg et al. [68] 2012	Germany	13	EG: 10 children with Ataxia Age: 15.4 (3.5) CG: none	UCT	Microsoft Xbox Kinect/ commercial games	Kinect games: Table Tennis, Light Race, and 20000 Leaks
Lee and Song. [90] 2012	Korea	15	EG: 27 participants with type 2 diabetes Age: 73.8 (4.77) CG: 28 participants with type 2 diabetes Age: 74.3 (5.20)	RCT	Sony PlayStation 2 EyeToy/ commercial games	EyeToy games: Wishi Washi, Keep Ups, bowling, bubble pop, boot camp, and Kung foo
Kwon et al. [83] 2012	Korea	15	EG: 13 participants with acute hemiparetic stroke Age: 57.15 (15.42) CG: 13 participants with acute hemiparetic stroke Age: 57.92 (12.32)	RCT	GestureTek IREX/ commercial games	IREX games: Bird and Ball, Drum, Coconutz, Soccer, and Conveyor

Table A.1 continued from previous page

Cho et al. [33] 2012	Korea	16	EG: 15 participants with stroke Age: 64.0 (7.1) CG: 14 participants with stroke Age: 63.7 (8.8)	RCT	GestureTek IREX/ commercial games	IREX games: Bird and Balls, Coconuts, Drums, Juggler, Conveyor, and Soccer
Ashkenazi et al. [8] 2013	Israel	14	EG: 9 participants with DCD Age: 5.6 (0.5) CG: none	UCT	PlayStation 2 Eye-Toy/ commercial games	EyeToy games: Volleyball, Bowling, Touchdown , Music games, Boot camp, Ghost, Kitty, and Monkey
Lee [86] 2013	Korea	14	GG: 7 participants with stroke Age: 71.71 (9.14) CG: 7 participants with stroke Age: 76.43 (5.80)	RCT	Microsoft Xbox Kinect/ commercial games	Kinect games: - Kinect sports (Boxing and Bowling) - Kinect adventure (Rally Ball, 20.000 Leaks, and Space Pop)
Sin and Lee [167] 2013	Korea	19	EG: 18 participants with hemiplegic stroke Age: 71.78 (9.42) CG: 17 participants with hemiplegic stroke Age: 75.59 (5.55)	RCT	Kinect Xbox 360/ commercial games	Kinect games: - Kinect sports: Boxing and Bowling - Kinect adventure : Rally Ball, 20,000 Leaks, and Space Pop
Ortiz-Gutierrez et al. [128] 2013	Spain	14	EG: 25 participants with Multiple Sclerosis Age: 39.69 (8.13) CG: 25 participants with Multiple Sclerosis Age: 42.78 (7.38)	CT	Kinect Xbox 360/ commercial games	Kinect games: Kinect Sports, Kinect Joy Ride, and Kinect Adventures
Luna-Oliva et al. [101] 2013	Spain	16	EG: 11 participants with CP Age: 7.91 (2.77) CG: none	UCT	Kinect Xbox 360/ commercial games	Kinect games: Kinect Sports I, Kinect Joy Ride, and Kinect Disneyland Adventures

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Peters et al. [135] 2013	USA	12	EG: 5 participants with chronic stroke Age: 69.4 (9.2) CG: 7 participants with chronic stroke Age: 65.0 (7.5)	RCT	- Sony PlayStation 2 EyeToy/ commercial games	EyeToy games: Play 2 and Kinetic
Bao et al. [13] 2013	China USA	12	EG: 5 participants with subacute stroke Age: 61.4 (7.9) 18 healthy participants Age: 59.2 (5.0) CG: none	UCT	Kinect Xbox 360/ commercial game	Kinect games: Fruit Ninja game: when fruit pops up on the screen, patients need to use their paretic hands to slice the fruit immediately
Kim et al. [79] 2013	Korea	17	EG: 18 healthy older adults Age: 68.28 (3.74) CG: 14 healthy older adults Age: 66.21 (3.87)	RCT	Kinect Xbox 360/ commercial games	Kinect games: "Your Shape Fitness Evolved software, Zen" which includes movements derived from exercise programs based on Tai Chi and yoga
Lee and Shin. [89] 2013	Korea	16	EG: 27 participants with diabetes mellitus Age: 73.78 (4.77) CG: 28 participants with diabetes mellitus Age: 74.29 (5.20)	RCT	Sony PlayStation 2 EyeToy/ commercial games	EyeToy games: Wishi Washi, Keep Ups, bowling, bubble pop, boot camp, and Kung foo
Singh et al. [168] 2013	Malaysia	16	EG: 15 participants with stroke Age: 65.4 (9.8) CG: 13 participants with stroke Age: 67.0 (8.4)	CT	- Nintendo® Wii Fit Plus with Balance Board/ commercial games - Kinect Xbox 360/ commercial games	- Wii game: Balance Bubble - Kinect game: Rally Ball
Subramanian et al. [173] 2013	Canada	17	EG: 16 participants with chronic stroke Age: 60.0 (11.0) CG: 16 participants with chronic stroke Age: 62.0 (9.7)	RCT	Computer Assissted Rehabiliation ENvironment (CAREN) Optorak+ stereoscopic glasses / commercial game	CAREN game: A 3D VE (CAREN) simulated a supermarket scene. At the end of the aisle, participants have to point the finger toward 6 consumer products placed just beyond arm's length (shopping task)

Table A.1 continued from previous page

Jaume-i-Capo et al. [73] 2014	Spain	15	EG: 9 participants with CP Age: 27–57 CG: none	UCT	Microsoft Kinect/ prototype game	Prototype game: reach objects outside span user by moving center of mass (COM)
Sucar et al. [175] 2014	Mexico USA	8	EG: 6 participants with chronic stroke Age: 52.0 (14.66) CG: none	UCT	Gesture Therapy platform (GT): it is composed of a vision module which gets the input video stream from a camera and pressure data from a controller (gripper)/ prototype games	Prototype games: - Steak: touch the steak to prevent it from burning. - Clean window: remove stains from window glass - Fly killer: kill a buzzing mosquito that approaches at different heights with an insecticide sprayer (pressure sensor)
Manresa-Yee et al. [104] 2014	Spain	8	EG: 5 patients with CP Age: 5-41 CG: none	UCT	SINA: a vision-based interface which works with head movements to replace the mouse/ prototype games and exercises	Prototype games and exercises: - Action/reaction applications - Movement applications: - SINAPaint: drawing and painting - Cognitive applications: SINAMemory: matching pairs of cards by turning them. - The visualization of presentations: click on an element in the screen - Educative games and applications - Online educative and entertaining activities. - Internet surfing and communication applications
McEwen et al.[108] 2014	Canada	12	EG: 1 participant with dementia Age: 78 CG: none	UCT	GestureTek IREX/ commercial games	IREX games: Soccer, Snowboarding, Birds & Balls, Formula Racer, and Juggler.

Table A.1 continued from previous page

Vernadakis et al. [189] 2014	Greece	13	EG1: 21 previously injured young competitive male athletes Age: 16 (1) EG2: 21 previously injured young competitive male athletes Age: 16 (1) CG: 21 previously injured young competitive male athletes Age: 16 (1)	RCT	Microsoft Xbox Kinect/ commercial games	Kinect games: Rally Ball, Reflex Ridge, River Rush, and 2000 Leaks
Ulasli et al. [184] 2014	Turkey	7	EG: 1 participant with Metachromatic leukodystrophy (MLD) Age: 22 CG: none	UCT	Microsoft Xbox Kinect/ commercial games	Kinect sports games: dart game, tennis, and football
Pompeu et al. [137] 2014	Brazil USA	13	EG: 7 participants with PD Age: 72 (9) CG: none	UCT	Microsoft Xbox Kinect/ commercial games	Kinect adventures game: Space Pop, 20.000 Leaks, Reflex Ridge, and River Rush
Galna et al. [54] 2014	UK	8	EG: 9 participants with PD Age: 68.22 (8.27) CG: none	UCT	Microsoft Kinect/ prototype game	Prototype game: the players took on the role of a farmer picking fruit from a tractor. As the tractor moved through the environment, players had to reach out to pick fruit and drive (by stepping) to avoid obstacles

Table A.1 continued from previous page

Shin et al. [165] 2014	Korea	16	Study1: EG: 7 participants with chronic stroke Age: not specified CG: none Study2: EG: 9 participants with acute or subacute stroke Age: 46.6 (5.8) CG: 7 participants with acute or subacute stroke Age: 52.0 (11.9)	Study1: UCT Study2: RCT	RehabMaster™: a task-specific game-based VR rehabilitation system using PrimeSense™ 3D awareness sensor, infrared projectors combined with standard RGB and infrared CMOS image sensors/ prototype games	Prototype games/ exercises: - Imitate some of 40 different motions performed by an avatar - Underwater fire: use two weapons to target the fish on the display - Goalkeeper, Bug hunter: control a goalkeeper's (or hunter's) hands on the display to catch a football (or bug). - Rollercoaster: imitate the postures displayed by the system, which simulate those adopted during a rollercoaster ride
Rand et al. [140] 2014	Israel	13	EG: 15 post stroke participants Age: 29-69 CG: 14 post stroke participants Age: 42-78	RCT	- Microsoft Xbox Kinect/ commercial games - Sony PlayStation 2 EyeToy/ commercial games - Sony PlayStation 3 MOVE/ commercial games - SeeMe system using Microsoft Kinect/ commercial games	- Kinect games: Bowling and 20,000 Leaks - EyeToy games: Kung Foo and Slap Stream - Move game: Start the Party CD - SeeMe games: Ball and Cleaner
Lozano-Quilis et al. [100] 2014	Spain Saudi Arabia	20	EG: 6 participants with multiple sclerosis (MS) Age: 48.33 (10.82) CG: 5 patients with multiple sclerosis (MS) Age: 40.60 (9.24)	RCT	RemoviEM: Kinect-based virtual rehabilitation system / prototype games	Prototype games: - TouchBall: touch virtual objects with hands, before they disappear, keeping the feet in a predefined zone - TakeBall: move virtual objects from an initial position to a final position using both hands before they disappear - StepBall: step on virtual objects before they disappear

Table A.1 continued from previous page

McEwen et al. [109] 2014	Canada	20	EG: 30 post stroke participants Age: 62.2 (14.1) CG: 29 post stroke participants Age: 66.0 (15.8)	RCT	GestureTek IREX/ commercial games	IREX games: Soccer goaltending, Birds & Balls, Juggler, Conveyor, Sharkbait, Snowboarding, and Formula Racer
Ustinova et al. [185] 2014	USA	12	EG: 15 participants with mild-to-moderate chronic traumatic brain injury (TBI) Age: 30.6 (8.5) CG: none	UCT	Microsoft Xbox Kinect/ prototype games	Prototype games: Virtual Teacher (VT), Virtual Challenger (VC), Courtyard, Skateboard, Boat, and Octopus
Sandlund et al. [154] 2014	Sweden	12	EG: 15 participants with CP Age: 11 years and 1 month CG: none	UCT	Sony PlayStation 2 EyeToy/ commercial games	20 different games of EyeToy Play 3
Pavao et al. [134] 2014	Brazil	12	EG: 1 participant with spastic hemiplegic CP Age: 7 CG: none	UCT	Microsoft Kinect/ prototype games	Prototype games: the child saw himself: -projected inside an aquarium, which contained holes that had to be stopped using the upper or lower limbs -on top of a moving trailer, had to overcome obstacles by jumping, squatting and performing side-to-side movements of the body

Table A.1 continued from previous page

Ni et al. [121] 2014	Canada	12	EG: 8 participants with CP Age: 8-12 CG: none	UCT	Microsoft Kinect/ prototype games	Prototype games: - DodgeWall: focuses on lower limb movements; the users must contort themselves to fit through cutouts in large polystyrene foam walls moving toward them on a track - Reach: targets upper limb motions; the users reach for and grab food items from various points on the game screen and give them to their pet
Palacios-Navarro et al.[130] 2015	Spain Ecuador	14	EG: 7 participants with PD Age: 67 (3) CG: none	UCT	Microsoft Kinect/ prototype game	Prototype game: make lateral leg movements to reach one of the two moles, which were presented in a random order, either to the right or to the left of the user
Sato et al. [156] 2015	Japan	17	EG: 29 healthy participants Age: 70.07 (5.35) CG: 28 healthy participants Age: 68.50 (5.47)	RCT	Microsoft Kinect/ prototype games	Prototype games: - Apple game: grasp apples distributed using both arms - Tightrope standing game: users had to place their feet along a straight line (tight rope) and grab targets at specified time - Balloon popping game: pop balloons when they passed through the area where users' buttocks were by bending their hips and knees and squatting down - One-leg standing game: stand on one leg and use the knee to touch a ball that appeared in front it

Table A.1 continued from previous page

Hoda et al. [67] 2015	Canada Saudi Arabia Qatar	13	EG: 3 participants with stroke Age: 65 (12.5) CG: 45 healthy users as ground truth Age: 39 (13.7)	CT	Microsoft Kinect/ prototype games	Prototype games: - Basketball game: grab a ball and move it vertically to the net - Touching Cup game: reach a pill bottle, flex the fingers of the opened arm and grasp the box
Chen et al. [30] 2015	Taiwan China	14	EG: 6 post stroke participants Age: 68.5 (14.6) CG: none	UCT	Microsoft Kinect/ prototype game	Prototype game: upper extremity rehabilitation gardening game (UERG game): do gardening tasks by making reaching-to grasp activity, expend forward, abduction and adduction movements, compositionality movement, fine movement, balance and coordination movement by both hands
Shin et al. [164] 2015	Korea	20	EG: 18 participants with chronic stroke Age: 53.3 (11.8) CG: 17 participants with chronic stroke Age: 54.6 (13.4)	RCT	RehabMaster (PrimeSense)/ prototype games and exercises	- Rehabilitation training module that asks the participant to imitate specific motions that are performed by an avatar - Rehabilitation games that facilitate rehabilitation exercises using gaming concepts
Yoon et al. [198] 2015	Korea	19	EG: 20 participants with Brain tumor Age: 48.6 (11.3) CG: 20 participants with Brain tumor Age: 50.0 (17.5)	RCT	GestureTek IREX/ commercial games	IREX games: Birds and Balls, Conveyor, Drums, Juggler, Coconuts, and Soccer

Table A.1 continued from previous page

Straker et al. [172] 2015	Australia	19	EG: 10 participants at risk of DCD Age: 9–12 year olds CG: 11 participants at risk of DCD Age: 9–12 year olds	Crossover RCT	- Sony PlayStation 3 with Move and Eye input devices/ commercial games - Microsoft Xbox360 with Kinect input device/ commercial games	Range of non-violent games at the start of the Active video game condition: Sports Champions, Start the Party, TV Superstars, EyePet, Yourshape Fitness Evolved, Motion Sports, Kinect Adventures, Free Riders, Dance Central, Dr. Kawashima's Body and Brain Exercises Two further games; Racket Sports and Cross Board 7 were provided at around week 7 of the AVG condition to help maintain interest
Gonsalves et al. [55] 2015	Australia	14	EG: 21 children with DCD Age: 10-12 CG: 19 TD children Age: 10-12	CT	- Sony PlayStation 3 Move/ commercial game - Microsoft Xbox Kinect/ commercial game	- PlayStation Move Sports Champions: table tennis - Xbox Kinect Sports
Lee [88] 2015	Korea	13	EG: 10 participants with stroke Age: 63.3 (13.40) CG: none	UCT	GestureTek IREX/ commercial games	IREX games: Airborne Rangers, Birds and Balls, Coconut, Conveyor, Drums, Juggler, and Soccer
Lin and Chang [92] 2015	Taiwan	10	EG: 3 participants with development disabilities Age: (1) 4 years and 1 month, (2) 6 years and (3) 3 years and 11 months CG: none	UCT	External webcam + Scratch 2.0/ revised and remixed game already designed by another one	A video pop balloon game: As the balloon changes position, the user uses their hands (or any part of their body) to move in the air

Table A.1 continued from previous page

Zocolillo et al. [202] 2015	Italy	18	EG: 11 participants with CP Age: 6.89 (1.91) CG: 11 participants with CP Age: 6.89 (1.91)	Crossover RCT	Microsoft Xbox Kinect/ commercial games	Kinect games: - Kinect Adventures Package: Space pops, 20.000 Leaks, and Rally Ball - Three games in Kinect Sports package and were virtual simulation of three sports: box and volley mainly.
Ren et al. [145] 2015	China	15	EG: 20 healthy participants Age: 24.7 (0.9) CG: 20 healthy participants Age: 24.9 (1.2)	RCT	Microsoft Kinect/ prototype exercises	Prototype exercises: therapeutic symmetric abduction (SA), asymmetric abduction (ASA), symmetric flexion/extension (SFE), and asymmetric flexion/extension (ASFE) shoulder motions providing Kinect-based skeleton-matching feedback instead of traditional mirror feedback
Bower et al. [21] 2015	Australia	15	EG: 8 participants with stroke Age: 60.8 (16.1) CG: 8 participants with stroke Age: 60.9 (14.0)	RCT	PrimeSense ‘Carmine’ depth camera/ prototype games	Prototype games: Ball Maze, Fridge Frenzy, Tentacle Dash, and Bubble Fish involving weight shifting movements of the torso and upper limb activity.
Karahan et al. [77] 2015	Turkey	19	EG: 48 healthy participants Age: 71.3 (6.1) CG: 42 healthy participants Age: 71.5 (4.7)	RCT	Kinect Xbox 360/ commercial games	Kinect games: Kinect Adventures, Kinect Sports, and Kinect Sports Season two
Song et al. [16] 2015	Korea	13	EG: 20 participants with stroke Age: 51.37 (40.6) CG: 20 participants with stroke Age: 50.10 (7.83)	RCT	Microsoft Xbox Kinect/ commercial games	Kinect games: Kinect Sport, Kinect Sport Season 2, Kinect Adventure, and Kinect Gunstri
Iosa et al. [69] 2015	Italy	14	EG: 4 participants with stroke Age: > 65 years CG: none	UCT	Leap motion controller/ prototype game	Leap motion games: caterpillar count and dots

Table A.1 continued from previous page

Ofli et al. [125] 2016	USA Czech Republic	11	EG: 6 independently living elder participants Age: 74-91 CG: none	UCT	Microsoft Kinect/ prototype games and exercises (interactive coaching system)	A set of 12 exercises, which included activities of upper and lower extremities, primarily focusing on improving balance and strength
Shih et al. [163] 2016	Taiwan	19	EG: 10 participants with PD Age: 67.5 (9.96) CG: 10 participants with PD Age: 68.8 (9.67)	RCT	Microsoft Kinect/ prototype exercises	Prototype exercises: - Reaching task 1: Standing in a given area and reaching toward a stationary target at different heights, depths and in different directions - Reaching task 2: Standing in a given area and tracking a moving object while extending arm and immersing the hand into the object as it flew in 3D space - Obstacle avoidance: Standing in a given area and preparing to avoid upcoming obstacles that randomly approached from varying directions by moving body sideways or up/-down - Marching: Alternating steps without going forward while following dynamic bars that automatically rose and fell at a predetermined speed and frequency
Bronner et al. [23] 2016	USA	13	EG: 14 healthy participants Age: 26.6 (9.5) CG: none	UCT	Kinect Xbox 360/ commercial games	Kinect games: Dance Central for the Xbox 360

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Sevick et al. [160] 2016	USA	11	EG: 4 participants with CP Age: 8–17 CG: none	UCT	Microsoft Kinect+ free Internet videogames/ commercial games	Free internet games focusing on upper extremity movements: Refriger-Raiders (Jerry), Refriger-Raiders (Tom), What's the Catch (Jerry), Robot Unicorn Attack, Fruit Ninja, Tower-Inator, Angry Birds, GrumbleGum, Star Wars: Jedi vs. Jedi, Shotgun vs. Zombie, Lateral Collateral 2, Highway Madness, Penalty Shootout, Hoops Mania, Air Hockey, Marathon Runner, Upstream Kayaking, G-Switch, Basket Shot, Harry Potter Quiddithch, Cyclomaniacs, Spiderman Racing, Ultimate Baseball, 1 on 1 Soccer, Guitar Geek, and Music Catch 2
Seamon et al. [159] 2016	USA	8	EG: 1 participant with Progressive Supranuclear Palsy Age: 65 CG: None	UCT	Microsoft XboxKinect/ commercial games	Kinect game YourShape : Pump It, Yoga, Wall Breaker, and Stack 'Em Up
Rand et al.[142] 2016	Israel	19	EG: 13 participants with stroke Age: 59.1 (10.5) CG: 11 participants with stroke Age: 64.9 (6.9)	RCT	Sony PlayStation 2 EyeToy/ commercial games Microsoft Xbox Kinect/ commercial games	Kinect games: Bowling (Sports CD), Table Tennis (Sports CD), 20,000 Leaks (Adventures CD) EyeToy games : Wishi washi, Ghosts, Kong fu (CD 1)
Turkbey et al. [183] 2017	Turkey	19	EG: 10 participants with stroke Age: 38–79 CG: 9 participants with stroke Age: 47–79	RCT	Microsoft Xbox Kinect/ commercial games	Kinect games: Bowling and Mouse Mayhem

Table A.1 continued from previous page

Collado-Mateo et al. [40] 2017	Spain	21	EG: 41 participants with fibromyalgia Age: 52.43 (9.83) CG: 35 participants with fibromyalgia Age: 52.58 (9.42)	RCT	Microsoft Kinect/ prototype game	VirtualEx-FM compromising three environments: - Warm-up: imitate the movements that appear on the screen - Postural control and coordination : interact with an apple that appears and disappears around them - Mobility skills, balance and coordination: step on virtual footprints.
Lee et al. [87] 2017	Taiwan	20	EG: 26 participants with stroke Age: 59.35 (8.95) CG: 21 participants with stroke Age: 55.76 (9.59)	RCT	Microsoft Xbox Kinect/ commercial games	Kinect games: - Kinect Sports (Darts, Golf, Table Tennis, and Bowling) - Your Shape: Fitness Evolved (Virtual smash and Light race) - Kinect Adventures (Space pop, Rally Ball, and River rush)
Park et al. [131] 2017	Korea	17	EG: 10 participants with stroke Age: 62 (17.14) CG: 10 participants with stroke Age: 65.30 (10.51)	RCT	Microsoft Xbox Kinect/ commercial games	Kinect games: - Kinect Sports Pack: boxing, table tennis, and soccer - Kinect Sports Pack 2: golf, ski, and football
Camara et al. [25] 2017	Brazil	14	EG: 28 participants with CP Age (months): 73.34 (34.06) CG: none	UCT	Microsoft Xbox 360 Kinect/ commercial games	Kinect games: - Kinect Motion Explosion package: Balance Beam and Star Hop
Vanbellingen et al. [187] 2017	Switzerland Netherlands	13	EG: 13 participants with stroke Age: 24–91 CG: none	UCT	Leap motion controller/ commercial games	Free access games in the Leap Motion App Store©: Dots Trial, Cut the Rope, Playground, and American Sign Language Digits

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Wang et al. [191] 2017	China	21	EG: 13 participants with stroke Age: 55.33 (8.40) CG: 13 participants with stroke Age: 53.38 (7.65)	RCT	Leap motion controller/ commercial games	Leap motion games: petal-picking game, piano-playing game, Robot-assembling game, object-catching with balance board game, firefly game, and bee-batting game
Oña et al. [126] 2018	Spain	9	EG: 5 participants with PD Age: 45-72 CG: none	UCT	Leap motion controller/ prototype games	Prototype games: - Piano: press a piano key with the appropriate finger Reach Game: touch a cube on the screen - Sequence Game: memorize a sequence reproduced through color change - Pinch Game: move a cube by closing and opening the hand - Grab Game: resize the cube until it disappears by performing pincer movements - Flip Game: spin the palm towards to rotate a tray
Nuic et al.[122] 2018	France	15	EG: 10 participants with PD Age: 64.0 (5.8) CG: none	UCT	Microsoft Xbox Kinect/ prototype game	Prototype game: Toap Run :collect coins and avoid obstacles in three different environments
Aşkın et al. [9] 2018	Turkey	19	EG: 18 participants with stroke Age: 53.27 (11.19) CG: 20 participants with stroke Age: 56.55 (9.85)	RCT	Microsoft Xbox Kinect/ prototype games (KineLabs)	Two games of KineLabs developed by a research team of Hong Kong Polytechnic University: - Good View Hunting: clean or delete dirty spots - Hong Kong Chef: making food

Table A.1 continued from previous page

Adams et al. [4] 2018	USA	13	EG: 15 participants with stroke Age: 46-91 CG: none	UCT	Microsoft Kinect/ SaeboVR software system	SaeboVR software system : picking up, moving, and placing virtual objects: Grocery Shopping, Putting Away Groceries, Preparing Breakfast, Pet Shopping, Pet Feeding, Pet Bathing, Garden Planting, Garden Harvesting, Preparing Dinner, Organizing a Closet, and Volunteering at a Soup Kitchen; as well as a Ball and Boxes practice activity.
Bacha et al. [11] 2018	Brazil	19	EG: 23 healthy older adults Age: 69.3 (5.34) CG: 23healthy older adults Age: 69.3 (5.34)	RCT	Microsoft Kinect/ commercial games	Kinect adventures games: Space Pop, 20,000 Leaks, Reflex Ridge, and River Rush.
Jung et al. [75] 2018	Korea	9	EG: 4 participants with CP Age: 8-11 CG: none	UCT	Microsoft Kinect/ commercial games	Kinect games: Soccer, Beach volley ball, and Bowling.

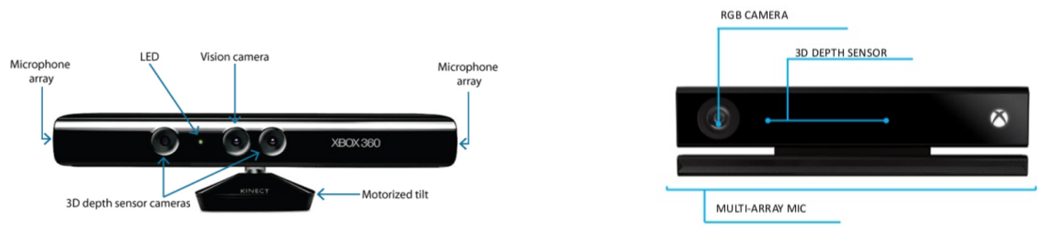
EG: Experimental Group; CG: Control Group; UCT: Uncontrolled trial (without a control group); CT: Controlled trial (with a control group); RCT: Randomized Controlled Trial; Country: affiliations of all authors; Age in years is expressed in mean (standard deviation) or range; Prototype game: designed by the researchers; Commercial game: commercially available game; CP: Cerebral Palsy; IDD: intellectual and developmental disabilities; DCD: Developmental Coordination Disorder; PD: Parkinson's disease; TD: Typically Developing.

Appendix B

Preliminaries: Kinect and Unity

Along the process of our work in serious games for balance rehabilitation for elderly people and the automation of the Functional Reach Test (FRT), we used Microsoft Kinect^{TM} as an input device. Kinect is a motion sensing device used primarily for exergaming. The term exergaming refers to active playing of a video game involving physical exertion. It comes from a combination of the two words "Exercise" and "game" or "gaming". By exercise, it is meant physical activity that requires body movement, and game refers to an interaction with a user interface imposing rules and generating feedback. Hence, the interaction in exergames is fulfilled by body movements. As Kinect requires full body motion for controlling the game; elderly are encouraged to move their body to interact with the game and perform the physical activity without getting bored. That could help in increasing their mobility and staying fit. Together with Microsoft Kinect^{TM}, we used also Unity engine for setting the virtual environment of the games. Unity offers several mechanisms that allow to set an environment which is entertaining and motivating at the same time. The integration between Kinect and Unity has been done by means of a wrapper developed by RF-Solutions.

In this appendix, we introduce both versions of this sensor that we used along different phases of the thesis project and focus on the elements that we deployed when developing their corresponding applications and executing both tests and experiments to validate the work elaborated. Afterwards, we introduce the main functions of Unity that allowed us to develop these applications.



(a) (b)

Fig. B.1 Kinect sensors: (a) Kinect v1 [1] and (b) Kinect v2 [3].

B.1 Microsoft Kinect

Kinect was first released in 2010 for the gaming console Xbox 360 (Kinect v1) enabling the players to control and interact with the game without the need for a controller; it provided a natural user interface by means of body gestures and voice commands. In 2011, Kinect Software Development Kit (SDK) was released featuring real time tracking of human limbs. Its low cost and high resolution of its color and depth images attracted the attention of developers and researchers to deploy it in a wide range of applications including physical therapy and rehabilitation for elderly people [193]. In 2013, a new version of Kinect (Kinect v2) was released as part of XboxOne platform featuring enhanced capabilities. In our work, we manipulated both Kinect cameras (see Figure B.1). Initially, we worked with Kinect v1, later on we replaced it with Kinect v2 following its release. In our applications, we were particularly interested in skeletal information; the subject of the following section.

B.1.1 Skeleton data

Kinect Xbox 360 includes an RGB camera, a depth sensor, and a four-microphone array hence providing full 3D body tracking, face recognition, and voice recognition capabilities [200]. The depth sensor is formed by an infrared projector and an infrared depth camera to acquire depth data. This latter is acquired based on a method called structured light where a pseudorandom infrared dot pattern is projected onto the scene by the IR projector and captured by the infrared camera. By matching a dot observed in an IR image with a dot in the projector pattern, its 3D position can be constructed by means of triangulation. Using this data, Kinect SDK can recognize human skeleton in real time. An estimation algorithm based on random decision forest predicts 3D location of human skeletal joints and has been implemented in the SDK [166]. To train this algorithm, a large dataset composed of many synthetic depth images of humans of different sizes, shapes, and poses sampled from a motion capture database was used. As a result, Kinect SDK gives information about 20 skeletal joints and tracks up to 2 full users.

In comparison with Kinect v1, Kinect v2 employs a different method for depth data acquisition known as Time of flight (ToF). The ToF principle relies on computing the round trip time that an emitted pulse of light takes to travel to an object and back to the sensor array to determine the distance to points on the surface. This method has more stability, improved precision, and is less prone to interference so it allows capturing better quality depth images by providing a dense depth map. Regarding, skeleton and joints information, the second version uses a similar method for human segmentation and skeletal tracking though it was not fully disclosed by Microsoft. Kinect SDK 2.0 features 25 joints in the skeletal tracking by adding the 3D locations of joints like hand tip, thumb tip and neck joints besides to tracking up to 6 full users. As we used mostly Kinect Xbox one sensor in our work, only the skeleton joints provided by Kinect v2 is shown in Figure B.2.

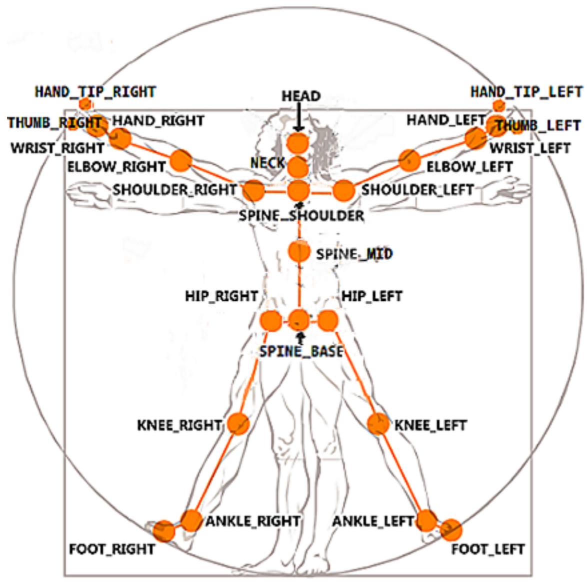


Fig. B.2 Skeleton joints provided by Kinect v2 [3].

B.1.2 Accuracy

Kinect v1 captures depth and color data with an acquisition rate of 30 frames per second (fps) with a resolution of of 640×480 pixels for the RGB camera and 320×240 pixels for the IR depth one. Extensive literature has been conducted evaluating the accuracy of depth information provided by this first Kinect generation. As our work is focused on applications related to physical therapy, rehabilitation, and balance assessment of elderly people, we were particularly interested in the accuracy of the skeletal tracking for these applications. In that regard, Clark et al. [37] examined the validity of Kinect for the assessment of static balance and reaching tasks against a multiple-camera 3D motion analysis system considered as a benchmark reference. Twenty healthy individuals performed three postural control tests (lateral reach, forward reach, and single leg standing balance). Their skeletal data were collected and then analyzed. In comparison to the benchmark reference, the results obtained using Kinect and its SDK were of excellent concurrent validity suggesting that Kinect can be used in clinical screening programs for many different patient populations however for some outcome measures it exist some proportional biases. Moreover, authors of [123] assessed the accuracy and robustness of joint localization and pose estimation provided by official Microsoft Kinect SDK. Five subjects performed six different exercises that are usually found in elderly exercise routine and are focused on the upper and lower extremities, besides these exercises present some challenges for pose estimation algorithm. The participants were captured and their skeletons have been estimated by Microsoft Kinect and a marker-based motion capture system at the same time. The results were then compared between the two systems concluding that kinect v1 has a high potential for healthcare applications regarding its low cost however its skeletal tracking in the context of elderly people coaching is struggling due to occlusions caused by other body parts or use of chairs for example. The authors indicated also that body postures such as standing and arms exercising are much accurate in joint estimation, and in general it could be used for assessing general trends in movement.

With the release of Kinect v2, most of the interest of researchers and developers has shifted to this sensor since it features better cameras resolutions with (1920×1080 pixels) and (512×424 pixels) for color and depth data respectively. As mentioned earlier, the Time of flight method is used in this device to acquire depth data which gives better results in comparison to structured light method employed in Kinect v1, however this method is prone to several artifacts induced by light reflections due to the scene geometry or the reflectance properties of some materials [190]. Thus, several studies have been conducted to evaluate its accuracy and compare it with its predecessor. For instance, authors of [190] extended their work discussed above to include the evaluation of Kinect V2. They analyzed motion data of 10 different subjects who performed 12 exercises, the data were collected from three different viewpoints by three systems concurrently (Kinect v1, Kinect v2, and a motion capture system used as a baseline). Joint position accuracy and bone length estimation of kinect skeletons were compared with those of the motion capture system. Results showed that overall Kinect v2 outperforms Kinect v1 as it offers better robustness and accuracy when estimating joint positions except for the feet. In addition, it tracks human movement with more reliability yet there are partial body occlusions. Moreover, Clark et al. [38] basically cloned the same experiment reported in [37] and described earlier in the text. In this study, they used Kinect Xbox One to assess its reliability and concurrent validity for standing balance and postural control assessment. For that, 30 healthy individuals performed several dynamic and static balance tests. 3D skeleton position data were acquired from Kinect and a marker-based three dimensional motion analysis (3DMA) system. Findings suggest that trunk angle data was very good for the reach and assessment of limits of stability, indicating that the Kinect V2 could be used in the instrumentation of these tests. Nevertheless, results of medial–lateral range and path length were poor to modest in comparison of the results obtained by the 3DMA with the exception of single leg eyes closed balance. At the end, Kinect v2 can be used as a reliable and valid tool for assessing some balance exercises and tests.

B.1.3 Ranges

Depth accuracy range of both Kinect sensors has been evaluated and discussed in several articles. In [56], the authors performed a metrological comparison between Kinect v1 and Kinect v2. Evaluation was done using a standard artefact at 1m and 2m range and at three different angles to determine the accuracy and precision of these two sensors in the respective ranges. Further measurements were performed for distances up to 6m and up to 4m for Kinect v1 and Kinect v2 respectively. For that, Microsoft Kinect SDK was used to acquire the data and store the measurements. As a result, authors reported that both sensors performed similarly at 1m range with a precision ranging between 1.5 mm and 6 mm, however Kinect v2 outperformed Kinect v1 at 2 m range providing better and more accurate measurements with indifferent effect of incidence angles on the precision of measurements. For larger distances, Kinect v1 measurement range goes until 6 m with decreasing in precision as the distance increases. In contrast, Kinect v2 shows much more stability within the 4m range as mentioned in the technical specifications. To conclude, the authors highlighted that Kinect v2 could be used for same applications as of Kinect v1, with improved precision and accuracy. The accuracy distribution of Kinect v2 was further assessed in [195]. Authors determined a cone model of its depth accuracy by positioning a screen as a planar surface perpendicularly pointed towards Kinect v2 or with a specific angle. The authors reported that the accuracy error distribution can be viewed as an elliptical cone containing three areas of different accuracy. That said, Kinect v2 has a stable and good accuracy within the central cone, however this accuracy may get affected depending on the horizontal and vertical displacement. In conclusion, Table B.1 presents a summary of the ranges and field of view of both Kinect v1 and Kinect v2 besides to other main technical specifications.

Table B.1 Summary of the main technical specifications of both Kinect v1 and Kinect v2.

	Kinect v1	Kinect v2
Color resolution	640×480 @30fps	1920×1080 @30 fps
Depth resolution	320×240	512×424
Sensor	Structured light	Time of flight
Maximum depth range	6 m	4.5 m
Minimum depth range	40 cm	50 cm
Field of view (H, V)	(57.5°, 43.5°)	(70°, 60°)
Body tracking	2	6
Skeleton joints	20 joints	25 joints
Tilt motor	Yes	No
USB standard	2.0	3.0
Supported OS	Win 7, Win 8	Win 8

B.2 Unity

For the development of our applications in this work, we used Unity3D: a cross-platform game engine for creating interactive and customized games and simulations. It is flexible and offers powerful tools and functionalities in order to provide a better experience for both developer and player.

B.2.1 Physics

Unity disposes of built-in physics engines that provide a convincing physical behavior of objects in a game when subjected to some force. Game objects are the most fundamental objects in unity representing characters, scenery, or special effects. They act as containers for components to implement the real functionality since they cannot do anything on their own. Among the components that handle the physical simulation and used during the development process, we state the following:

- Rigidbodies: are one of the main components added to game objects to enable physical behaviour. As soon as a rigidbody is attached to a gameObject, the latter starts to obey to gravity laws. To move an object according to incoming collisions, one or more colliders are then added.

- Colliders: They are invisible components designed to define the shape of an object in case a collision takes place, however having the exact same shape is not required to

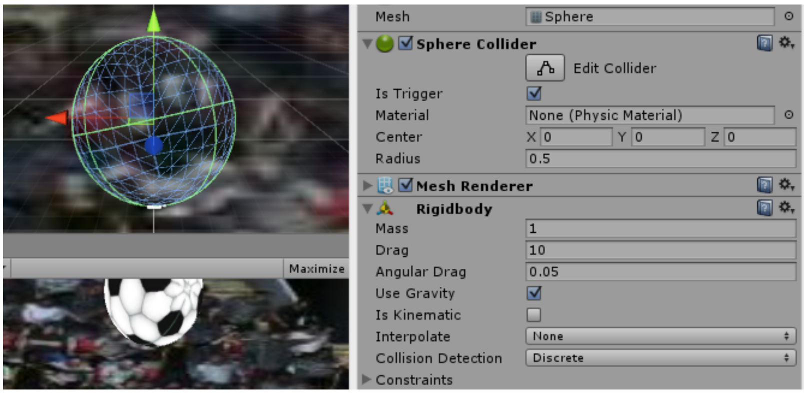


Fig. B.3 An example of a sphere collider in unity.

simulate the collision as a rough approximation is usually sufficient. When a collision occurs, a response to the collision event can be coded in a script function and called by the physics engine. An example of sphere collider can be seen in Figure B.3.

- Triggers: A collider can be configured as a Trigger in order to simply detect when a collider enters the space of another collider and let it pass through. In the same way as with colliders, a trigger calls a function script in order to respond to the event detected.

B.2.2 Kinect and Unity

To have a natural user interface, we interfaced the developed applications with Microsoft Kinect. The integration of Unity with Kinect was achieved by means of a wrapper offered by RF-Solutions; a package featuring all necessary scripts and demos for the development of the applications with Kinect as it gets data directly from the sensor while it is connected to the same machine. The package can be downloaded from the Unity3D asset store [wra].

At the beginning, the Kinect sensor is initialized waiting for users. As soon as a player steps in front of the sensor, the game application detects its posture and gesture and subsequently its corresponding silhouette or character is displayed on the screen. Colliders are added to the player's kinect skeleton to define interactions with the gameObjects.

B.2.3 Code sample from the Reach game

Reach game consists of reaching virtual elements (balls) that appear on the screen with the user's hands by moving his centre of mass. These balls are represented by 3D game objects (spheres) in Unity, however the user silhouette is in 2D. To ensure the interaction with the game objects, a 3D sphere collider is then assigned to each joint of the skeleton returned by Kinect.

```
// create joint colliders
numColliders = sensorData.jointCount;
jointColliders = new GameObject[numColliders];

for(int i = 0; i < numColliders; i++) {
  string sColObjectName = ((KinectInterop.JointType)i).ToString() + "
   Collider";
  jointColliders[i] = new GameObject(sColObjectName);
  jointColliders[i].transform.parent = transform;

  SphereCollider collider = jointColliders[i].AddComponent<
   SphereCollider>();
  collider.radius = 0.4f;
}
```

To ensure the interaction with the elements, we also added colliders to the balls through the graphical interface of Unity as shown in Figure B.3. When the user is detected by Kinect, the five balls get distributed around the user in a form that allows him to interact naturally with them.

```
if(manager.IsInitialized() && manager.IsUserDetected()) {
    //get the position of the user
  long userId = manager.GetUserIdByIndex(playerIndex);
    Vector3 posUser = manager.GetUserPosition(userId);
    //example of positioning the central element
    float x1 = 0.5f;
    float y1 = 0.9f;
    float z1 = posUser.z - Camera.main.transform.position.z -0.2f;
    if (object1 != null) {
      object1.transform.position = Camera.main.ViewportToWorldPoint(new
   Vector3(x1, y1, z1));
  }
}
```

When the user touches one element, a collision is detected and the corresponding ball disappears and reappears after a certain time.

```
void OnTriggerEnter(Collider other) {
    if (((other.name.Equals ("HandRightCollider")) || (other.name.Equals
    ("HandLeftCollider"))) && (rend.enabled == true)) {
        Instantiate (CubeExplosion, transform.position, transform.
   rotation);
        rend.enabled = false;
        StartCoroutine(WaitingToReappear(rend));
      }
```

```
}
```

For monitoring purposes, a csv file is created where the game parameters are saved for a later use.

```
string saveFilePath = "C:\\Users\\Ines\\Desktop\\ReachingData.csv";
if (isSaving) {
  using (StreamWriter writer = File.AppendText(saveFilePath)) {
     string sLine = string.Format("{0:F3};{1:F3};{2:F3}; {3:F3}; {4:F3};
    {5:F3}; {6:F3}", user_id, theDate, Game_duration, Real_duration,
   Distance_from_camera, Game_pattern, Motivational_objects);
     writer.WriteLine(sLine);
  }
}
```

B.3 Summary of the appendix

In this appendix, we introduced some preliminaries about the technology and the work environment that we used in the development of the applications that we discussed in the previous chapters. Unity is a powerful tool to design the environment and the program desired with much flexibility and efficiency. Using Kinect as system's interface makes the interaction natural, efficient, and easy to understand for the elderly target group.