Nicolás Jacobo Valencia Jiménez

Multisensory Environment for Proprioception Improvement in Children with Down Syndrome

Vitória - Brazil

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A Ph.D. Thesis presented to the Postgraduate Program in Electrical Engineering (PPGEE), Federal University of Espirito Santo (UFES), in partial fulfillment of the requirements for the degree of Doctor in Electrical Engineering

Federal University of Espirito Santo - UFES, Brazil
Postgraduate Program in Electrical Engineering

Supervisor: Prof. Dr. Anselmo Frizera Neto
Supervisor: Prof. Dr. Teodiano Freire Bastos Filho

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To children with Down syndrome who need our love and care to lead an inclusive life.

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Abstract

Down Syndrome (DS) is one of the most common genetic disorder worldwide and the most common cause of intellectual disability, which generates problems regarding the functionality and independence to perform Activities of Daily Living (ADLs). Most of the impairments associated with DS are thought to originate from a sensory dysfunction, i.e., the fact that the sensory stimuli are badly processed and integrated. There are few studies about the effects of a virtual environment-based intervention applied to motor development, postural control or proprioception improvement in children with Down Syndrome (CwDS). This research aims to verify the effects of an intervention protocol with Virtual Environment (VE) through a game platform based on an RGB-D camera arrangement to train proprioception in CwDS.

This Ph.D. Thesis provides a new approach of a game-based system through a Multisensory Environment (MSE) using automated analysis of corporal movements with a set of RGB-D cameras. This research allowed to verify the effects of an intervention protocol to train proprioception in CwDS. The system is implemented following the requirements raised by psychologists and physical therapists. The system is proposed as a complement to conventional therapies, providing support to professionals in the area to generate objective parameters for analysis during physical training and therapy.

The main contributions of this research are: (i) An exploratory study with a Smart Mirror Environment (SME) platform to provide visual feedback and a proprioception assessment to CwDS. (ii) The implementation of a markerless multicamera-based system to measure movement parameters, in order to reduce errors and inaccuracies related to self-occlusion issues, generating parameters as positions, joints angular amplitudes, and velocities of fifteen body joints. (iii) The development of a clinical intervention based on a game platform that uses parameters of the markerless camera-based system, generating a new scenario in aid technological tools focused on the Down syndrome population.

The results obtained throughout this study confirm that Multisensory Environments (MSEs) are a promising tool to be incorporated into the rehabilitation and training process of individuals with proprioception dysfunctions as well as an intervention system that helps children with DS to develop their skills, and at the same time providing objective parameters about their progress.

Keywords: Serious games, Virtual environment, Children with Down syndrome, RGB-D cameras, Motor development, Assistive devices.

List of Figures

List of Tables

List of abbreviations and acronyms

DS	Down Syndrome
CwDS	Children with Down Syndrome
ADLs	Activities of Daily Living.
IBGE	Instituto Brasileiro de Geografia e Estatística
MSE	Multisensory Environment
RMSE	Root Mean Square Error
UFES	Universidade Federal do Espírito Santo
IoT	Internet of Things
RGB-D	Red, Green, Blue, Depth (cameras)
POF	Polymer Optical Fiber
GUI	Graphical User Interface
SME	Smart Mirror Environment
IMU	Inertial Measurement Unit
CoG	Center of gravity
BPM	Psychomotor Battery
DOF	Degrees of Freedom

Contents

1 Introduction

1.1 Motivation

Down syndrome (DS) is the most common non-inherited cause of cognitive deficit as a result of the presence of all or a portion of an extra copy of chromosome 21 (HSA21)(ARYA; KABRA; GULATI, 2011). DS has an incidence of 1 in 750 live births and is considered one of the most frequent causes of learning difficulties (DE MELLO MONTEIRO et al., 2017). According to 2010 Census of the Brazilian Institute of Geography and Statistics (IBGE), there are more than 300 thousand people with DS in Brazil (IBGE; STATISTICS, 2013). Many medical and health-related complications are associated with the syndrome, including cardiac and respiratory problems (MALAK et al., 2015). Dynamic motor dysfunction is also widespread among individuals with DS, which includes more extended motion and reaction times, balance and postural deficits, in addition to co-contraction of agonist and antagonist muscle pairs (MAZUREK et al., 2015; GALLI et al., 2008). Noticeable in children, these deficits may have a causal link to delays in achieving motor development milestones (CAPIO et al., 2018). In fact, the motor development of infants and children with Down syndrome (CwDS) is delayed, due to generalized muscle hypotonia and ligament laxity that is characteristic of these individuals (NAITO et al., 2015).

DS affects deeply the life of these people and of their families, since patients can be unable to complete even simple daily tasks, which make them dependent on others to live (KETCHESON et al., 2017; NATIONAL DOWN SYNDROME SOCIETY, 2018). The neuropathological basis for motor dysfunction in DS is unknown, but cerebellar dysfunction, delayed myelination and proprioceptive and vestibular deficits have been invoked as potential contributors (GALLI et al., 2008; TOVAR; WESTERMANN; TORRES, 2018). In the first few years of life, early physiotherapy has been focused on facilitating motor control and coordination to achieve developmental goals (TOFFALINI et al., 2017). However, once the children start walking (which is often delayed by an average of 12–18 months) (RODENBUSCH et al., 2013), very few of them continue to receive physiotherapy. There are numerous reports in the literature suggesting that children with DS begin to develop orthopedic problems in early childhood and would benefit from specific biomechanical assessment and management (TOFFALINI et al., 2017; CORTES et al., 2013; MACEDO et al., 2015).

Most of the impairments associated with DS are thought to originate from a sensory dysfunction, i.e., the fact that the sensory stimuli are badly processed and integrated

(CLARK et al., 1999; WU et al., 2015; NAITO et al., 2015). The result of this incomplete or distorted process is the creation of an abnormal mental representation of the external world. This in turn may produce motor impairments and deficits in cognitive skills, like generalization, space awareness, language usage and social behaviour (COVACI et al., 2015; MALAK et al., 2015), and induces distress and discomfort, frequent concentration losses, and disengagement from the proposed activities (LANCIONI; CUVO; O'REILLY, 2002; DEL RIO GUERRA; Martin Gutierrez; ACEVES, 2018). The theory of sensory integration posits that the learning process depends on the ability of processing and integrating the sensory information and integrating them to plan and organize behavior (BUNDY; LANE; MURRAY, 2002; NACHER et al., 2018), whose sensorial construction is made by the proprioceptive sense.

Proprioception is the spatial awareness of the body and its segments (CABIBIHAN et al., 2013). Deficits in proprioception are associated with DS, and CwDS's improvements are generally very small and very slow without an appropriate stimulus. Still, it is acknowledged that intensive support from the childhood can help to alleviate the symptoms (CARTER; STEPHENSON, 2012). Some therapies have been developed, but they must be deeply customized and constantly adjusted according to the patient's needs (GALLI et al., 2008; WINDERS; WOLTER-WARMERDAM; HICKEY, 2019). Many therapeutic interventions have the goal of teaching some basic skills so that the patient can acquire autonomy in his/her daily life, e.g., through practices that promote gross and fine motor coordination, attention and social interaction (GHIANI et al., 2016; SVENDSEN; ALBU; VIRJI-BABUL, 2011).

Some conventional multisensory treatments require a suitable space, called Multisensory Environment (MSE), a room intended to stimulate the vestibular, proprioceptive and tactile sense of the user, train the integration and identification of different stimuli, and engage the user in useful activities (HURST; TOBIAS, 2011; IAROCCI; MCDONALD, 2006; LIZETH et al., 2017). Currently, with the technological advances in therapeutic interventions, new trends to an assistive technological-based tool used in multisensory treatments are using different forms of stimuli (BARGAGNA et al., 2019; DEL RIO GUERRA et al., 2019). Multisensory interventions based on multi-cameras RGB-D are among possible approaches to help children with DS (GARZOTTO et al., 2019; DEL RIO GUERRA; Martin Gutierrez; ACEVES, 2018). For example, an environment with devices that capture the user's movements, combined with serious games that verify their correctness, can improve the experience of an appropriate stimulus (KONSTANTINIDIS et al., 2017; WUANG et al., 2011).

Several studies have explored the capabilities of devices such as RGB-D cameras and other sensors for physical training and therapy (ALESII et al., 2013; SVENDSEN; ALBU; VIRJI-BABUL, 2011; BORK et al., 2017). However, it is necessary to identify their functionalities and requirements to contribute effectively to the user's necessities (BRANDÃO et al., 2011). The main draw of a game-based system in a sensorized environment is its capacity of allowing clinicians to control the characteristics of the virtual environment while modifying the degree of challenge to suit individual user needs (DE TROYER, 2017; LIZETH et al., 2017; PARÉS et al., 2005).

This research proposes a game-based system into a MSE for CwDS using automated analysis of corporal movements with RGB-D cameras. The intervention system is implemented following a well-established protocol to objectively elicit cognitive and proprioceptive skills, in addition to practical needs and requirements raised by psychologists and physical therapists. The system is proposed as a complement to conventional therapies, providing support to professionals in the area to generate objective parameters for analysis during physical training and therapy.

1.2 Justification

In many kinds of research, multisensory environments (MSEs) were developed to offer a digitally enhanced space where sensory stimuli are originated from digitally improved objects ("smart objects") or from the entire "smart environment" through multimedia digital projections, ambient sound, or lights embedded in the physical space (GARZOTTO et al., 2019; SALTER; DAVEY; MICHAUD, 2014; SHAMS; SEITZ, 2008; TAM; GELSOMINI; GARZOTTO, 2017).

Multisensory interventions —integrated today in many programs both in therapeutic centres and in schools in US, Canada, Australia, and UK— attempt to improve the sensory discrimination, i.e., the ability to focus on and discriminate among different simultaneous stimuli, and sensory integration, i.e., the ability to interpret properly multiple sensory stimuli simultaneously (TETTEROO et al., 2015; SACKS; BUCKLEY, 2003).

Serious games can create an immersive environment from recreational resources to aid in physical and motor rehabilitation and training (ABELLARD, 2017). Those technologies can assist the user in the correct execution of movements through stimulation from interactive elements of digital games, offering a broad scope of possible assistance to health and health-care (BERNARDINI; PORAYSKA-POMSTA; SMITH, 2014; DEL RIO GUERRA et al., 2019). Games can also generate motor skills, spatial skills, shape identification, and curiosity to the player (GLEGG, 2017; AMADO SANCHEZ et al., 2017).

On the other hand, virtual reality-based therapy is one of the most innovative and promising recent developments in rehabilitation technology (DE TROYER, 2017). This technology allows users to interact with a computer-generated scenario (a virtual world), making corrections and increasing intensity of training while providing feedback (CAMEIRAO et al., 2010). Users can interact with displayed images, move and manipulate virtual objects and perform other actions in a way that attempts to immerse them within the simulated environment (COVACI et al., 2015).

This kind of system, although able to provide solutions and assist in the coaching of the users, must be designed carefully so as not to bring adverse effects (KONSTANTINIDIS et al., 2017). Thus, for the development of these games, a domain analysis of the topic and studies of the playful elements to integrate serious goals and motivational resources are needed (MENEZES et al., 2014; ABDEL RAHMAN, 2010; TOFFALINI et al., 2017).

In summary, this research shows three important aspects of the MSE developed to improve the skills of CwDS: first, the implementation of a body movement estimation system with an arrangement of RGB-D multicameras; second, a platform of serious games for proprioception training in CwDS; and third, the implementation of an assessment protocol to evaluate motor skills and proprioception for children with down syndrome (CwDS).

1.3 Contributions

Accordingly, the main contributions of this Ph.D. thesis are:

1. The development of an exploratory study with a Smart Mirror Environment (SME) platform to provide visual feedback and a proprioception assessment to CwDS. The discussion of the data warn that body experiences may be fundamental for motor and self-perception aspects. CwDS implicitly have a developmental deficit, therefore, It was found that they should be provided with sensory and bodily experiences in order to promote neuropsychomotor development.

2. The development of a markerless camera-based system to measure movement parameters. The markerless system developed here uses two RGB-D cameras in order to reduce errors and inaccuracies related to self-occlusion issues, generating parameters as positions, joints angular amplitudes, velocities and accelerations of fifteen body joints.

3. The development of a clinical intervention through a multisensory environment for proprioception improvement in children with Down syndrome (DS), as well as a clinical relevance analysis of the movement parameters performed during a focused intervention with a game platform.

1.4 Structure of this document

This Ph.D. thesis is composed of five chapters. Chapters 1 is compounded by the motivation that leaded to the developed work, as well as the scientific issues and justification of this Ph.D. proposal, including its hypothesis and main objectives.

Chapter 2 describes the theoretical background, presenting a literature study regarding the evaluation of proprioception skills in Children with Down Syndrome (CwDS), in addition to methods and techniques related to measurement systems to help in their movements. The chapter presents the state-of-the-art review, including available approaches towards current technology trends in DS intervention.

Chapter 3 provides a detailed explanation of the preliminary assessing proprioception system developed, demonstrating the significance of the parameters obtained with the virtual immersion.

Chapter 4 presents the methods used to implement a markerless system based on color-depth cameras arrangement, analyzing and validating the accuracy in joint angle estimation compared to other measuring systems.

Chapter 5 describes the game-based multisensory environment (MSE) developed and its effect of a motor development intervention in Children with Down Syndrome.

Finally, Chapter 6 provides the concluding remarks of this thesis and outlines some general discussion together future research directions.

2 Theoretical Background

This Chapter presents aspects related to individuals with Down Syndrome (DS), their health difficulties and some training and therapies possibilities. Additionally, this Chapter defines Multisensory environments (MSEs) and shows their therapeutic and educational effectiveness. Finally, several existing technologies for motion human tracking and serious games are shown, with focus on their use for CwDS.

2.1 Proprioception

Proprioception comes from a Latin word (*proprius* + reception) meaning unconscious perception of movement. It has been defined as the awareness of the body in space (RADÁK, 2018). Proprioception is the use of joint position sense and joint motion sense to respond (consciously or unconsciously) to stresses placed upon the body by alteration of posture and movement (NORRIS, 2011). Proprioception encompasses three aspects, known as the 'ABC of proprioception', which are: agility, balance and coordination. Agility is the capacity to control the direction of the body or body part during rapid movements, whereas balance is the ability to maintain equilibrium by keeping the line of gravity of the body within the body's base of support, and coordination is the smoothness of an activity, which is produced by a combination of muscles acting together with appropriate intensity and timing (HOUGLUM, 2015).

Proprioception, or kinesthesia, is the sense that lets us perceive the location, movement, and action of parts of the body, including our sense of equilibrium and balance, senses that depend on the notion of force (WOLFF; SHEPARD, 2013). It encompasses a complex of sensations, including perception of joint position and movement, muscle force, and effort (JONES, 2000). These sensations arise from signals of sensory receptors in the muscle, skin, and joints, and from central signals related to motor output (RADÁK, 2018).Proprioception enables us to judge limb movements and positions, force, heaviness, stiffness, and viscosity (VERHAGEN et al., 2004). It combines with other senses to locate external objects relative to the body and contributes to body image (TAYLOR, 2009).

2.2 Trisomy 21

Down syndrome (DS), also known as trisomy 21, is a genetic condition that typically causes some level of learning disability and certain physical characteristics (NATIONAL

DOWN SYNDROME SOCIETY, 2018). DS is related to a neuropsychomotor development delay and muscular hypotonia and may be related to other pathologies such as congenital heart disease, auditory and visual problems, as well as alterations in the cervical spine, obesity, premature aging, thyroid disorders, short stature, and significant medical co-morbidities (NATIONAL DOWN SYNDROME SOCIETY, 2018; MALAK et al., 2015). (WINDERS; WOLTER-WARMERDAM; HICKEY, 2019). Some characteristic difficulties in DS are shown in the next sections.

2.2.1 Motor development

Typical children usually master certain skills, such as walking, sitting, talking, and using utensils by a certain age. CwDS are known to develop these skills somewhat later than children of their age, often slower than typical children (GALLI et al., 2014; SACKS; BUCKLEY, 2003; GALLI et al., 2008). These delays in motor development reduce infants' opportunities for exploring and learning about the world around them and therefore further affect cognitive development, in such a way that their poor oral motor control may impact the development of language skills (AMADO SANCHEZ et al., 2017). For example, typical children are saying their first words between eight and tweenty-three months. A child with DS may take up to four years to say his/her first words (MALAK et al., 2015). However, this does not mean that a child with DS will never develop the same skills as typical children (RODENBUSCH et al., 2013).

Hypotonia is a typical characteristic in individuals with DS, which is related to the state of elastic muscle tension, allowing the contraction after receiving the central nervous system impulse (COPPEDE et al., 2012; GALLI et al., 2014). Hypotonia reduces postural control and proprioception, influencing the sensory and motor experiences, leading to a neuropsychomotor development delay, late gait acquisition, and affecting the fine and gross motor skill performance (BEQAJ et al., 2018).

Physical therapy in DS is indicated with the aim of preventing and attenuating neuropsychomotor development disorders, stimulating motor responses close to the normal pattern and avoiding atypical patterns in movement and posture (BEQAJ et al., 2018). When the child acquires gait, it is important to perform postural and balance training, increasing proprioception and motor coordination. In the young and adult phase, individuals with DS are less active, increasing their hypotonia and muscle weakness (ALMEIDA; MOREIRA; TEMPSKI, 2013). At this stage a physiotherapeutic approach is indicated, based on the findings in the kinetic-functional assessment (ALMEIDA; MOREIRA; TEMPSKI, 2013).

2.2.2 Expressive language, grammar and speech clarity

CwDS show specific delays in learning to use spoken language relative to their non-verbal understanding. Almost every CwDS will have expressive language that is delayed relative to their language comprehension. The CwDS experience two types of expressive difficulty: delay in mastering sentence structures and grammar, and specific difficulties in developing clear speech production (NATIONAL DOWN SYNDROME SOCIETY, 2018).

The gap between the children's understanding and their ability to express themselves is a cause of much frustration and can sometimes lead to behaviour problems. It can also result in the children's cognitive abilities being underestimated. Language delay also leads to cognitive delay as much human learning is through language, and language is internalized for thinking, remembering, and self-organization (NATIONAL DOWN SYNDROME SOCIETY, 2018).

2.2.3 Short-term memory

Short-term memory is the immediate memory system which holds information "in mind" for short periods of time and supports all learning and cognitive activity. It has separate components specialized for processing visual or verbal information (NAITO et al., 2015).

Studies suggest that the processing and recall of spoken information is improved when it is supported by relevant picture material. This information has led to educators stressing the importance of using visual supports including pictures, signs and print when teaching CwDS, as this approach makes full use of their stronger visual memory skills (SVENDSEN; ALBU; VIRJI-BABUL, 2011).

2.2.4 Training and Therapy

Many therapeutic interventions have the goal of teaching basic skills to increase autonomy in daily life, e.g., through practices that promote gross and fine motor coordination, attention and social skills (DAVIS, 2008). Physical therapy in DS is indicated in the first months of life, with the aim of preventing and attenuating neuropsychomotor development disorders, and to stimulate motor responses to avoid atypical patterns in movement and posture (TOVAR; WESTERMANN; TORRES, 2018). When the child acquires gait, it is also important to perform postural and balance training, increasing proprioception and motor coordination (NAITO et al., 2015). Studies also indicate that in young and adult phase, individuals with DS are less active, increasing their hypotonia and muscle weakness. Thus, at such stage, a physiotherapeutic training approach is indicated, which is based on the individual findings in functional assessment (JUNG; CHUNG; LEE, 2017).

People with Down syndrome usually have some level of independence by the time they become adults. Different types of specialized therapies, counselling, and training can help them to learn necessary skills and manage emotional issues (NATIONAL DOWN SYNDROME SOCIETY, 2018), such as shown in Figure 1. Capio et al. (2018) studied the fundamental movement skills that show delayed development in CwDS. Another author reported the differences that could be observed between neurotypical participants and those with DS (MACIAS et al., 2018). The common types of therapy and training include: speech and language therapy, physiotherapy, occupational therapy, nutritional counselling, and vocational training (KETCHESON et al., 2017).

Figure 1 – Different types of specialized therapies for training of multiple skills in CwDS (Source: Adapted from NATIONAL DOWN SYNDROME SOCIETY (2018)).

However, with the technological advances in therapeutic interventions, new trends of therapy and training like assistive technological-based tools are used (MAZUREK et al., 2015). In next section, new concepts of treatment using different forms of stimulus are shown.

2.3 Current technology trends in DS interventions

The use of technologies by individuals with Down syndrome (DS) is an emerging field of study (KUMIN; LAZAR; FENG, 2012). New trends in training and therapies are based on the application of technology, such as Virtual Environments (VEs). In recent years, there has been a growing trend towards using Augmented Reality (AR) and Virtual Reality (VR) devices, and as such, new applications are now being developed that are of use to society (MARTÍN-GUTIÉRREZ et al., 2017). In the literature, there are currently few studies on interactions with VR and AR, and even less on users with DS. What is clear is that further research is needed on 3D gestures and interactions within AR and VR environments to identify whether devices currently being manufactured suit all user needs and adapt to all types of users (DEL RIO GUERRA et al., 2019). Thus, for the development of these environments, a domain analysis of the topics and studies of the playful elements to integrate serious goals and motivational resources are needed (SILVEIRA et al., 2019)

Few relevant scientific contributions exist related to technology usability studies that have selected individuals with DS as users. The study by Nacher et al. (2018) analyses touch gestures on interactive touch screens performed by CwDS. Cortes et al. (2013) analysed the usability of applications that are used by CwDS, however, the general recommendations focus more on software programming than on the hardware itself. Other works performed with users who have DS have attempted to stimulate their cognitive abilities (BRANDÃO et al., 2010) and design a system for training the tongue, which includes exercises to facilitate movement (MIYAUCHI; KIMURA; NOJIMA, 2013).

VEs can assist CwDS in the correct execution of movements through stimulation from interactive elements, offering a broad scope of assistance to health, and can also generate motor skills, spatial skills, shape identification, and curiosity to them (DE TROYER, 2017). Studies as proposed by DEL RIO GUERRA, Martin Gutierrez e Aceves (2018) suggest a methodology for evaluating the ease with which touch gestures, body movements and eye movements can be performed by individuals with DS. Bargagna et al. (2019) propose using a robotic kit to promote education and collaborative learning in a play setting. Felix et al. (2017) studied how to improve reading and writing skills using a multimedia tool, with significant improvement being found.

Such interfaces play a considerable motivational role, generating a feedback to the children while evaluating their performance. This allows them to interact with their own movements, making corrections and increasing intensity of training while providing feedback (DEL RIO GUERRA et al., 2019). For example, Torres-Carrión, González-González e Carreño (2014) worked on an emotional development assessment tool using the platform Kinect. Alt, Geiger e Höhl (2018) studied Mid-Air gestures for large interactive displays, and the means by which users receive feedback. Also, CwDS interacted with displayed images and performed different actions in a way that attempted to immerse them within a simulated environment, improving and repeating their movements, especially if they could observe them on the screen (DE MELLO MONTEIRO et al., 2017; GLEGG, 2017; CABREIRA; HWANG, 2015).

2.3.1 Multisensory Environments (MSEs)

Multisensory approaches have been largely considered in past years and this has resulted in the adoption of two main approaches. The first one refers to objects, and the second one refers to spaces. The usage of toys to stimulate the children's senses, especially for children with cognitive difficulties as CwDS, is exploited in various methodologies (BRODIN, 1999). Exploration through senses is the best motor of learning simply and especially thank the repetition of tasks. These toys reflect this concept and emphasize it through the usage of different materials and simple shapes. Repetition of tasks can be effective in terms of relaxation, acquaintance with the toy and, subsequently additional stimuli like light, and sounds can be added afterward to motivate children (MACEDO et al., 2015). More sophisticated solutions can be achieved by considering the environment in which the child plays (CORTES et al., 2013).

The expression MSE is often referred to a room to discover or explore. The goal of a MSE is to offer a soothing, nonthreatening and relaxing environment that promotes a general feeling of restoration and refreshment by engaging people with DS (with the close support of caregivers) with pleasurable, explorative experiences while keeping controlled the amount, intensity and quality of stimuli (CARTER; STEPHENSON, 2012; BERNARDINI; PORAYSKA-POMSTA; SMITH, 2014; SHAMS; SEITZ, 2008; BRULE et al., 2016; RINGLAND et al., 2014).

Studies have been conducted to explore the therapeutic and educational effectiveness of MSEs, which report improvements of the ability to adapt to circumstances and the mitigation of some stereotypes during the sessions inside the room (IAROCCI; MCDONALD, 2006; LANCIONI; CUVO; O'REILLY, 2002; SHAMS; SEITZ, 2008). However, MSEs have limitations since they offer a restrained capability for the user to interact with objects, producing a "cause" and receiving an appropriate stimulus as an "effect" to establish a cause-effect relationship, fundamental in the development of cognitive skills (GARZOTTO et al., 2019).

Several studies have explored the capabilities of different devices, such as RGB-D cameras and other sensors, to generate responses or "effects" during physical training and therapy (ALESII et al., 2013; SVENDSEN; ALBU; VIRJI-BABUL, 2011; BORK et al., 2017). Hovorka e Virji-Babul (2006) ran a study based on Virtual reality (VR) and Augmented reality (AR) technologies in which users with DS had to perform everyday tasks. ABDEL RAHMAN (2010) state that motor training with virtual reality during therapy sessions promise encouraging results in this population. DEL CIELLO DE MENEZES et al. (2015) provide a revision of existing literature on rehabilitation therapies using AR apps. Ramli e Zaman (2011) proposes usability factors that need to be taken into account when developing applications for users with DS, especially when using AR. In the field of education, several different studies have been performed involving AR and VR. McMahon et al. (2016), for example, successfully used AR to teach scientific terminology. Lopes et al. (2018) analyzed brain activity when children with DS entered virtual reality using VR technology. However, it is necessary to identify their functionalities and requirements to contribute to the user's necessities effectively (BRANDÃO et al., 2011).

The main drawback of a game-based system in a sensorized environment is its capacity of allowing clinicians to control the characteristics of the virtual environment while modifying the degree of challenge to suit individual user needs (PARÉS et al., 2005). Section 2.3.2 presents some color-depth cameras needed to get information for non-invasive human motion analysis, in order to obtain possible solutions to build a "cause-effect" environment.

2.3.2 Color-depth Cameras

Motivated by emerging research questions that require objective evaluation of intervention outcome, there is an increasing demand for quantitative movement assessment, which does not possess an advanced motion lab with an elaborated whole-body motion capture system, especially if multiple movement analysis systems are needed and a cost-efficient alternative is attractive (MÜLLER et al., 2017).

Human motion analysis is an essential technology for various industrial or personal applications. Most previous systems use either multiple image sensors or multiple motion sensors (WU et al., 2005), which can be classified as either marker-based or marker-free capture (MENEZES et al., 2014). Although marker-based systems for gait analysis, such as Vicon, can track human motion with great accuracy (Figure 2), marker-free systems have many advantages (SVENDSEN; ALBU; VIRJI-BABUL, 2011). Most importantly, they can eliminate the difficulty of applying markers to users with physical or cognitive limitations (CAMEIRAO et al., 2010).

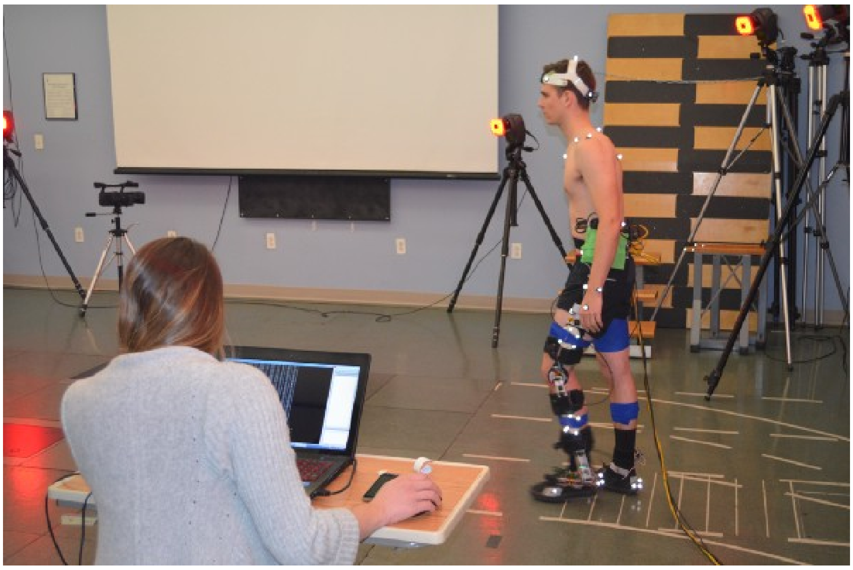

Figure 2 – Marker-based systems to track human motion (Source: Pfister et al. (2014)).

However, most of marker-free systems require a surface model. Therefore, 3D surface reconstruction is a prerequisite to marker-free capture (MÜLLER et al., 2017;

MENEZES et al., 2014). The advent of off-the-shelf depth sensors, such as color-depth cameras (KONSTANTINIDIS et al., 2017), make it easy to acquire depth data, which are known to be very useful for gesture recognition (COVACI et al., 2015). However, the motion capture with depth sensors is a challenging issue due to the limitations of accuracy and range (ABELLARD, 2017).

Three-dimensional camera systems that integrate depth assessment with traditional two-dimensional images, such as the Microsoft Kinect[1], Intel Realsense[2], StereoLabs Zed[3], and Orbecc[4], hold great promise as physical function assessment tools. When combined with point cloud and skeleton pose tracking software they can be used to assess many different aspects of physical function and anatomy (CLARK et al., 2019).

Increasing interest in using color-depth cameras for general purpose motion capturing of humans has emerged, especially for clinical and scientific motion analysis of gait (GEERSE; COOLEN; ROERDINK, 2015; CLARK et al., 2015), detection of falls (STONE; SKUBIC, 2015; STARANOWICZ; RAY; MARIOTTINI, 2015), but also as instrument for physical therapy (HUO et al., 2015; ILG et al., 2012; MOUSAVI HONDOR; KHADEMI, 2014). Due to its low cost, it Kinect sensor has been used as a cost-efficient alternative to expensive gold standard motion capturing systems (GEERSE; COOLEN; ROERDINK, 2015; STARANOWICZ; RAY; MARIOTTINI, 2015).

The Kinect v2 uses time of flight measurements. The term "time of flight" describes the method to determine the distance to an object by measuring the time a laser pulse needs to travel from the sensor to the object and back (MÜLLER et al., 2017). The Kinect v2 sensor has a horizontal field of view of about 70 degrees and can cover 4.5 meters in depth reliably. The depth resolution of the Kinect v2 sensor, however, depends not only on the distance but also on the view angle from which a plane is measured (YANG et al., 2015). In addition, the error of the joint position estimation algorithm increases with the view angle, which is likely caused by partial self-occlusion (WANG et al., 2015). Motion capturing from only one side using Kinect sensors might therefore introduce biases and unnecessary inaccuracies in the estimation of joint positions. Due to the limited size of the tracking volume of the Kinect sensor, single sensor approaches were mostly constrained to examinations of body posture and balance during stance or of walking on a treadmill (CLARK et al., 2015; PFISTER et al., 2014). In order to cover a larger volume, setups with multiple Kinect sensors have been proposed (KAENCHAN et al., 2013; GEERSE; COOLEN; ROERDINK, 2015; STARANOWICZ; RAY; MARIOTTINI, 2015; MÜLLER et al., 2017; CARVALHO, 2018; SILVEIRA, 2019; RAMIREZ DUQUE, 2019; AVELLAR, 2019).

[1] <https://developer.microsoft.com/en-us/windows/kinect>
[2] <https://www.intelrealsense.com/>
[3] <https://www.stereolabs.com/>
[4] <https://orbbec3d.com/>

Figure 3 – Color-depth camera system used to track human motion (Source: Clark et al. (2019))

It is important to emphasize that an environment with devices that capture the user's movements, combined with serious games that verify their correctness, can improve the experience of rehabilitation (WUANG et al., 2011). Several studies have explored the capabilities of these devices, such as RGB-D cameras, and other sensors for physical training and therapy systems (ALESII et al., 2013; SVENDSEN; ALBU; VIRJI-BABUL, 2011; BORK et al., 2017). However, to build an efficient game system, it is necessary to identify its functionalities and requirements, in order to contribute to the effective user's needs (BRANDÃO et al., 2011).

2.3.3 Serious Games

Serious games can create an immersive environment from recreational resources to aid in physical and motor rehabilitation and training (Figure 4) (ABELLARD, 2017). In fact, game technologies can assist the user in the correct execution of movements through stimulation from interactive elements of digital games, offering a broad scope of possible assistance to health and health-care (BERNARDINI; PORAYSKA-POMSTA; SMITH, 2014). Games can also generate motor skills, spatial skills, shape identification, and curiosity to the player (GLEGG, 2017).

Virtual reality-based therapy is one of the most innovative and promising recent developments in rehabilitation technology (DE TROYER, 2017). This technology allows users to interact with a computer-generated scenario (a virtual world), making corrections and increasing intensity of training while providing feedback (CAMEIRAO et al., 2010). Users can interact with displayed images, move and manipulate virtual objects and perform

Figure 4 – Serious games scheme (Source: Adapted from DJAOUTI (2011)).

other actions in a way that attempts to "immerse" them within the simulated environment (COVACI et al., 2015).

This kind of system, although able to provide solutions and assist in the recovery of the users, must be designed carefully not to bring adverse effects (KONSTANTINIDIS et al., 2017). . For example, González-Ferreras et al. (2017) proposed a video game for improving verbal skills, in particular prosody, focusing on the design and evaluation of the educational video game, from a point of view about how appealing is. Another game is the Beesmart, developed for Kinect, to improve users' day-to-day motor skills (AMADO SANCHEZ et al., 2017). Silva et al. (2017) demonstrated that the use of exercises on the Wii consoles could improve physical condition, functional mobility, and motor proficiency in adults with DS. Sinaga, Prananta e Fadlyana (2016) found fine motor skills of CwDS who used Wii consoles to be inferior to neurotypical children, whereas Berg (BERG et al., 2012) found that the use of Wii consoles could help DS children to improve their postural stability, limits of stability, and the motor proficiency.

For their part, Salah, Abdennadher e Atef (2017) performed a study on individuals with DS to study the cognitive difference acquired through the use of educational games using a computer and AR; and Martín-Sabarís e Brossy-Scaringi (2017) also studied the use of AR applied to users with DS using the game Pokémon Go. Thus, for the development of these games, a domain analysis of the topic and studies of the playful elements to integrate serious goals and motivational resources are needed (MENEZES et al., 2014; ABDEL RAHMAN, 2010; TOFFALINI et al., 2017).

3 Assessing Proprioception in Children with Down Syndrome through a Smart Mirror Environment[1]

In order to understand the CwDS movements and the possibilities of a multisensory environment (MSE) implementation, it is necessary to built a motor assessment configuration for visual feedback. With the results of an assessment tool it is possible to recognize the behavior of the CwDS, their capabilities and shortcomings. Besides, it is possible to identify the strengths and weaknesses of the measurement system, the virtual environment implemented and to understand the scope and the clinical feasibility of the proposed tool.

Based on the requirements of an evaluation system where CwDS can observe their own body and surroundings without generating invasiveness, as well as the requirement to obtain objective parameters to physiotherapists and other clinical evaluators, this Chapter presents the development of a Smart Mirror Environment (SME) for CwDS using automated analysis of corporal movements with a RGB-D camera. The protocol was raised due to the practical needs and requirements of psychologists and physical therapists. The system is proposed as a complement to conventional assessment, providing support to professionals in the area to generate objective parameters for analysis during physical assessment, training and therapy.

3.1 Smart Mirror Environment (SME)

The following sections approach the system architecture developed in this Chapter, beginning with the depth-camera (Kinect V2) in Section 3.1.1, besides the information about the software and strategies implemented in the virtual interface developed in Section 3.1.2.

3.1.1 Depth-camera

The Kinect v2 is a 3D sensor composed of an RGB camera (resolution of $1920 * 1080$ pixels), an infrared camera (resolution of $512 * 424$ pixels), and an infrared emitter. The

[1] This chapter is mainly based on the following publication:
Valencia-Jimenez, N., Da Luz, S., Santos, D., Souza, M., Bastos-Filho, T., Frizera-Neto, A., The effect of smart mirror environment on proprioception factors of children with Down syndrome. Research on Biomedical Engineering (2020). <https://doi.org/10.1007/s42600-020-00041-3>

sensor is based on a depth measurement method with the time-of-flight (ToF) technology, as shown in (YANG et al., 2015). The field of view is 70° horizontally and 60° vertically, and the depth detection range is since 0.5 until 4.5 meters (distance to the sensor). Each Kinect v2 sensor requires a dedicated USB 3.0 controller, thus each sensor has to be connected to a dedicated computer (MÜLLER et al., 2017).

Through the Kinect v2 software development kit (SDK) Microsoft provides color and infrared data streams, depth images, body index images and skeleton information (MÜLLER et al., 2017). For application with different Operative Systems, other SDKs are used. Nuitrack SDK, OpenNI 2.0 software, and NiTE2.2 API (Application Programming Interface) are examples of compatible SDKs on Linux and IOS.

3.1.2 System Architecture

The SME was developed here to evaluate the proprioception performance to detect and quantify CwDS movements, generating support to therapists through a report of the required parameters. The SME was implemented using C# language and the Unity Game Engine Development Platform[1] and follows a one-tier architecture with three layers (sensor, data processing, and data storage) in a single software package, as shown in Figure 5. All data is stored on the local system (i.e., using a PC with an Intel Core i5 (i5-5287U) 5th generation processor and 8 GB RAM). Children gestures are tracked using the Kinect V2® Sensor, which tracks 15 body joints. The sensor operates mainly with a latency between 60 and 80 ms. To establish communication between the RGB-D camera and the SME on Unity, the Nuitrack SDK[2] was used. The SME generates visual stimuli, providing feedback through a projector, and the tracking is activated once the therapist starts a new therapy/training. The stored data helps specialists to observe motor patterns of the child in the SME and track how the proprioception improve over several intervention sessions. Thus, a permanent monitoring system and appropriate feedback for clinical staff, parents, and developers is supplied.

Unity Game Engine Development Platform was implemented to create the virtual interface due to the necessity to develop an interactive game platform in the next step. In Figure 6 the SME flowchart is shown. After the software starts, it is possible to observe the online sensor capture. Before to record the joint data, the system verifies if the user personal data is complete and if there is any user in front of the camera. Afterward, the recorded data is saved, together with the user name, pushing the "stop" interface button.

The SME allows the children to see their virtual reflex while performing specific movement tasks. At the same time, the SME shows to the evaluator the joint estimation

[1] <http://unity3d.com>
[2] <https://nuitrack.com/>

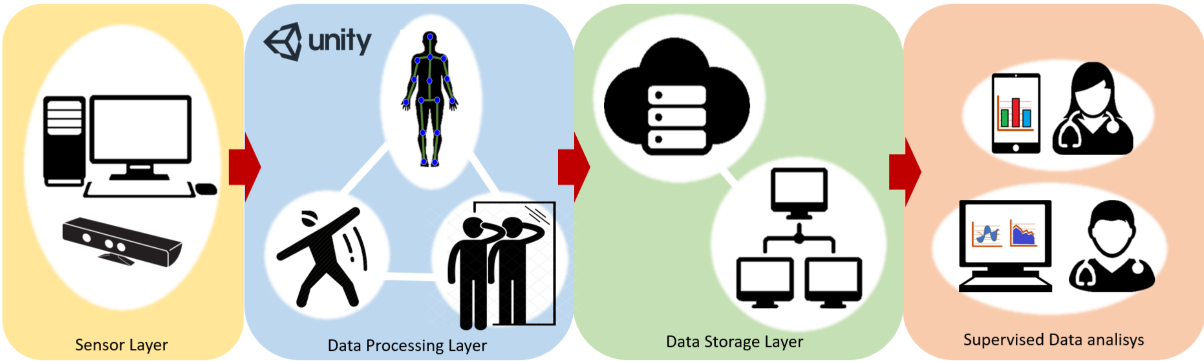

Figure 5 – SME architecture with three layers: sensor layer (data capturing), data processing layer (patterns recognition and GUI), and data storage layer (digital records) to be accessed by evaluators.

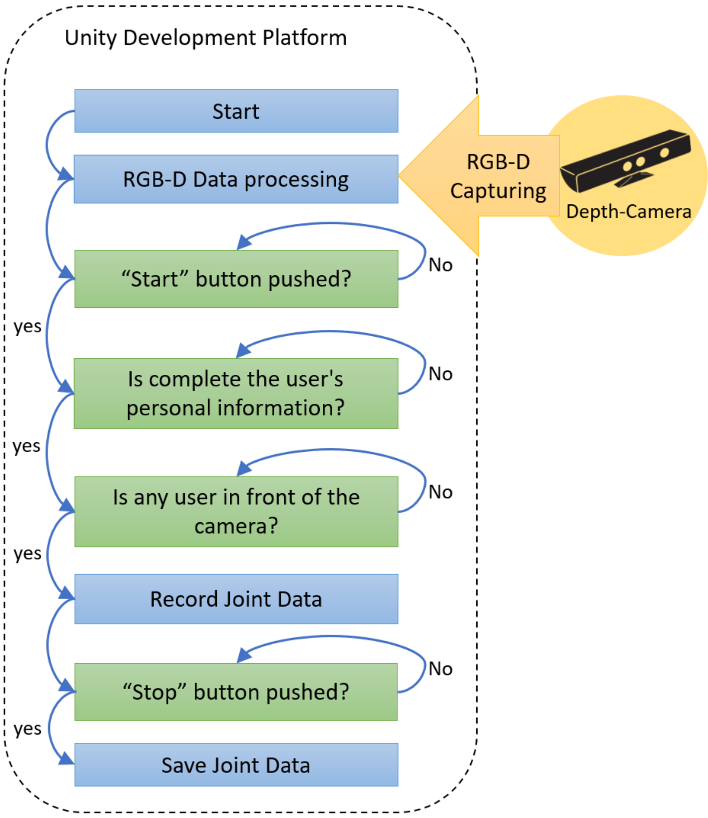

Figure 6 – Smart Mirror Interface flowchart.

with a skeletal approximation of the user (Figure 7.b), and specific angle estimation (range of motion), configured depending on the evaluation (Figure 7.c). The joint estimation is used to obtain kinematic patterns and is recorded during the assessment. The SME saves the positions of the tracked body articulations in three dimensions, and all data is provided to the evaluator to posterior analysis with the user personal information (Figure 7.a).

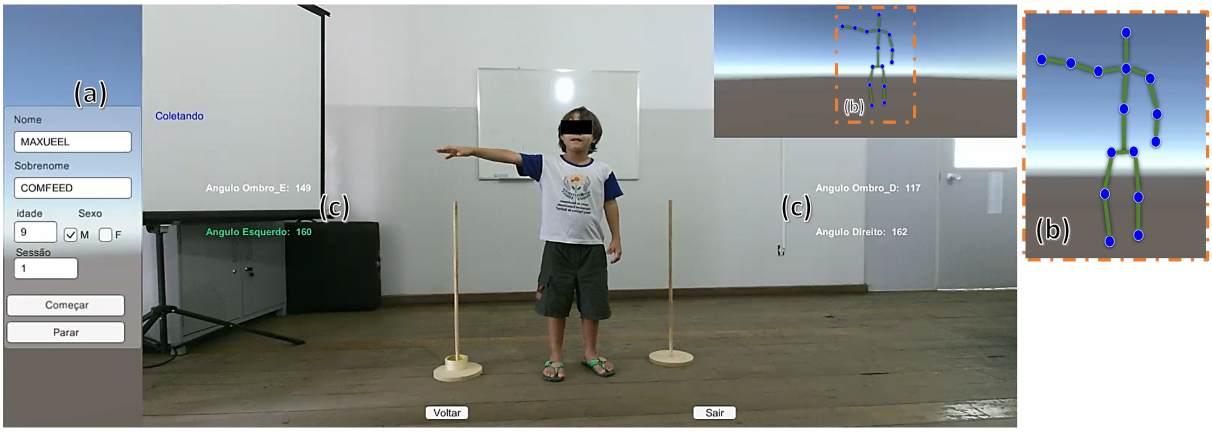

Figure 7 – Smart Mirror Interface. (a) User personal information. (b) Joint estimation generated for the cameras arrangement. (c) Instant angle estimation configured for the evaluator.

The SME was located in a room with enough space to the camera range, which has a white wall to show the interface projection, as shown in Figure 8. The camera is located in specific place to capture all possible movements' angles, and the virtual reflex is captured, generating feedback, such as a mirror effect. According to the clinical analysis performed, the system can be configured to show specific range of movement (articulation angles). For example, if the movement of the child's arms is relevant, the system is configured to indicate the angle of the elbow joint in both arms of the child while performing the performance protocols. To calculate the required angles, the law of cosine was used, such as suggested by different authors (CHEN et al., 2017; XU et al., 2018).

3.2 Experimental Setup

3.2.1 Participants

The sample was composed of 12 CwDS (6 male, 6 female), average aged 9.17 ± 0.4 years old. These children were non-probabilistically chosen from two rehabilitation centers of the "Associations of Parents and Friends of Exceptional Children" (APAE), both located in Vila Velha and Serra, Brazil. Inclusion criteria were: children able to walk without personal assistance and/or assistive devices/orthosis; without any other neurological

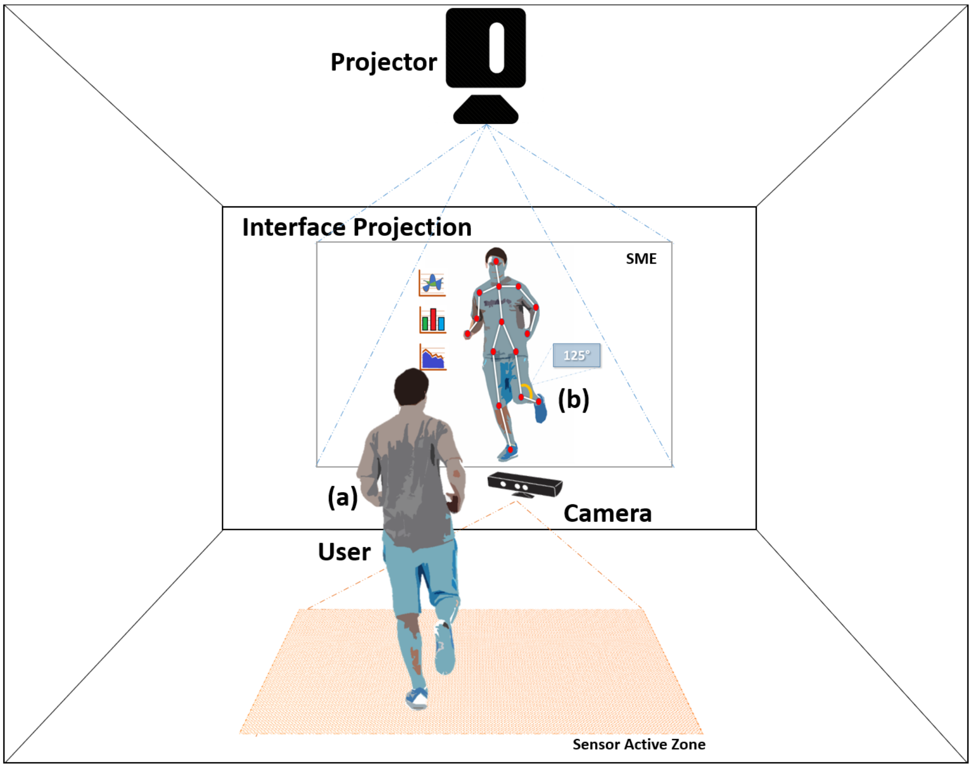

Figure 8 – Smart Mirror Environment (SME) in a suitable space. (a) The user performs different movements in front of their virtual reflex, while the system records kinematic parameters. (b) Joint angles are calculated depending on medical requirement.

alterations, or associated respiratory or osteomyoarticular pathologies (not due to DS); and ability to understand and obey simple verbal commands. The study was approved by the Research Ethics Committee of the Federal University of Espirito Santo, Brazil (CAAE 64797816.7.0000.5542), and all parents or legal guardians signed an informed consent form, authorizing their children to participate of the study.

3.2.2 Intervention Protocol

For this study, the data collection was conducted in two different days to each child. The first evaluation was developed without feedback in the SME, and the second (one week later) was developed with the feedback of the SME. The Assessment Protocol is divided in two different elements: first the reach and fit function; and second, a Body Sense Factor (BSF) (FONSECA, 2012) to analyze proprioception level, which includes the activities: kinesthetic sense, right-left discrimination, self-image, gesture imitation, and body drawing. Each element has a maximum score of 4 (better performance) and a minimum of 1, as shown in Table 1. These activities are analyzed based on a set of tasks that can detect functional deficits in psychomotor terms, covering sensory and perceptual integration, which is related to the child's learning potential. Each activity is explained as follows:

- Reach and fit function. Remove a ring from a hatrack and take it to another hatrack one meter away. As shown in Figure 9, the ring should be removed from the lower left, taking it to the upper right end of the other hatrack and vice versa. Each child must perform the task twice.
- Kinesthetic sense. Sign different parts of the body, as head, mouth, hands, etc.
- Right-left discrimination. Determine which of each of their eyes, hands and legs belongs to each hemisphere of the body.
- Self-image. Put the arms outstretched and flex them until touching the nose tip with the fingertips for 4 times, twice for each hand.
- Gesture imitation. Imitate the movements of the evaluator, who outlines in the air, and with his/her hands, simple geometric figures, such as a square or a circle.
- Body drawing. Draw a design of himself/herself before using the SME and after using it and compare them.

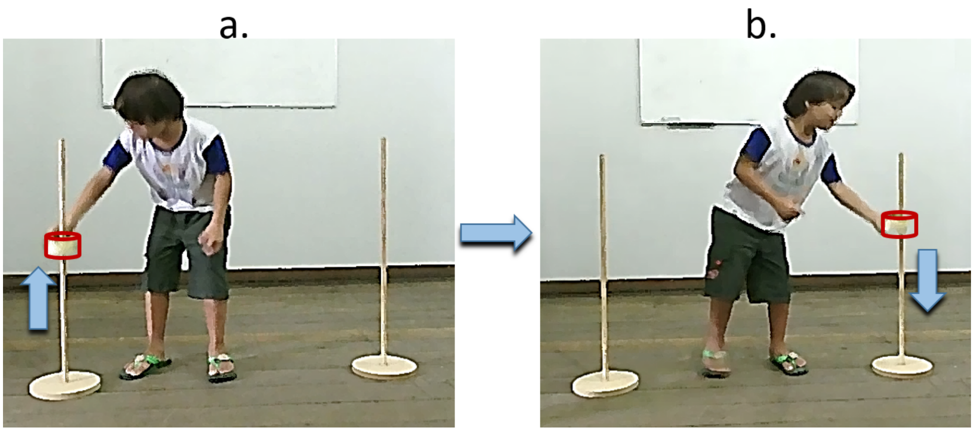

Figure 9 – Performance of reach and fit function: a) Child removing the ring. b) Child placing the ring.

Table 1 – Correlation between the score and the performance scale of the child assessment, based on Fonseca (2012).

Score	Performance	Profile
1	Incomplete and disorderly (weak)	Apraxic
2	With difficulty in control (satisfactory)	Dyspraxic
3	Controlled and appropriate (good)	Eupraxic
4	Perfect, harmonious and well controlled (excellent)	Hyperpraxic

3.2.3 Statistical analysis

The results were subjected to statistical analysis using the nonparametric Wilcoxon test to correlate the performance in reach and fit functions, as well as the proprioception level (score of BSF) with and without feedback. This test was applied using Matlab, which essentially calculates the difference between each set of pairs and analyzes these differences. The model assumes that the data are continuous and come from two matched populations, following the same person, in this case. As it is a non-parametric test, it does not require a particular probability distribution of the dependent variable in the analysis.

3.3 Results

The overall results of the assessment protocol activities (see Figure 10) show that the children in the sample obtained higher average scores on the self-image activity, both with SME implementation (m=3.66) and without (m=3.41). The lowest average score was in the right-left discrimination activity, both with SME implementation (m=1.41) and without (m=1.16).

The results were subjected to statistical analysis using the nonparametric Wilcoxon test to correlate the performance in reach and fit functions, and proprioception level (score of BSF) with and without feedback. Comparing children's performance on the tasks with and without visual feedback, the data suggest a significance value in the kinesthetic sense activity (p=0.014), with an increasing of 29,9%. The increments in the performance of the right-left discrimination, self-image, gesture imitation and body drawing was 21.4%, 7.3%, 24.1%, 9.5%, respectively. Similarly, when considering the child's total performance (sum of BSF activities), also there was a significance value (p=0.007) between performances with and without feedback, validating the fact that CwDS improve their performance using the SME. The average sum of the activities for the BSF with and without feedback are m=11.92 and m=10.42, respectively (maximum score=20), increasing 16.8%, evidencing that CwDS need training with the SME (or similar tools with visual feedback) to improve their proprioception.

The SME has the functionality of showing and saving different parameters of children movements for further analysis, according to the needs of the evaluator. As presented in Figure 11, it is possible to compare the performance of the reach and fit function of the intervention protocol in two different children, which were captured by the SME to determine the range of motion in elbow joints during flexion-extension movement. As shown in Figure 11.a, the neutral arm position or a complete arm extension configures zero degrees. In Figure 11.b the child executes the reaching and fitting movements with the two arms. During the reaching movement, the child increases slowly his/her range of

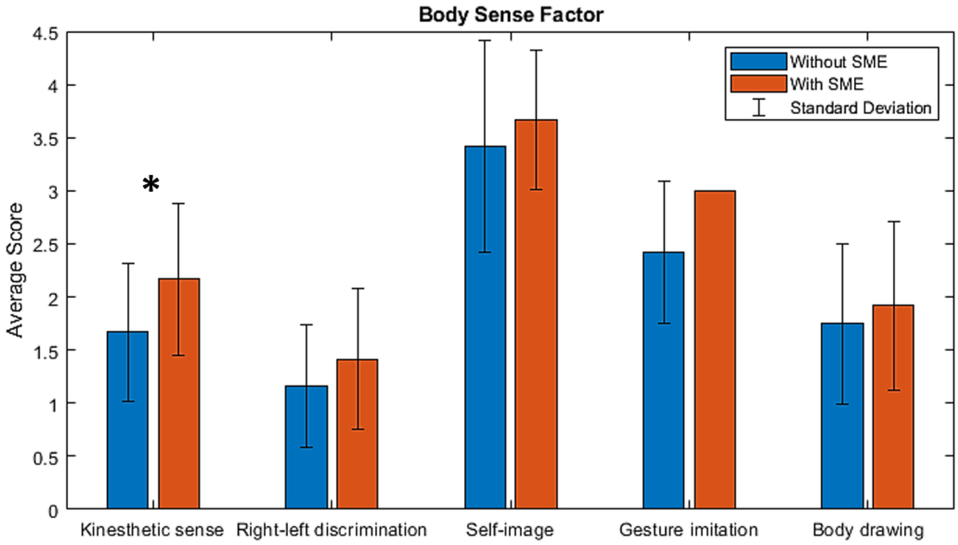

Figure 10 – Correlation between the performance with and without the SME implementation. Note: Wilcoxon test with p value (significance) <0.05; * = statistically significant values.

motion in the elbows until obtaining the hoop and then flexes his/her arms, bringing the hoop close to the body. Afterwards, the child puts the hoop in the hatrack, decreasing the range of motion in elbows. In the movement shown in Figure 11.c, the child executes most of the movement with the right arm, and keeps the ring close to the body until putting the hoop in the hatrack. At the same time, the left arm performs free flexion-extension movements.

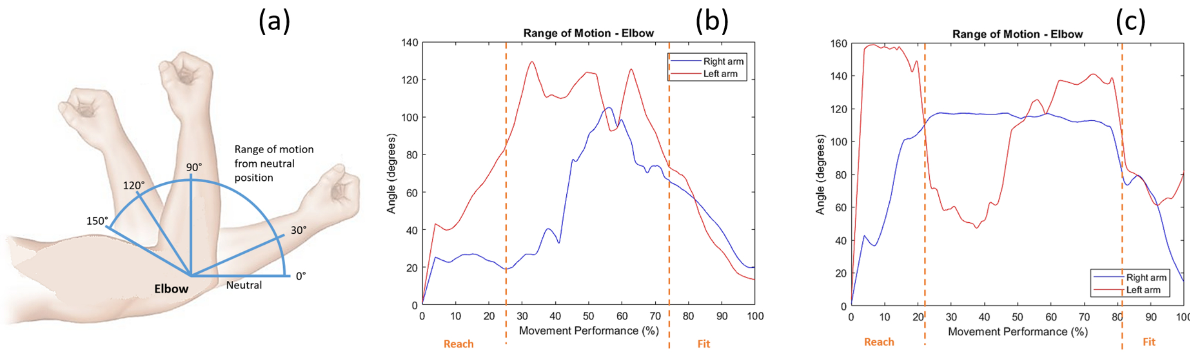

Figure 11 – Range of motion of the elbow joints, performing the reaching and fitting activity. (a) Flexion-extension movement from neutral position. (b) Child 7 performing the activity with both arms simultaneously. (b) Child 2 performs the activity just with the right arm.

For the analysis of the gesture imitation activity of the BSF, conducted with the data recorded by the SME, it is possible to compare the movement developed for each child with the proposed movement made by the evaluator. In this case, it is a bilateral gesture (with both hands) similar to a circumference, as shown in Figure 12.a. It was found that all the children understood the geometric gesture performed by the evaluator, but only 58.3% performed the movements in spatial agreement (similar scale size or similar design form). Some children imitated the movement on a smaller or higher scale than that achieved by the evaluator, being possible to see different adaptations to the same circular gesture. Figure 12.b shows the trajectories of the index fingers of Child 5, who developed a similar design with her fingers. In other case, Child 10 performed a bigger design, almost completing a circumference with each hand, showing a bilateral motor coordination impairment (Figure 12.c).

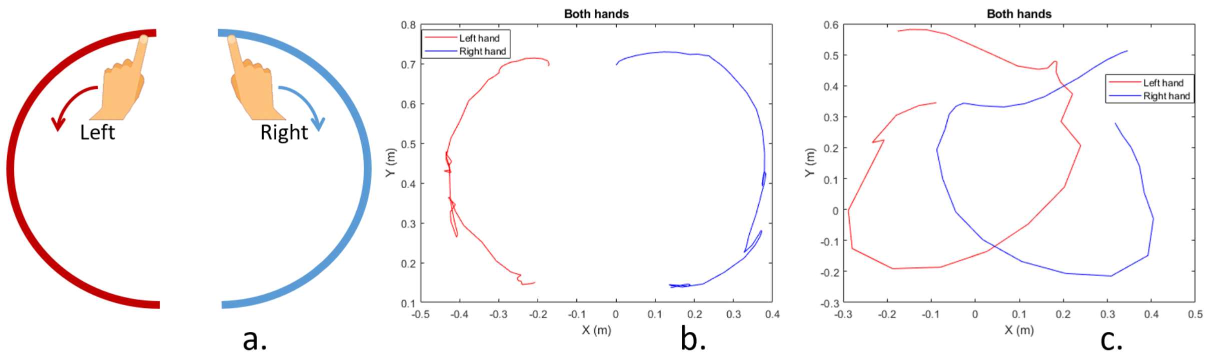

Figure 12 – Gesture imitation performing a circumference. (a) Suggested gesture performed by the evaluator. (b) Imitation performed by Child 5. (c) Imitation performed by Child 10.

As far as right-left discrimination is concerned, the CwDS showed difficulty in distinguishing the hemisphere sides and related them to a specific body part, such as found in literature (ELLIOTT; WEEKS; CHUA, 1994; GROUIOS; YPSILANTI; KOIDOU, 2013). None of the CwDS was able to make a complete discrimination between the two hemispheres of the body. In Table 2, the demanded tasks and the percentage of CwDS that accomplished them are explicit. Globally, in only 30% of the times the children performed the task correctly.

On the other hand, an interesting result was found in the body drawing activity performed for each child. The drawings made after the motor tasks with visual feedback, using the SME, presented cleaner and wider strokes compared to the drawings made before interacting with the SME, including the designs where the child did not draw the form of a human body. Figure 8 shows four examples of these self-drawings.

3.4 Discussion

Systems such as the one presented in this Chapter may provide more significant interaction with the environment to CwDS, stimulating and expanding their several senses. With the results obtained so far, it is possible to highlight that all task and kinematic parameter performed by the children, measured by our virtual immersion system, can be

Table 2 – Percentages of children with DS that manage to perform each task correctly.

Task assigned	Correctly performed (%)
Show right hand	41,67
Show left hand	33,33
Show right foot	25,00
Show left foot	33,33
Point at right eye	16,67
Point at left eye	33,33

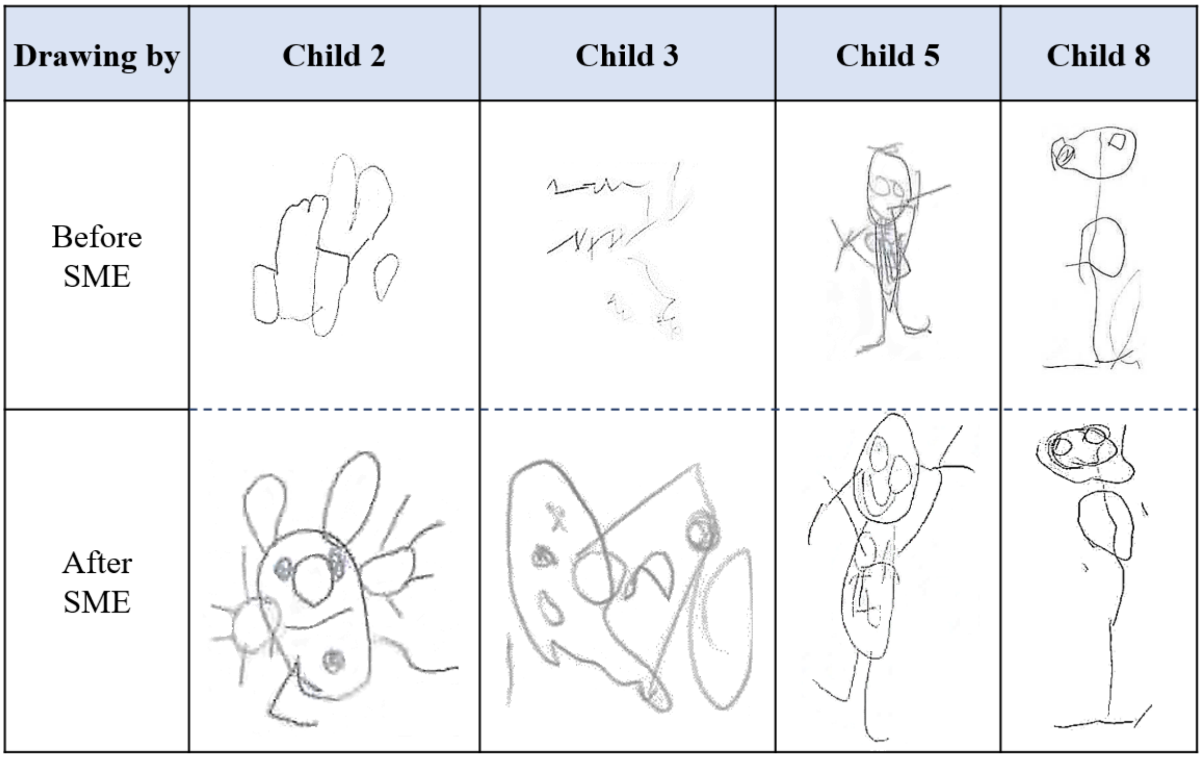

Figure 13 – Examples of self-drawing before and after using the SME performed by CwDS.

further analyzed to get more parameters of interest. The system can capture parameters of 15 joints in the body and store position and orientation data with temporal reference. Thus, the analysis presented in this work can be used to analyze movements developed in articulations of legs, torso, hip or any other body segments required by the evaluator. This system was developed to achieve the requirements of professionals in psychology and physiotherapy, with the purpose of understanding and analyzing basic motor tasks in CwDS.

The CwDS evaluated in this research had an average proprioception score close to the half established by the BSF (m=10), which, according to Fonseca (2012), is an indicator of specific psychomotor learning difficulties. This finding corroborates several studies, suggesting a developmental delay in these children (REDDY et al., 2010; SCAPINELLI; LARAIA; SOUZA, 2016; VIMERCATI et al., 2015). In addition, the findings indicate that these CwDS need more stimulation to satisfactorily develop certain body skills, as shown in (SUGIMOTO et al., 2016).

For the CwDS of this sample, the visual feedback generated by the SME provided information that showed a statistical increment of the Kinesthetic sense, in which the evaluation performed by different activities required motor performance and, thus, the visual information, guided by the BSF required actions. The positive influence of visual feedback on the proprioception of CwDS can be explained by the activation of the cortical motor system through somatosensory and visual stimulation (LENT, 2008).

The results on the link between proprioception and performance (in reach and fit function in CwDS) show that the activity execution was not influenced by the visual feedback offered. This result can be explained by the specificity of the motor action involved in these functions, where the movement was directed at a target and not in the interaction with the SME. This kind of repetitive activities can be analyzed using the system to measure the movement developed by the child and to compare it with prior similar activities. We believe that the accompaniment by physiotherapy staff can improve the quality of the performed movements by these children, such as their proprioception and gross motor skills.

Considering each BSF activity, the kinesthetic sense showed a statistically significant difference when the visual feedback was offered. In the case of CwDS, this result can be explained by the influence of the somesthetic system, where the visual information provided by the feedback implied a better performance (ADAMOVICH et al., 2009; DEL RIO GUERRA et al., 2019).

The BSF activities, such as right-left discrimination, self-image, gesture imitation, and body drawing, were not statistically different in the score, but showed important results in the spatial awareness, working memory and attention span, abilities that need to be improved in CwDS. In fact, the results show that the recurring practice using our SME can improve the understanding of shapes and sizes, as well as the ability to follow instructions. In the right-left discrimination, we find that no CwDS was able to distinguish the hemispheres of the body, suggesting a necessary tool to train that specific ability.

In the self-drawing activity, it is important to consider that the visual feedback offered to the children provided an improvement in their body drawings shape. Visual information served as a support for improving the motor skills in the graphic record of the children's body. Drawing as product of this integration was also influenced by the visual system.

3.5 Remarks of this Chapter

A Smart Mirror Environment (SME) was developed using a depth camera (RGB-D) to provide visual feedback and proprioception assessment to CwDS. A virtual mirror interface was designed to analyze three-dimensional movements of different body segments of the children, which provided objective data to posterior analysis. The discussion of the data warns that body experiences may be fundamental for motor and self-perception aspects of CwDS. In fact, CwDS implicitly have a developmental deficit, therefore, they should be provided with sensory and bodily experiences in order to promote neuropsychomotor development.

Based on the findings, the next step of this research is the use of a RGB-D multi-camera system, in order to reduce the occlusion generated by the children's body, as well as to improve the acquisition of kinematic parameters, which will be shown in Chapter 4.

In the same way, a platform of serious games is necessary to train the different activities evaluated with the SME, which will be shown in Chapter 5.

It is important to emphasize that the information obtained by the SME was used to develop different kinds of therapies and trainings through virtual environments, thus contributing to the psychomotor development of CwDS.

4 Color-Depth Cameras arrangement towards measuring the accuracy in Joint Angle Estimation: A Comparative Study[1]

There is a clear and growing interest in developing technological-based tools that systematically analyze human movement. Notably, there are many advantages to implement automated systems to detect human motion for applications associated with children in a healthcare context or to assess mobility impairment of ill and elderly people (HASHIMOTO et al., 2007). Automated quantification of body motion to support specialists in the decision-making process, such as stability, duration, coordination, and posture control is the desired result for those technological-based approaches (CASAMASSIMA et al., 2014; VAN DEN NOORT et al., 2013). Despite recent advances in this area, automated quantification of human movement for children with sensory processing and cognitive impairments, as well as adults with mobility disabilities, presents multiple challenges due to factors as accessibility barriers, markers attached to the body, and high cost of the system.

Automated analysis of body movements typically involves obtaining 3D joint data as position and orientation, which are estimated in two different ways using intrusive or no-intrusive approach, also known as wearable and non-wearable technologies (HERRAN; GARCÍA-ZAPIRAIN; MÉNDEZ-ZORRILLA, 2014). Wearable systems are portable and can be used by people with movement impairments in unstructured scenarios (SHULL et al., 2014). However, advances in non-wearable sensing technologies and processing techniques have appeared to measure, with high accuracy, human biomechanics in although highly-structured environments (WONG et al., 2015). Camera-based markerless systems can be then used in scenarios when users does not admit wearable device to capture their data (HERRAN; GARCÍA-ZAPIRAIN; MÉNDEZ-ZORRILLA, 2014). In addition, Markerless systems can eliminate the difficulty of applying markers to users with physical or cognitive limitations (CAMEIRAO et al., 2010).

This Chapter presents the development of a color-depth cameras arrangement with the aim to generate objective human movement parameters. The data fusion process between two color-depth camera systems is detailed. Afterward, a comparison among

[1] This chapter is mainly based on the following publication:
Nicolas Valencia-Jimenez, Arnaldo Leal-Junior, Leticia Avellar, Laura Vargas-Valencia, Pablo Caicedo-Rodríguez, Andrés A. Ramírez-Duque, Mariana Lyra, Carlos Marques, Teodiano Bastos, Anselmo Frizera, A Comparative Study of Markerless Systems Based on Color-Depth Cameras, Polymer Optical Fiber Curvature Sensors, and Inertial Measurement Units: Towards Increasing the Accuracy in Joint Angle Estimation. Electronics (2019). <https://doi.org/10.3390/electronics8020173>

the arrangement of the color-depth cameras developed and wearable devices as intensity variation-based POF sensor, and IMUs was also conducted to asses human joint elbow angles. These wearable sensors (POF and IMU) were chosen due to their compactness, which would not cause occlusions for the markerless camera system. This systematic comparison aimed to study the trade-off between the markerless feature of the vision system and its accuracy by comparing it with wearable technologies for joint angle measurements.

4.1 RGB-D Fusion System

The following sections approach the skeleton joint tracking using depth-cameras (Section 4.1.1), as well as the system architecture developed to fuse the joints data from each camera system (Section 4.1.2).

4.1.1 Human Body Analysis through Skeleton Joint Tracking

A computer vision framework composed of an unstructured and scalable network of RGB-D cameras is used here to automatically estimate joint position. The depth-camera implemented (Kinect V2), is detailed in Section 3.1.1. This visual sensor network counteracts typical problem as occlusion and narrow field of view. Consequently, the system uses a distributed architecture for processing the videos of each sensor independently.

Due to this system being developed in Linux, each Kinect v2 estimates the user skeleton joint tracking through NiTE2.2 API[1], released by PrimeSense (SHOTTON et al., 2011). NiTE2.2 is a middleware component that allows for skeleton and gesture detection and their algorithms to perform functions as scene analyzer (separation of users from background) and accurate user joint tracking, through OpenNI interfaces, as shown in Figure 14.

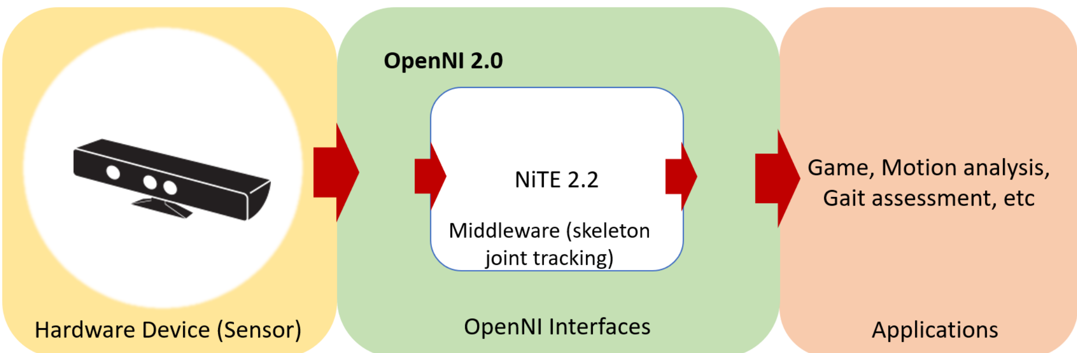

Figure 14 – Three-layered view of OpenNI concept.[2]

[1] <https://structure.io/openni>

The OpenNI 2.0 API provides a uniform interface that third-party middleware developers can use to interact with depth sensors. Applications are then able to make use of both the third-party middleware, as well as underly basic depth and video data provided directly by the OpenNI.

Subsequently, the joint positions provided by each sensor are merged, representing a shared reference to fuse them and generate a global joint position (CARVALHO, 2018). Figure 15 shows an example of the 15 joints positions resulting through the software Rviz[1], a 3D visualizer for displaying sensor data and state information from Robot Operating System (ROS), which will be detailed in Section 4.1.2.

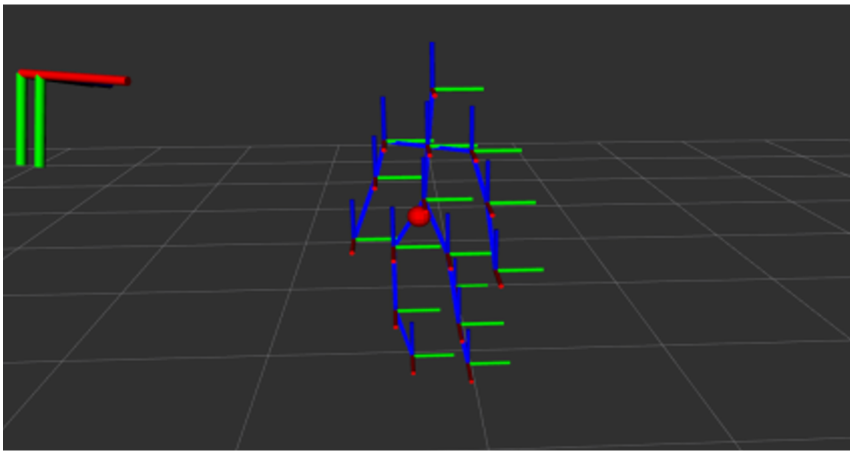

Figure 15 – Skeleton joint tracking (3-D) in Rviz environment.

4.1.2 System Architecture Overview

This system was designed as a distributed and modular architecture using the open source project Robot Operating System (ROS). The architecture developed here was built using a node graph approach. This system consists of a number of nodes to local video processing, distributed around a number of different hosts and connected at runtime in a peer-to-peer topology. The inter-node connection is implemented as a hand-shaking and occurs in XML-RPC (Remote Procedure Call protocol), which uses XML (Extensible Markup Language) to encode its calls. The node structure is flexible, scalable and can be dynamically modified, i.e., each node can be started and left running along an experimental session or resumed and connected to each other at runtime.

The vision system is composed of two RGB-D cameras, as shown in Figure 16. Each camera is connected to a workstation equipped with a processor Intel Core i5 and a GeForce GTX GPU board (in this work we used a GTX960 board and a GTX580 board)

[2] Based on the OpenNI user guide on <https://github.com/OpenNI/OpenNI/blob/master/Documentation/OpenNI_UserGuide.pdf>

[1] <http://wiki.ros.org/rviz>

to execute local data processing. All workstations are connected through a local area network synchronized using Network Time Protocol (NTP) and managed through ROS. A server workstation is responsible for transforming each position received into a global coordinate system, fusing data using a Kalman filter and then saving the position data in a .txt file in JavaScript Object Notation (JSON) format. The saved merged data can be analyzed by third-party software like Matlab.

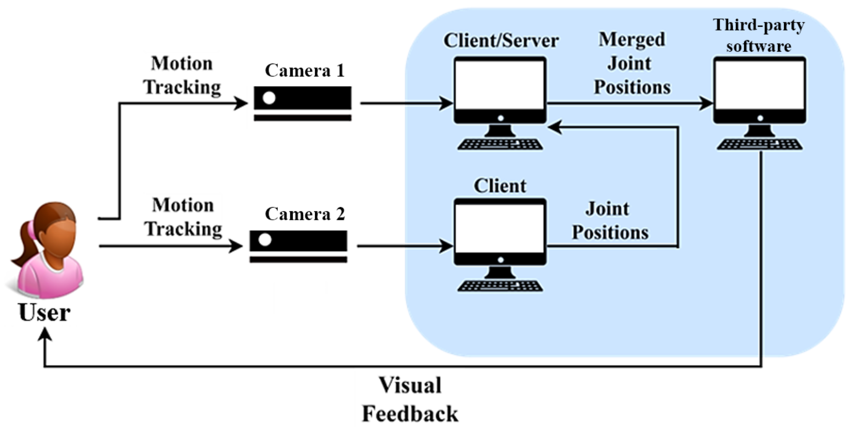

Figure 16 – Configuration of the RGB-D system.

Each workstation has two primary processes: user detection and position/orientation estimation of fifteen joints. The detection process targets the user points to be people in the scenario, using the software OpenNI/NiTE, which does the client task, sending the movement estimation to the server over the network. The extrinsic (transformation from 3-D world's coordinate system to the 3-D camera's coordinate system) and intrinsic (transformation from the 3-D camera's coordinates into the 2-D image's coordinates) calibration of each RGB-D camera is performed using both the OpenCV package and the multi-camera network calibration tool provided by OpenPTrack[2] (see Figure 17).

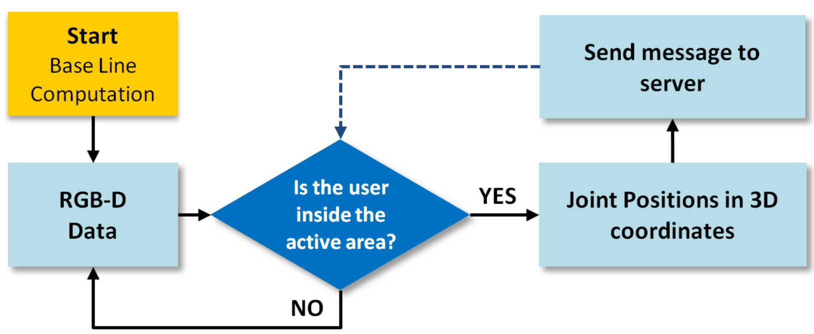

Figure 17 – Client flowchart.

[2] <http://openptrack.org/>

The workstation with the highest processing capacity is also used as the system server, which is responsible for the joint fusion process (using a Kalman filter), as made by Carvalho (2018). Data fusion with Kalman filtering has been studied by several researchers focused on using a multi-Kinect setup (MOON et al., 2016). When the server receives a message with the position data of a client, it checks the time interval between the last received message and the current message. If this interval is greater than 33 ms, the system discards the received measurement and resumes counting the intervals from the next measure to receive. This is made to do not use the merging data with a very discrepant time. If the data is within the time interval, the system transforms the client coordinate system into the global coordinate system defined in the extrinsic calibration process. The aforementioned procedure results in an acquisition frequency of 30 Hz for the markerless camera-based system. It is worth to mention that this interval can be controlled to achieve different acquisition frequencies. Then, the data is inserted into the Kalman filter, and the saved data is processed through a low-pass Butterworth filter used to eliminate noise and to achieve a smoother estimate (see Figure 18).

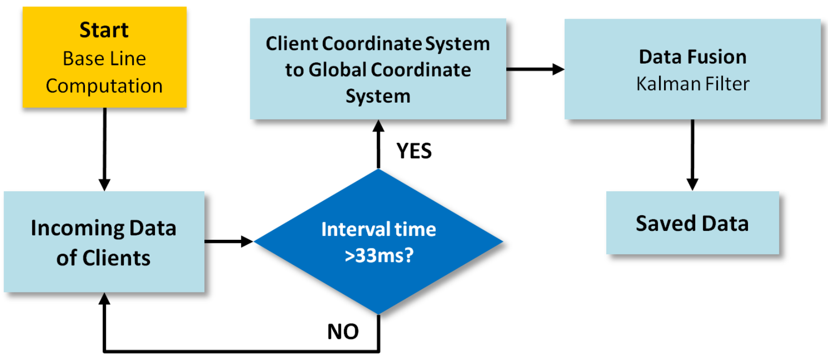

Figure 18 – Server flowchart.

The RGB-D fusion process is executed to obtain kinematic parameters and corporal patterns to be shown in an assessment interface that detects and quantifies the user's movements. The system can produce parameters such as range of motion and positions of the tracked body articulations in three dimensions. In the same way, the system can be configured to show specific articulation angles. We use the law of cosine to calculate the elbow angle, as suggested by different authors using depth-cameras (CHEN et al., 2017; NGUYEN; LEE, 2012; YONGBIN QI et al., 2014; XU et al., 2018). Equation 4.1 shows the relation between the forearm d_1 and upper arm d_2 lengths as shown in Figure 19. The blue dots shown in Figure 19 are identified using the software NiTE (such as aforementioned) where three points are identified (on the shoulder, elbow and hand), with (X, Y, Z) coordinates represented at each point.

$$\theta = \cos^{-1}\left(\frac{-d_3 + d_1 + d_2}{2 * d_1 * d_2}\right) \tag{4.1}$$

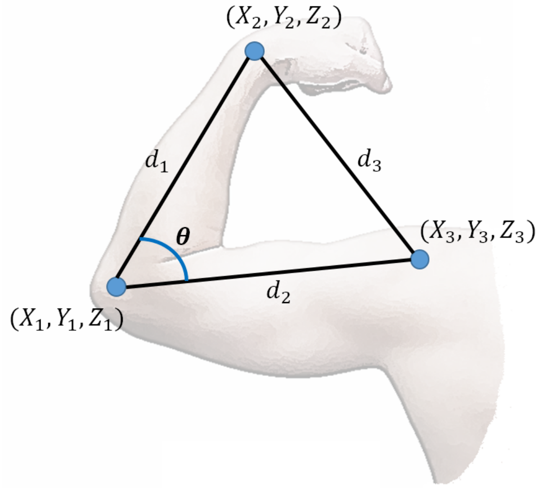

Figure 19 – Parameters to calculate the articulation angle of any joint.

4.2 Experimental protocol

Eleven participants without motor impairments were enrolled in this study. Six females, referred as F1, F2, F3, F4, F5 and F6, age: 27.3 ± 4.9 years, corporal mass 56.8 ± 16.3 kg, and five males, referred as M1, M2, M3, M4 and M5, age: 27.4 ± 3.3 years, corporal mass 70.2 ± 3.8 kg, as shown in Table 3. This research was approved by the Ethical Committee of UFES (Research Project CAAE: 64797816.7.0000.5542).

Table 3 – Characteristics of the participants of this research.

Subject	**Age (yrs)**	**Height (cm)**	**Weight (Kg)**
M1	30	163	67
M2	22	176	66
M3	30	173	73
M4	27	183	75
M5	28	170	70
F1	30	156	57
F2	32	158	46
F3	22	160	48
F4	23	163	53
F5	24	158	48
F6	33	176	89

Two IMU sensors (as implemented by Vargas-Valencia et al. (2016)), one POF curvature sensor (as implemented by LEAL JUNIOR, Frizera e Pontes (2017)), and an arrangement of two RGB-D cameras (detailed in Section 4.1.2) were used to estimate elbow joint angles. The IMU reference sensor was placed on the superior third of the right upper arm, and the second IMU was attached dorso-distally on the right forearm, as shown in Figure 20(e). In a standing neutral posture, both sensors were positioned with x-axis pointing cranially, z-axis laterally and y-axis orthogonal to x and z axes. These position have been suggested by different authors (PALERMO et al., 2014; SEEL; RAISCH; SCHAUER, 2014; EL-GOHARY; MCNAMES, 2012). Moreover, the POF curvature sensor was carefully aligned with the elbow joint in such a way that the sensitive zone of the optical fiber is located on the axis of rotation (flexion-extension axis).

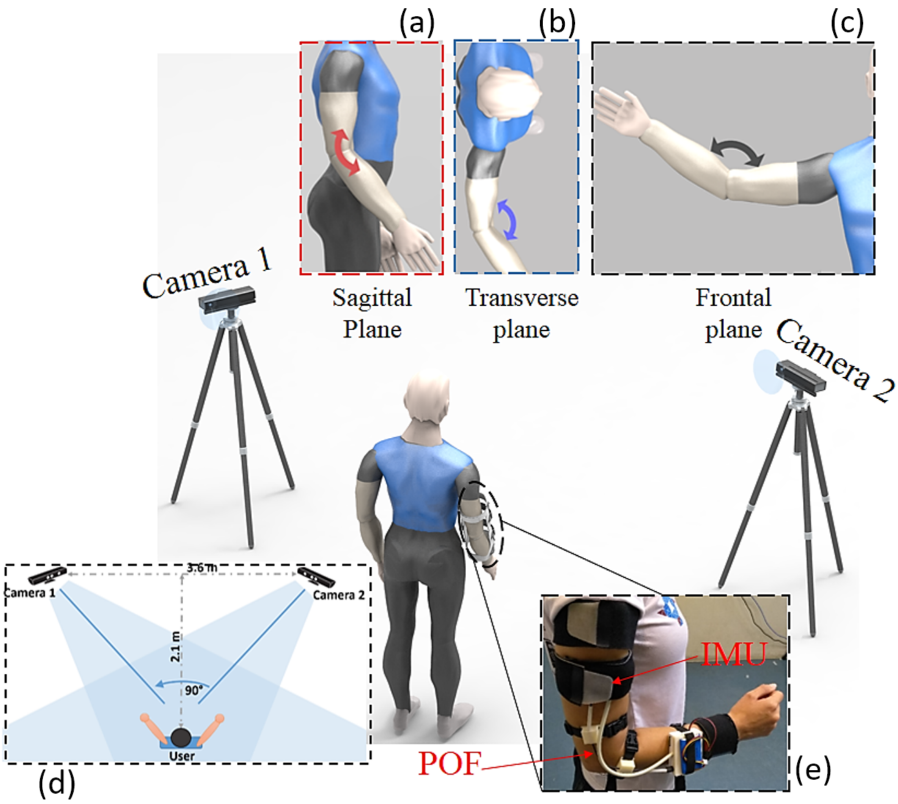

Figure 20 – Sensors' placement on the human upper limb, and movements performed during the experimental protocol. (**a**)User movement representation in sagittal plane; (**b**) transverse plane; and (**c**) frontal plane. (**d**) Top view of RGB-D system arrangement. (**e**) User using the IMU system and POF sensor.

In this experiment, the eleven participants (see Table 3) performed in a comfortable self-velocity flexion-extension movements on three planes: sagittal, transverse and frontal. Each participant was standing at the center of the room, observing the middle point between the two RGB-D cameras, see Figure 20(d). All trials started with a synchronization movement, which consisted of keeping the elbow in maximum extension on standing posture, then performing an elbow flexion of 90° and returning to the extended elbow position, where each transition lasted 5 seconds. Then, the subject was asked to perform three repetitions of flexion-extension on a specific plane. In the sagittal plane, the shoulder was in a neutral position and the participant performed elbow flexion-extension to get the maximum angle as possible (see in Figure 20(a)). In the transverse plane, the shoulder was in abduction (at max 90°) and kept in that position for 5 seconds before the elbow flexion-extension movements (Figure 20(b)). In the frontal plane, the shoulder was in abduction (at max 90°) and external rotation, so the palm of the hand was facing forward, as shown in Figure 20(c). These steps are summarized in Figure 21.

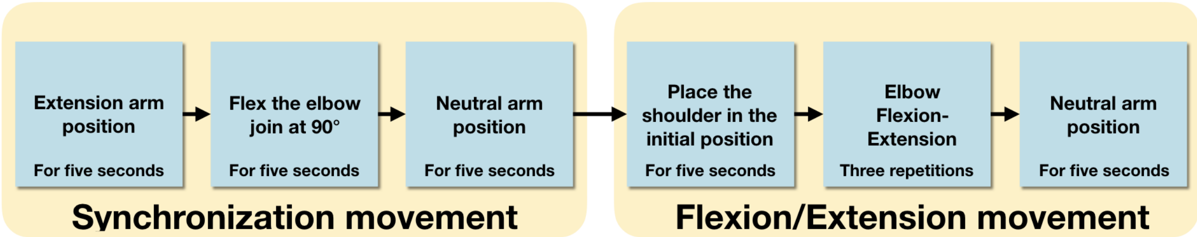

Figure 21 – Summary of the protocol's phases.

4.3 Results and Discussion

The comparison variables of the three systems were: (i) the correlation coefficient and (ii) the root mean squared error (RMSE) between the RGB-D cameras, IMUs and POF.

4.3.1 Sensor characterization

To validate the measurements of the camera-based system, an IMU-based system, a POF curvature sensor, and a goniometer as a standard reference were used. This reference has two adjustable lever locks, which are positioned to limit the flexion-extension motion between 20° (lower bound) and 90° (upper bound). The goniometer was placed and aligned with the elbow joint of the subject M1, then, this was asked to perform flexion-extension movements on the sagittal plane in such a way to reach both locks. Lastly, the data was acquired by the camera-based system and the IMUs. The POF curvature sensor was characterized using the procedure mentioned in LEAL JUNIOR, Frizera e Pontes (2017).

Table 4 shows the maximum and minimum angles for cameras system and IMUs, comparing with upper and lower bounds, respectively. The average error for the cameras system was 4.9°, with a maximum error of 9°, when compared to the goniometer for two values (90° e 20°), which is lower than the mean error presented in Tannous et al. (2016) $(14, 6°)$. However, only one camera was used for Tannous et al. (2016), carrying a higher self-occlusion, leading to errors on the angle assessment. Since our system consists of two cameras, the self-occlusion decreases, consequently, reducing the errors. Comparing with the goniometer, the IMUs' average error was 3.7°, which is lower than the camera-based system (expected result for a wearable sensor).

Table 4 – Maximum and minimum angles of camera-based system and IMU of each cycle for the first test.

	Cycle 1		**Cycle 2**		**Cycle 3**	
	Max [°]	Min [°]	Max [°]	Min [°]	Max [°]	Min [°]
Camera	87.4	21.0	82.6	12.8	99.0	22.2
IMU	94.6	22.9	94.4	22.7	94.7	23.0
Goniometer	90.0	20.0	90.0	20.0	90.0	20.0

4.3.2 Comparison among sensors

The camera-based system was compared with both IMU and POF. The comparison was conducted with respect to the correlation coefficient and root mean squared error (RMSE). Figure 22 shows the results obtained for all sensors in different planes, i.e., sagittal, transverse and frontal planes, for subject M1.

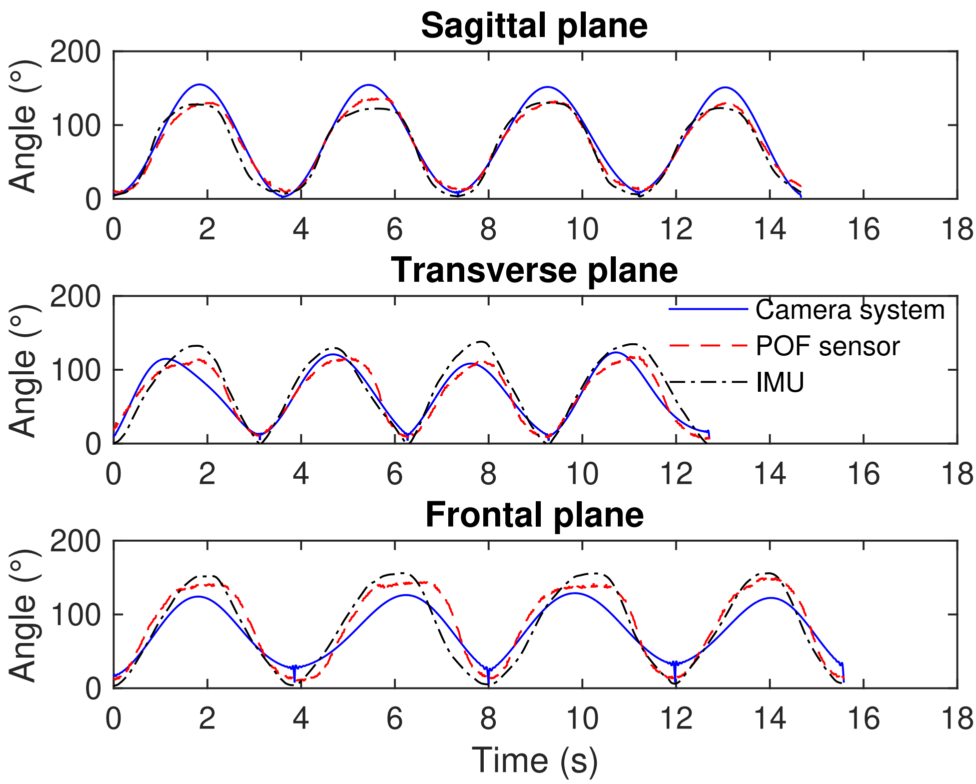

Figure 22 – Comparison among camera-based system, POF curvature sensor and IMU in sagittal, frontal and transverse planes, for subject M1.

The results presented in Figure 22 show a good correlation between the errors of the POF curvature sensor and IMU, especially on sagittal and frontal planes. Although we used the same number of cycles to compare the sensors, the period of each movement is different, due to that each subject was allowed to perform the movements at a comfortable self-velocity.

Furthermore, the range of movement at each plane is different, i.e., the movement at the sagittal plane occurs in a range of about 0-145°, whereas the one at the transverse plane reaches angles lower than 130°. Similarly, the angles at the frontal plane can be as high as 145° (as in the sagittal plane). From the experiments, the mean deviation between POF curvature sensor and IMUs was about 6.5% on the experiments in the sagittal plane. However, such deviation increased to about 10% on the transverse and frontal planes. The reason for this increase can be related to the POF positioning, since it is a critical factor on the angle assessment using such technology. In addition, it can be also related to the increase of the errors of the IMUs when the experiment was performed in planes different from the sagittal one, as reported in Vargas-Valencia et al. (2016). Regarding the camera-based system, the results at the sagittal plane show an overestimation of the angle, when compared to IMU and POF curvature sensor. In this case, the angles estimated by the camera system had a maximum value of about 160°, which is higher than the elbow range of motion (KIRTLEY, 2006). In contrast, the camera-based system underestimates the angles at the frontal plane when compared to the other two systems for angle assessment.

Such as aforementioned, the errors on the markerless camera system for angle assessment are related to issues, such as frame errors, exploitation of multiple image streams and self-occlusions. In order to further evaluate the errors obtained by the camera-based system, Table 5 presents the correlation coefficient, and RMSE between the camera system and the IMUs for each of the 11 participants in all three planes tested, whereas Table 6 presents the correlation and RMSE between the camera system and the POF curvature sensor.

Table 5 – RMSE and correlation coefficient for Cameras and IMU.

	Sagittal		**Frontal**		**Transverse**	
	R^2	RMSE[°]	R^2	RMSE[°]	R^2	RMSE[°]
M1	0.994 ± 0.0041	13.53±2.87	0.955 ± 0.0164	14.31±6.37	0.988 ± 0.0043	18.62±1.32
M2	0.994 ± 0.0023	10.21±1.86	0.983 ± 0.0213	11.96±4.67	0.991 ± 0.0052	14.48±4.53
M3	0.986 ± 0.0052	7.42±2.51	0.993 ± 0.0063	15.03±1.55	0.984 ± 0.0060	18.84±7.23
M4	0.984 ± 0.0058	13.02±3.12	0.982 ± 0.0026	9.99±3.94	0.992 ± 0.0031	15.89±6.59
M5	0.991 ± 0.0025	9.60±3.08	0.989 ± 0.0095	14.34±3.85	0.978 ± 0.0230	11.21±2.90
F1	0.993 ± 0.0011	11.83±2.93	0.976 ± 0.0098	16.42±2.41	0.991 ± 0.0077	17.61±3.67
F2	0.990 ± 0.0043	11.26±2.89	0.986 ± 0.0045	8.49±5.61	0.921 ± 0.0833	15.28±4.31
F3	0.974 ± 0.0136	12.04±5.39	0.990 ± 0.0046	14.89±1.90	0.956 ± 0.0543	16.73±2.89
F4	0.996 ± 0.0019	11.90±3.53	0.989 ± 0.0057	15.98±6.78	0.990 ± 0.0052	16.29±5.98
F5	0.993 ± 0.0079	9.89±0.77	0.994 ± 0.0020	12.56±3.74	0.987 ± 0.0037	19.42±5.03
F6	0.995 ± 0.0042	11.81±0.52	0.989 ± 0.0034	17.31±4.04	0.992 ± 0.0006	19.98±6.52

Tables 5 and 6 show a correlation coefficient higher than 0.9 in all analyzed cases,

Table 6 – RMSE and correlation coefficient for cameras and POF.

	Sagittal		Frontal		Transverse	
	R^2	RMSE[°]	R^2	RMSE[°]	R^2	RMSE[°]
M1	0.988 ± 0.0066	10.01±2.12	0.972 ± 0.0175	15.32±6.92	0.994 ± 0.0033	19.32±3.30
M2	0.977 ± 0.0055	10.90±1.67	0.985 ± 0.0065	11.28±0.97	0.985 ± 0.0080	14.98±4.83
M3	0.978 ± 0.0110	6.90±2.25	0.967 ± 0.0025	16.14±2.74	0.981 ± 0.0123	19.83±3.80
M4	0.955 ± 0.0208	12.00±2.83	0.916 ± 0.0106	13.35±4.23	0.965 ± 0.0165	13.53±5.28
M5	0.994 ± 0.0017	10.87±0.15	0.973 ± 0.0069	13.26±3.39	0.954 ± 0.0289	11.60±1.17
F1	0.975 ± 0.0178	11.52±3.24	0.978 ± 0.0196	14.84±1.09	0.970 ± 0.0205	17.84±3.44
F2	0.983 ± 0.0120	10.35±0.60	0.987 ± 0.0051	9.42±4.27	0.945 ± 0.0375	17.44±4.77
F3	0.982 ± 0.0085	7.72±1.59	0.978 ± 0.0070	17.17±1.80	0.982 ± 0.0083	17.86±5.20
F4	0.978 ± 0.0098	12.76±1.63	0.975 ± 0.0076	16.95±4.46	0.987 ± 0.0001	17.71±6.52
F5	0.989 ± 0.0097	8.11±0.81	0.977 ± 0.0070	13.56±4.30	0.979 ± 0.0131	19.28±5.49
F6	0.964 ± 0.0076	13.52±0.95	0.892 ± 0.0165	19.13±4.53	0.979 ± 0.0047	18.92±5.36

which indicates a high correlation between the sensors' outputs. In addition, the standard deviation of the correlation coefficient was below 0.01 in all the analyzed cases. Thus, it is possible to verify not only a high correlation between the data of the camera-based system compared to the wearable ones, but also that the results present a promising evidence of repeatability of such systems. The mean of correlation coefficients between the camera-based system and the IMUs were 0.990, 0.984 and 0.979 on the sagittal, transverse and frontal planes, respectively. It is noteworthy that higher correlations were obtained between the camera-based system and the IMUs than the ones comparing the markerless system with the POF curvature sensor. The mean of the correlation coefficients considering the later comparison was 0.978, 0.964 and 0.975 for sagittal, transverse and frontal planes, respectively.

Even though the proposed camera-based system presented a high correlation with the wearable sensors in all scenarios, the errors are considerable but awaited from a markerless system. Such as can be observed in Figure 22, there are deviations on the angle estimation of the camera-based system when compared to the wearable sensors (the mean error is 10.42° when compared with the wearable sensors). It is noteworthy that these errors are lower than the ones reported on the literature (SCHMITZ et al., 2014), which is mainly due to the use of two cameras to reduce the errors related to occlusions.

4.4 Remarks of this Chapter

This chapter presented the analysis and comparison of a markerless camera-based system for elbow angles assessment. The proposed markerless system uses two RGB-D cameras in order to reduce errors and inaccuracies related to self-occlusion issues.

The main contribution of this chapter is the development of an alternative non-wearable and markerless system, with lower-cost when compared to commercial motion capture systems used in human motion analysis.

The joint data fusion was implemented with the possibility to include more sensors, due to the system architecture. For this reason, modifying the cameras position and quantity of them could open the scope to more applications and human motor assessment tools.

The non-wearable system performance was compared to two wearable solutions, namely POF curvature sensor and IMUs, in flexion/extension movements performed in different planes (sagittal, transverse and frontal planes). The high correlations obtained in all experiments for the comparison with the wearable sensors (see Tables 5 and 6) indicate that the proposed markerless camera-based system can be a feasible solution for movement analysis applications and angle estimation.

The error mean is in agreement with the errors obtained in some sensing approaches for movement analysis (PIRIYAPRASARTH; MORRIS, 2007). Thus, this work can pave the way for movement analysis applications with markerless camera-based system. This also indicates the possibility of applying post-processing techniques aiming on error reduction.

5 Effect of an Intervention Based on Multisensory Environment for Proprioception Assessment in Children with Down Syndrome: Case Study

Chapter 2 showed aspects related to CwDS, their health difficulties and new trends in training and mobility therapies. That information was important to build the assessment system presented in Chapter 3, which showed the importance of motor analysis and the necessity of a focused system in individuals with Down syndrome. For that reason a multi-camera system arrangement was developed to generate objective parameters, as shown in Chapter 4. In the same way, Chapter 3 indicated the importance of an intervention tool through an immersive environment. For that reason, in this Chapter a game-based platform in a multisensory environment (MSE) is developed.

This chapter aims to verify the effects of an intervention protocol with Virtual Environment (VE) through a game platform to train proprioception in children with DS. This case study was carried out using a system designed with the purpose to evaluate the children's functional performance through data acquired using a system based on an RGB-D camera arrangement. A performance assessment protocol was implemented to analyse the movements of three children with DS (with 9.66 ± 0.69 years, at the beginning of experiments). The children underwent a physiotherapeutic intervention protocol of 12 sessions of game therapy, with 30 minutes length (approximately) each and a frequency of two sessions per week. Prior to the intervention, postural balance assessments were performed using two instruments: BERG scale (evaluation of static and dynamic balance); and the Psychomotor Battery by Fonseca (evaluation of tonicity and balance). An assessment was conducted after the therapy protocol to evaluate the effects of the implemented therapy, which evidenced an increase in the Berg scale score and an evolution in the children psychomotor profile.

A clinical intervention through a multisensory environment (MSE) requires a suitable space, a room intended to stimulate the vestibular, proprioceptive and tactile sense of the user, train the integration and identification of different stimuli, and engage the user in useful activities (ADAMOVICH et al., 2009; FRANCIULLI et al., 2016). However, with the technological advances in therapeutic interventions, new trends to assistive technological tools based on virtual environment therapies are considering different forms of stimulus (FRANCIULLI et al., 2016). Multisensory interventions based on RGB-D multi-cameras are among possible approaches to help CwDS (SILVEIRA et al., 2019). For example, an environment with devices that capture the user's movements, combined with serious games that verify their correctness, can improve the experience of an appropriate stimulus (CARVALHO DOS SANTOS et al., 2016).

In summary, this chapter shows two important aspects of a multisensory environment-based therapy developed to improve the proprioception skills of CwDS: first, the implementation of a platform of serious games for motor development training; second, the effects of a clinical intervention in CwDS through a serious game platform.

5.1 Multisensory Environment Architecture

To develop our Multisensory Environment (MSE), the depth-cameras arrangement proposed in Section 4.1.2 was implemented as a base. That computational vision framework composed of an unstructured and scalable network of RGB-D sensors was proposed to automatically estimate joint position of CwDS during their movements.

The contribution of our MSE is a movement analysis tool in the clinical context, as shown in Figure 23. The system uses a visual sensor network that counteracts typical problem as occlusion and narrow field of view. Consequently, the system is developed with a distributed architecture for processing joint position data of each sensor independently.

As detailed in Section 4.1.2 and shown in Figure 23, a human body analysis algorithm is executed for each client camera. Subsequently, the data from each sensor are transformed and represented respect to a shared reference to fuse them and generate the global joint position. Afterwards, the fused joint data are used as control input inside the game environment. To generate interaction in the game-based platform the spatial relation among child's movements and the targets' position is calculated, as detailed in Section 5.2.

The game-based system is implemented in five hierarchical levels using Unity (cross-platform game engine). As shown in Figure 24, the user interacts with the system through input and output devices (RGB-D cameras, display (projection), speakers). Output devices are controlled by graphics and sound engines, and the input devices are managed by the input manager. The game loop system, created in Unity, has control over the device's APIs, handles interaction through physics and artificial intelligence algorithms, and save data related to the user's movement parameters. The data are acquired from the user and stored for further analysis.

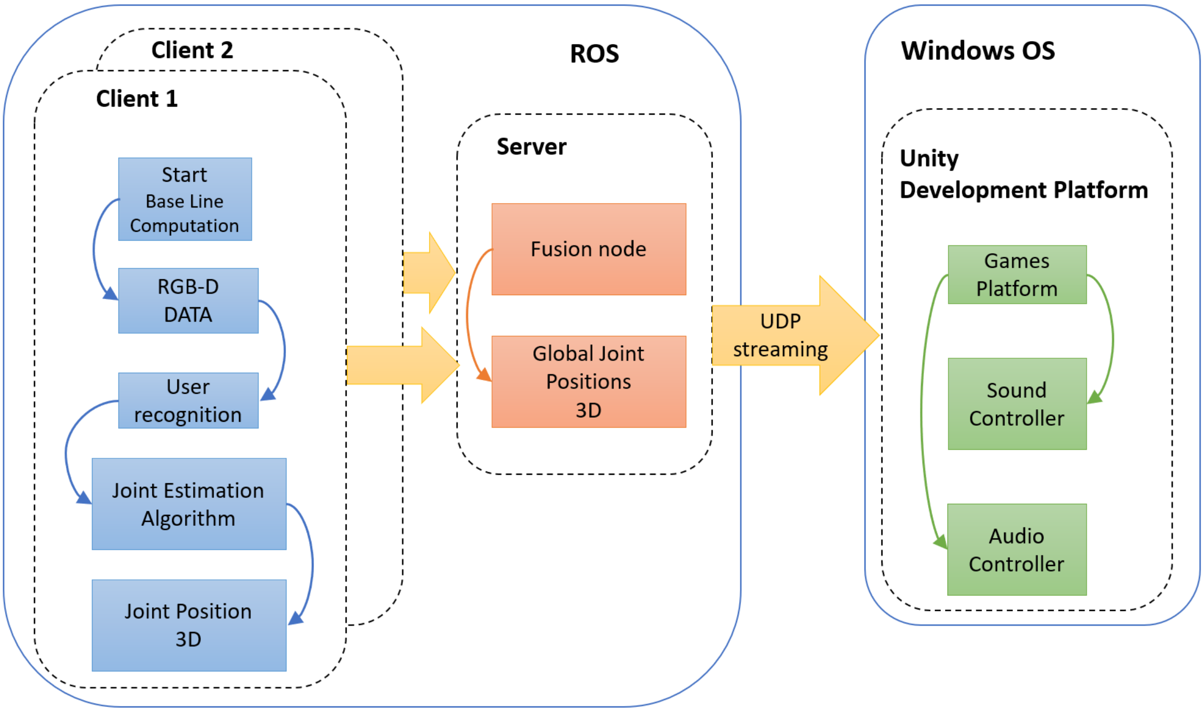

Figure 23 – System architecture of the multisensory environment (MSE).

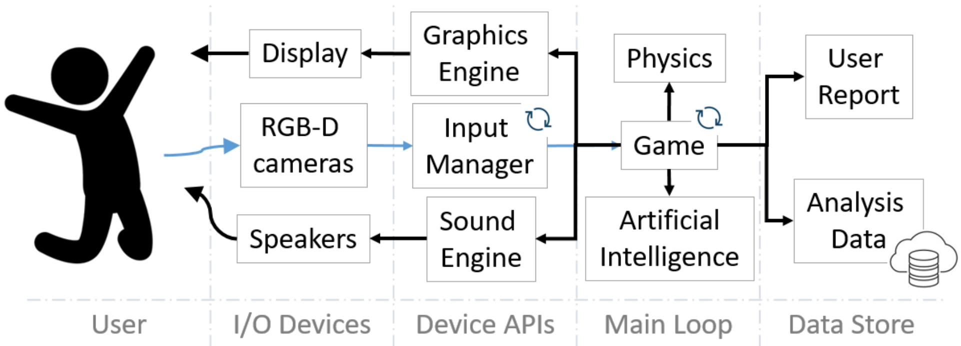

Figure 24 – User's interaction with the game-based system.

5.2 Game-based Platform

The computer vision system based on RGB-D cameras (Kinect) was used here to obtain kinematic parameters and generate a kinematic evaluation interface with the game platform to detect and quantify CwDS movements. The system allows body gesture recognition and obtain some parameters, such as articulations range of motion, limbs velocities, and positions of each body articulation in three dimensions.

A custom room was configured to support the system requirements, as shown in Figure 25. The experiment begins with the child positioned in front of the display projection and in the middle of the RGB-D cameras; then the measuring device captures his/her position parameters and corporal patterns necessary to generate the information established by the VE. With these data, feedback is shown to the child through the game platform, as well as quantitative values for the evaluator (therapist) that applies a kinematic evaluation protocol. The therapist is located in the room, out of the cameras' visual range, helping the child and promoting his/her correct movements for a specific game. The room has a window with a one-way mirror, behind which is the game-platform operator, controlling the game functions, observing the child's activity without being perceived.

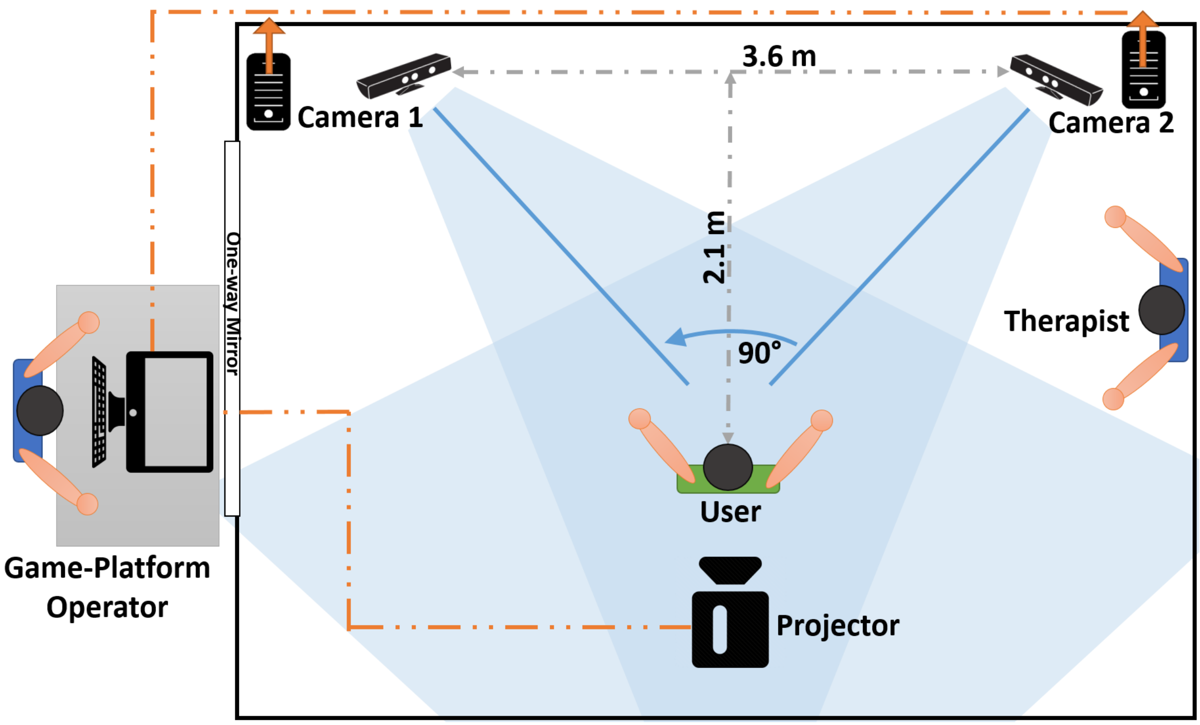

Figure 25 – Room setup implemented to the multisensory environment

The VE has the possibility of being configured in two different modes, according to the game characteristics and the stimulus generated to the child. The first configuration is designed for a set of games where the child has to make a frontal interaction with visual stimuli projected on the wall, and the camera system interprets the different child movements, as shown in Figure 26. The second configuration is used to train different gross-motor and cognitive skills in the children. In this case the game is projected on the floor generating a greater interaction, emulating the touchscreen function, as presented in Figure 27.

The game-platform implemented has three different games: "Left-Right", "The Catcher" (SILVEIRA, 2019), and "Whack-a-Mole" (SILVEIRA, 2019). When the game platform begins, it shows an interface asking for the child data (Figure 28.a). If the child is a new user, the interface asks for basic information as name, age, gender and the date of the current session (Figure 28.b). After that, the interface asks for the game to play (Figure 28.c).

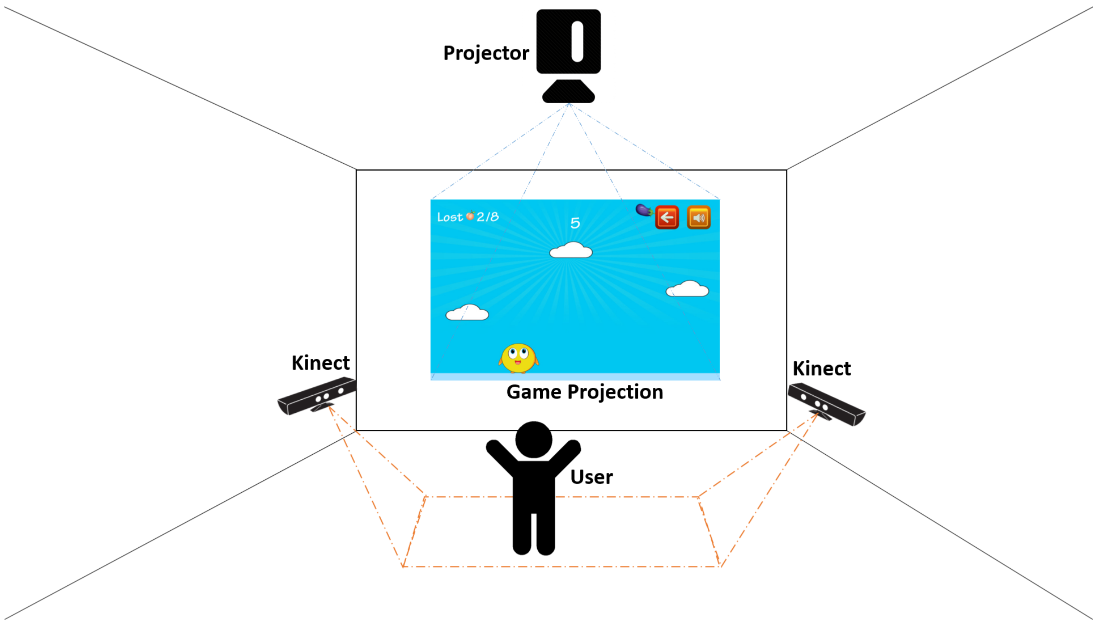

Figure 26 – Game environment configured for projection on the wall.

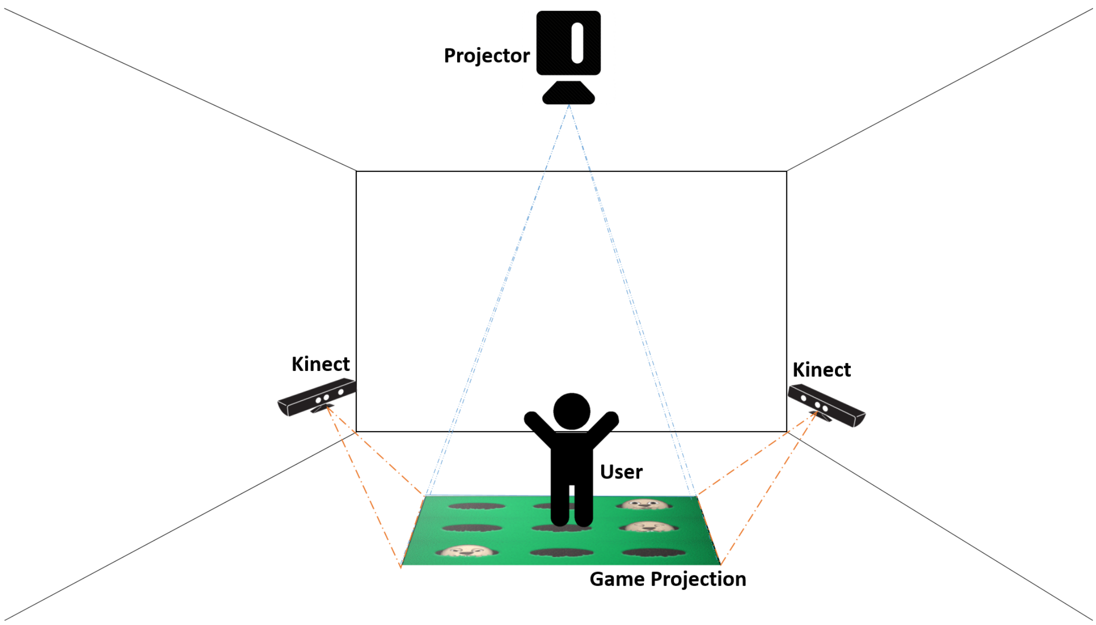

Figure 27 – Game environment configured for projection on the floor.

The platform saves the movements during each game length; the system begins to save movement data when the game starts, storing the tridimensional position of fifteen body joints. Each file has a specific identification for posterior analysis.

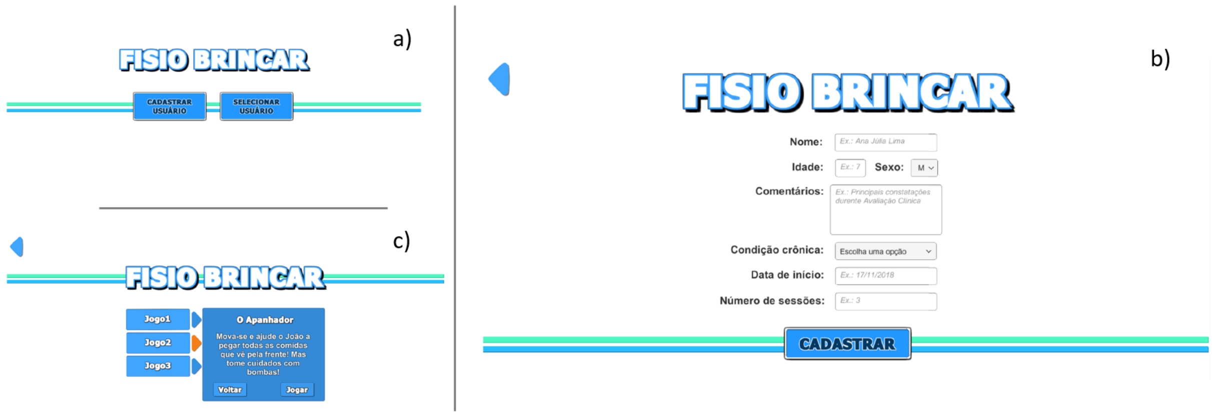

Figure 28 – Game interface. a) Initial interface asking for user. b) Interface for user registration. c) Interface to choose the game.

5.2.1 Left-Right Game

The "Left-Right" game analyzes the laterality ability of the children, providing them a mirror-type visual feedback, where a voice command determines which object/side the children must choose, e.g. "select the star on the right side", "select the balloon on the left side". The child has to move his/her hand (Figure 29) or foot (Figure 30) to select the correct object in the correct side, using the corresponding limb to select objects on each side. If the child selects the correct side with the correct limb, he/she earns a point. If the wrong limb is used, a voice command reminds the child to switch to the correct limb.

Figure 29 – Left-Right game environment for hands movements.

To help the child to choose the correct side, there are a variety of visual stimuli in the game. The stimuli are: colored "right" and "left" identification tags, different color for each side, different object to be selected, a blink behind the object that should be chosen, and right and left hand drawings in each side. The idea is that the child associates those images and colors with the correspondent side, serving as guide, as shown in the video on the link[1].

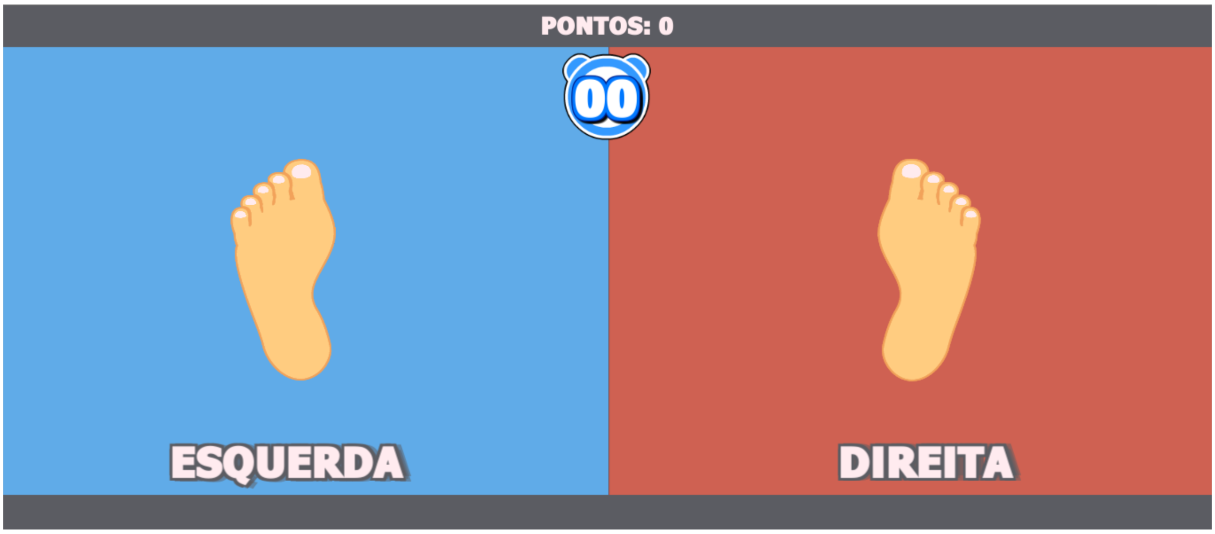

Figure 30 – Left-Right game environment for feet movements.

5.2.2 The Catcher Game

In The Catcher, the game character is responsible for picking up various kinds of food (like fruits, candies, pizza, etc.) that are falling randomly from the top of the screen, such as shown in Figure 31. The user controls the game character with his/her own body. Thus, the child needs to move to the left or right to control the character and pick up as many foods as possible. An example of an user playing the game is shown in the link[2]. In addition to food, bombs can appear randomly and, if caught, cause the character to lose one of the three lives. In this game, the projector's orientation would be directed to the front wall. The difficulty of the game is configured by three parameters: (i) number of bombs that appear between falling food; (ii) amount of food falling; (iii) speed with which items fall from the top of the screen. All of these parameters can be set by the physical therapist.

Another characteristic that can also be adjusted during the calibration step is the ratio between the user walk distance and the character walk distance. It is possible to configure the game in such a way that the child needs to take several steps to move the

[1] <https://youtu.be/dFeChN59XSk>
[2] <https://youtu.be/Cot3yxdT3gI>

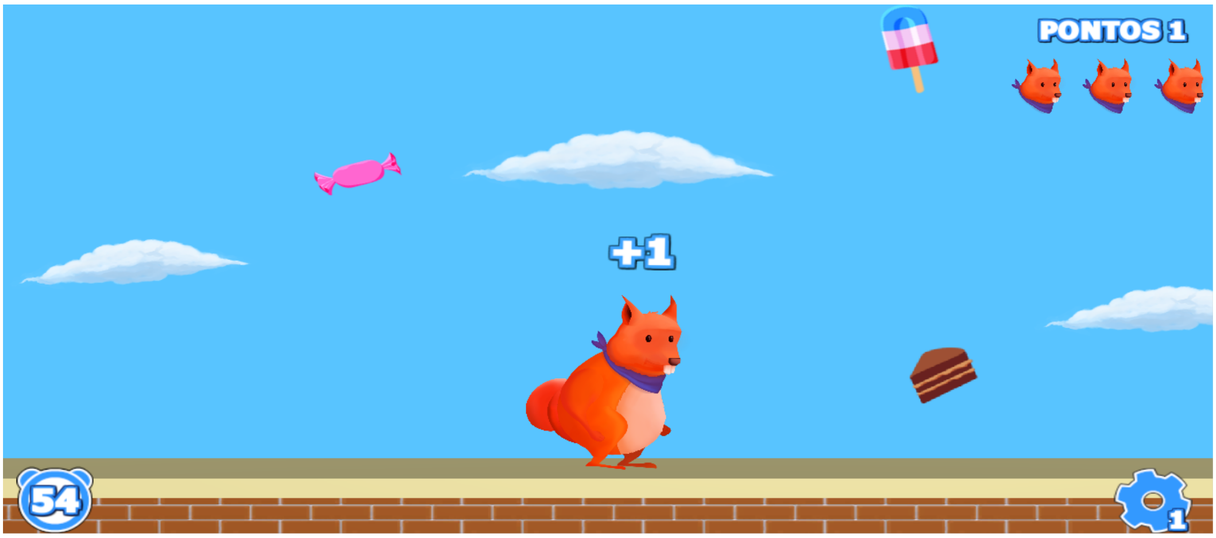

Figure 31 – The Catcher game environment.(SILVEIRA, 2019)

character from one end of the screen to the other. It is also possible to configure the game in such a way that the user can control the character with trunk inclination movements, shifting their center of mass while standing still. In this way, the therapist can adapt the game to patients with different levels of motor function impairment. Thus, the game includes exercises of lateral and anterior-posterior displacement, covering the activities of walking; trunk flexion and extension; and left and right lateral deviation/flexion of the trunk.

5.2.3 Whack-a-Mole Game

Whack-a-Mole is an interactive game in which the projector is oriented towards the floor. The main concept of this configuration is to allow an interaction between the child and objects projected on the floor. The game's graphical interface displays six burrows and a mole that emerges from a specific burrow, as shown in Figure 32. The child has to walk or jump on the mole and needs to physically step on the target in order to generate score. When the child steps on the projection of the mole, it returns to its burrow and reappears in a new position. If the user doesn't step on the mole, it stays in the same hole for a specific time, changing its location when the time is elapsed. An example of an user playing the game is shown in the link[3].

The difficulty of the game can be configured through three parameters: (i) the foot used by the child to step on the projection of the moles, which can be defined as right, left or both; (ii) the number of moles appearing simultaneously; (iii) the mole's appearance time until it returns to the burrow and reappears in a new position. All of these parameters can be set by the physical therapist. The physiotherapist can also increase the difficulty of

[3] <https://youtu.be/BzeJHZz97-8>

the levels based on their judgment and assessment of the child. Each level of the game lasts 60 s.

The game requires specific displacement exercises and movements from the child, in order to reach the targets (moles). Thus, constant postural adjustments are exercised to ensure the maintenance of dynamic balance, helping the CwDS to orientate spatially and acquire possible improvements in the proprioceptive sense.

Figure 32 – Whack-a-Mole game environment (SILVEIRA, 2019).

5.3 Case Study

The serious game protocol is composed of 12 sessions of game therapy, with the application of one session per week, 30 min each approximately. The child is assisted and constantly receives verbal commands from the physiotherapist during the intervention. In this protocol the three games were used (Left-Right, Whack-a-mole, and The Catcher), and the duration for each of them was 1 min, with three repetitions for game, including explanation and calibration time before the game execution. The physiotherapist explains and demonstrates to the child the correct way to use each game before the beginning of each of them. Depending on the motor behavior of the child for each session, the physiotherapist increased/decreased the games frequency/velocity.

5.3.1 Children's Abilities in the Multisensory Environment

Therapists and psychologists have defined specific groups of multisensory abilities that are characterized by different levels of motor complexity and cognitive effort, according to their main learning goals: proprioception (visual-motor coordination), left/right discrimination, and gross motor skills. In fact, each proposed game was thought to generate a complexity progression of both the movements and speed, in order to improve response from the child. The proposed abilities are as follows:

i) Proprioception. It is the ability to sense stimuli arising within the body regarding position, motion and equilibrium (ZUBRYCKI; KOLESINSKI; GRANOSIK, 2016). Through proprioception it is possible to know, for instance if an arm is above the head or hanging by the side of the body.

ii) Left/Right discrimination. It is possible to improve the ability (speed and accuracy) to discriminate between left and right body parts and movements (CAMEIRAO et al., 2010).

iii) Gross motor skills. Are larger movements a person makes with his/her arms, legs, feet, or entire body, and are fundamental to perform everyday functions, such as walking, running, and are also crucial for self-care operations like dressing (GALLI et al., 2008).

To evaluate the different activities the procedures of Vitor da Fonseca Psychomotor Battery (BPM) was implemented. The "Psychomotor Observation Manual" (FONSECA, 2012), in addition to expose the psychoneurological foundation of the modules or psychomotor tonicity factors, balance, laterality, body sense, spatiotemporal structuring, global praxis and fine praxis.

At the same time, the children undergo a physical and dynamic body balance evaluation through the Berg Scale (BERG et al., 1992), which evaluates the child's balance in 14 situations, representative of daily activities.

5.3.1.1 Psychomotor Battery (BPM)

Victor da Fonseca's BPM is a clinical instrument of psychoeducational observation that allows identifying, quantifying and qualifying functional deficits in the observed subject (child, adolescent, adult or senior). It is indicated for the psychomotor assessment of children aged 4-12 years.

This instrument is divided into 7 factors grouped inside 3 units, as follows: i) Evaluation of tonicity and balance factors; ii) Proprioception factors, composed of lateralization, body sense and spatiotemporal structuring subunits; iii) Evaluation of global apraxia and fine apraxia factors.

Each factor records the child's responses in a numerical rating (among 1 to 4), defined in behavioral terms, as shown in Table 7. To find the result of the "Psychomotor Observation Manual" (FONSECA, 2012), it is necessary to sum all factors, where the minimum score is 7 (one point per factor), and maximum score is 28 (4 points per factor).

The description of the rating after the sum is shown in Table 8.

Table 7 – Numerical rating description for each factor of the “Psychomotor Observation Manual” (FONSECA, 2012).

Score	Profile	Description
1	Apraxia	No response, imperfect, inadequate, incomplete and uncoordinated performance (very weak; overt dysfunctions)
2	Dispraxia	Poor performance, with poor control and deviating signs (weak and unsatisfactory)
3	Eupraxia	Complete, adequate and controlled performance (good and slight distortion)
4	Hiperpraxia	Perfect performance, accurate, economical and easily controlled.

Table 8 – Numerical rating description for the sum of all factors of the “Psychomotor Observation Manual” (FONSECA, 2012).

Score range	Psychomotor profile
27-28	Superior
22-26	Good
14-21	Normal
9-13	Dispraxic
7-8	Deficitary

5.3.1.2 Berg Scale

The Berg Scale evaluates the individual’s balance in 14 situations of daily activities, such as standing, getting up, walking, leaning forward, transferring, turning, among others (BERG et al., 1992). With the obtained score, it is possible to predict the risk of falling from the standing height.

The maximum score to be achieved is 56 points, and each item has an ordinal scale of five alternatives, ranging from 0 to 4 points, according to the degree of difficulty. Although, the main objective of this scale is the balance assessment in the elderly, people with neurological disorders, people with reduced mobility, and it can also be used with children.

5.3.2 Procedures and Intervention Protocol

An anamnesis with the children’s parents was carried out in the first and last session. The children underwent a body balance physical therapy evaluation through the

Table 9 – Numerical rating description for the Berg balance scale.

Score range	Description
45 or more	The patient is less likely to fall, safe ambulator without an aid device
Among 35 to 44	The patient has a slightly increased risk of fall, safe ambulator with an aid device
34 or less	Patient with a greater risk of falls, but may be able to ambulate with an aid device and a partner for safety concerns

Berg Scale (BERG et al., 1992). The proprioception, muscle tone and motor skills (fine and gross) were also evaluated in the first and last sessions by means of the instrument BPM by Fonseca (2012).

The proposed games were based on a set of tasks that can detect functional aspects in psychomotor terms, covering sensory and perceptual integration, related to the child's learning potential. Each activity is explained as follows.

Session 1:

1. Interview with child's parent to ask for clinical information.
2. Assess the child through the Berg's scale.
3. Assess the child through the BPM of Fonseca.
4. Explain to the child the Left-Right game functioning.
5. Ask the child to play the Left-Right game.
6. Explain to the child the The Catcher game functioning.
7. Ask the child to play The Catcher game.
8. Explain to the child the Whack-a-mole game functioning.
9. Ask the child to play the Whack-a-mole game.

Session 2 to 11: Activities 4 to 9 of session 1.

Session 12:

1. Explain to the child the Left-Right game functioning.
2. Ask the child to play the Left-Right game.
3. Explain to the child the The Catcher game functioning.

4. Ask the child to play The Catcher game.

5. Explain to the child the Whack-a-mole game functioning.

6. Ask the child to play the Whack-a-mole game.

7. Assess the child through the Berg's scale.

8. Assess the child through the BPM of Fonseca.

5.3.3 Participants of virtual environment intervention

Inclusion criteria for this study were as follows: children with clinical diagnosis of DS, between 7 and 12 years, classified with a deficient or dyspraxic psychomotor profile in the evaluation with the instrument "Psychomotor Battery by Vítor da Fonseca" and with scores lower than 44 points in the Berg Scale. Exclusion criteria are children with any other neurological alterations, or associated respiratory or osteomyoarticular pathologies (not due to DS); and ability to understand and obey simple verbal commands. The study was approved by the Ethics Committee of UFES/Brazil (number 1.629.376), and the parents or legal guardians signed an informed consent form, authorizing their child to participate of the study.

The aim of this work is to offer a clinical intervention for children with DS through a serious game. Considering this, more than 20 families, with children inside the inclusion criteria, were invited to carrY the intervention. However, different logistics and economical circumstances did not allow complete intervention for all families. For this, the sample consisted of two female children and a male child (9.66 ± 0.69 years , at the beginning of the experiments), with clinical diagnosis of DS (simple trisomy of chromosome 21) and associated hypothyroidism, with some episodes of fall, presenting a deficit psychomotor profile. The anamnesis of each child is shown in Table 10.

5.4 Results

The overall results of the intervention protocol activities with the MSE show that the children in the sample obtained higher average scores in the last session compared with the first one, showing an improvement in their proprioception and motor behavior. The next sections show two different analysis. In the beginning an assessment from each game perspective was implemented, showing how each child plays the game comparing the first and the last session. In the last part, the psychomotor profile of each child is shown, comparing their motor behavior before and after the 12 sessions of intervention.

Table 10 – Anamnesis of participants (children).

Child	**1**	**2**	**3**
Initial of Name	A	J	L
Genre	Male	Female	Female
Age (years)	8	9	10
Dominant side	Right	Right	Right
DS Associated pathologies	Hypothyroidism	Hypothyroidism	Hypothyroidism
Medicines	Levotiroxina 12,5 mcg Respiridona 0,5 mg	Levotiroxina 38 mg Montelucaste 0,5 mg	Puran T4 25 mg Trofanil 25 mg
Observations	Moderately severe hearing loss and use of hearing aid	–	Uses glasses for astigmatism correction (2.5º in each eye)

5.4.1 Game platform analysis

Each child plays the 3 games (Left-Right for Hands and Feet, The Catcher, and Whack-a-Mole) 3 times in each of the 12 sessions. To understand the child's performance during the game and find an improvement after the intervention, specific movements and a related analysis were chosen, as presented in Table 11. Different graphs to explain each movement and the evolution of each child, are presented in the next sections.

Table 11 – Movement analysis performed for each game.

Game	**Movements**	**Analysis**
Left-Right for Hands	Put the hand upward the shoulder	Hand-hip distance
		Abduction-adduction shoulder angle
Left-Right for Feet	Put one foot in front of the other	Foot-Center of gravity distance
The Catcher	The child moves around the room	Center of gravity position
	Trunk inclination	Lumbar flexion-extension angle
Whack-a-Mole	The child moves around the room	Center of gravity position
	Trunk inclination	Lumbar flexion-extension angle
	The angular change at knees	Knees flexion-extension angle

5.4.1.1 Left-Right game for Hands

For the purpose of this game, the movements of interest are the ones corresponding to the user's hands. The game starts when the child is placed in front of the projection, inside the sensor capturing zone. A voice command determines which object/side the child must choose. If the wrong hand is used, a voice command reminds the child to switch hands, saying for instance "use the left/right hand instead".

To analyze the children's movements during the Left-Right game for Hands, his/her hand-hip distance and the shoulder angle was taken as reference. The child 1 has problems with laterality in the first session of the game, as shown in Figure 33. In the Figure 33, it is possible to see the target required for the game, as boxes in the base of the Figure (blue indicates left, and red indicates right). At the same time, it is shown the child action/answer, where the child 1 has 5 hits and 4 fails. The game makes the initial request to "raise the left hand" (blue box in the base of the figure), an action that is not performed; on the contrary, the child raises the opposite hand and corrects it later for the requested hand and so on.

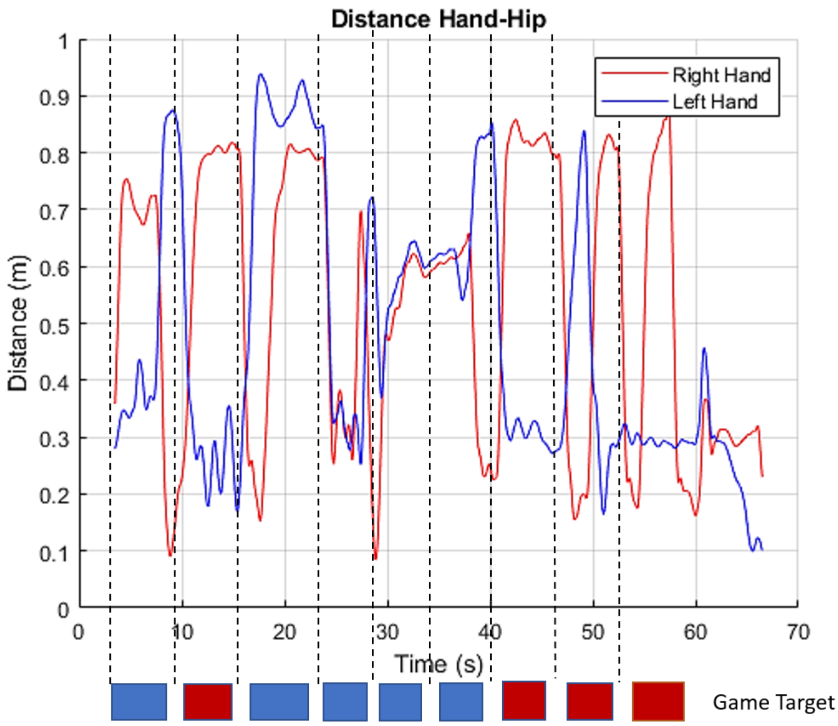

Figure 33 – Hand movements performed by child 1 during Left-Right game (first session).

The movements performed in the same game, after 12 sessions, can be observed in Figure 34, where the child answered perfectly to the game requirements, making 10 hits and zero fails, showing a clear improvement in the understanding of laterality. Other possibilities of movement analysis, such as shoulder angular amplitude and the corresponding angular velocity, where time of reaction to accomplish the command and the specific joint range of motion during the movement can be analyze, are presented in Figure 35.

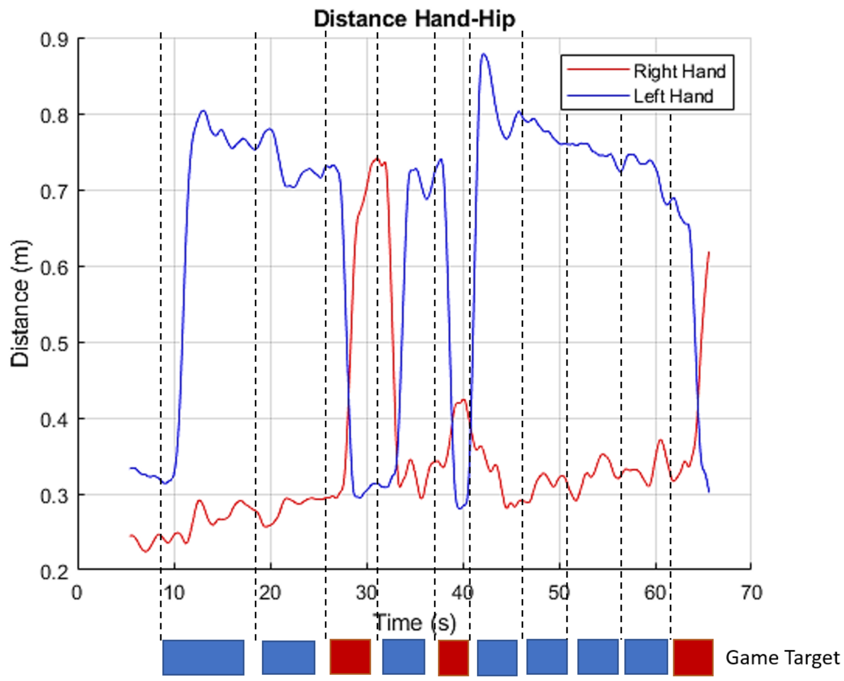

Figure 34 – Hand movements performed by child 1 during Left-Right game (last session).

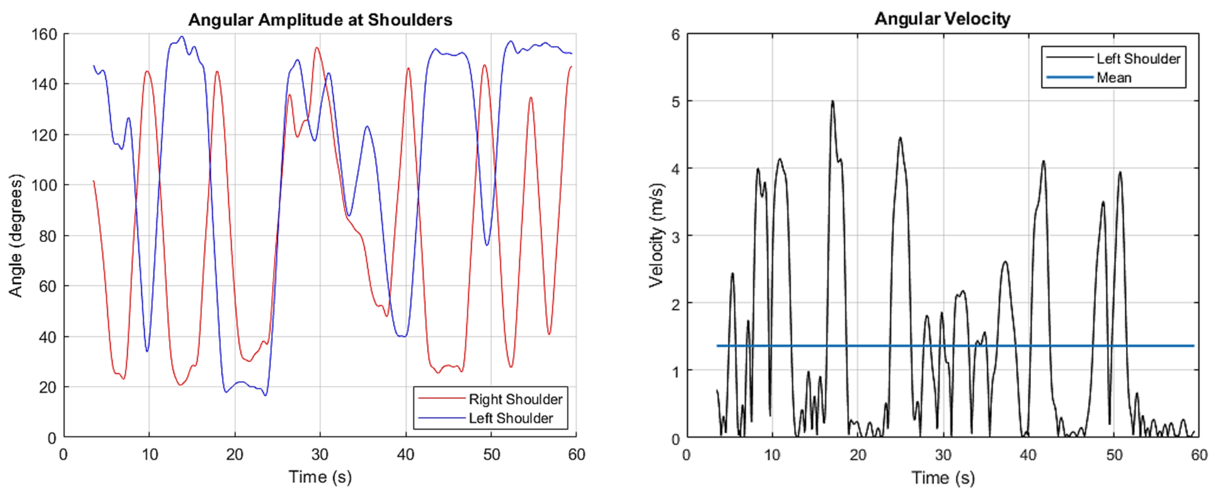

Figure 35 – Shoulder angular amplitude for both arms, and angular velocity for left shoulder, performed by child 1 during the first session of the left-right game.

To analyze the improvement of each child with the Left-Right game for hands, the average success rate of each session (3 times for session) was taken. The progress during all sessions of children 1, 2 and 3 is shown in Figures 36, 37 and 38, respectively. Comparing the first and last session, it is possible to affirm that all children showed an increase of the lateralization in upper limbs, where children 1, 2 and 3 have an improvement rate of 49,63%, 87%, and 59,34%, respectively, as shown in Table 12. Improvement rate was calculated following the Equation 5.4.1.1.

$$ImprovementRate = (FinalSuccessRate - InitialSuccessRate)/InitialSuccessRate \tag{5.1}$$

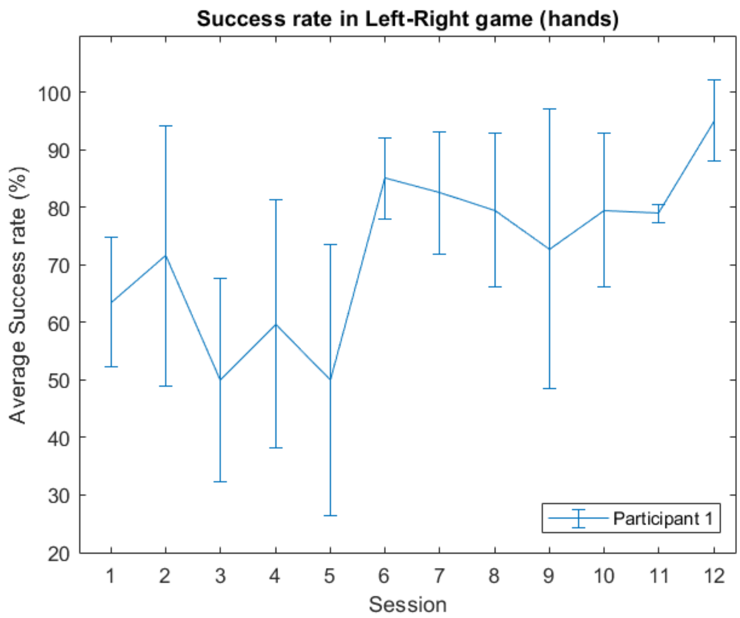

Figure 36 – Progress of child 1 during the intervention with the Left-Right game for hands.

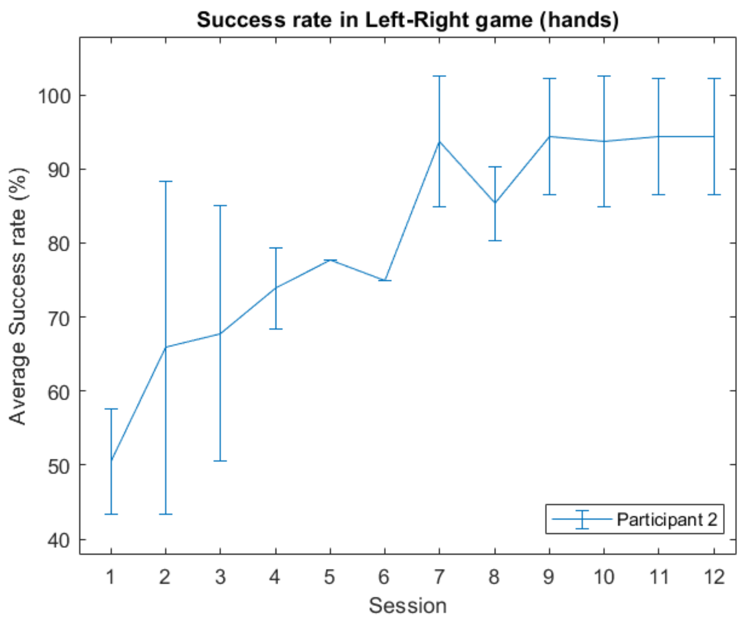

Figure 37 – Progress of child 2 during the intervention with the Left-Right game for hands.

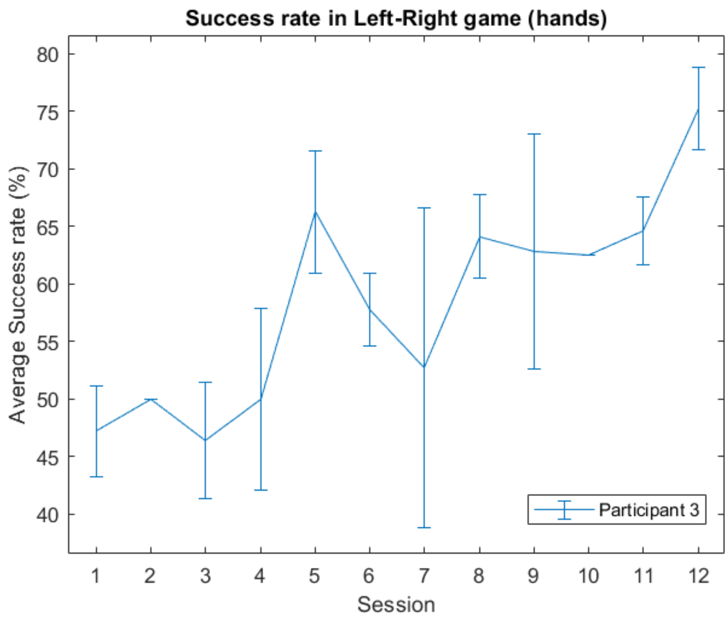

Figure 38 – Progress of child 3 during the intervention with the Left-Right game for hands.

Table 12 – Comparison between first and last session in left-right game (hands) for all children.

User	Session	Success rate	Improvement
Child 1	First	$63,49\% \pm 11,22\%$	49,63%
	Last	$95\% \pm 7,07\%$	
Child 2	First	$50,51\% \pm 7,14\%$	87%
	Last	$94,44\% \pm 7,86\%$	
Child 3	First	$47,22\% \pm 3,93\%$	59,34%
	Last	$75,25\% \pm 3,57\%$	

5.4.1.2 Left-Right game for feet

Similarly to the game focused on upper limb laterality, the game implemented to improve lower limb laterality showed excellent results. In this case, the child responds to the command "put the right/left foot in front". If the answer is appropriate the next command is "put feet together", otherwise the game repeats the command until the correct task execution.

Figure 39 shows the movement of each foot, comparing the distance between each foot to the center of gravity during the first session, performed by child 2. In the Figure, it is possible to see the target required for the game, as boxes in the base of the Figure (blue indicates left, and red indicates right), showing that the child has 4 errors and 4 hits, according to the requested game movements. For example, the game makes the initial request: “Put the left foot in front” (blue box in the base of figure), action that is not performed; on the contrary, the child puts it in front of the opposite foot.

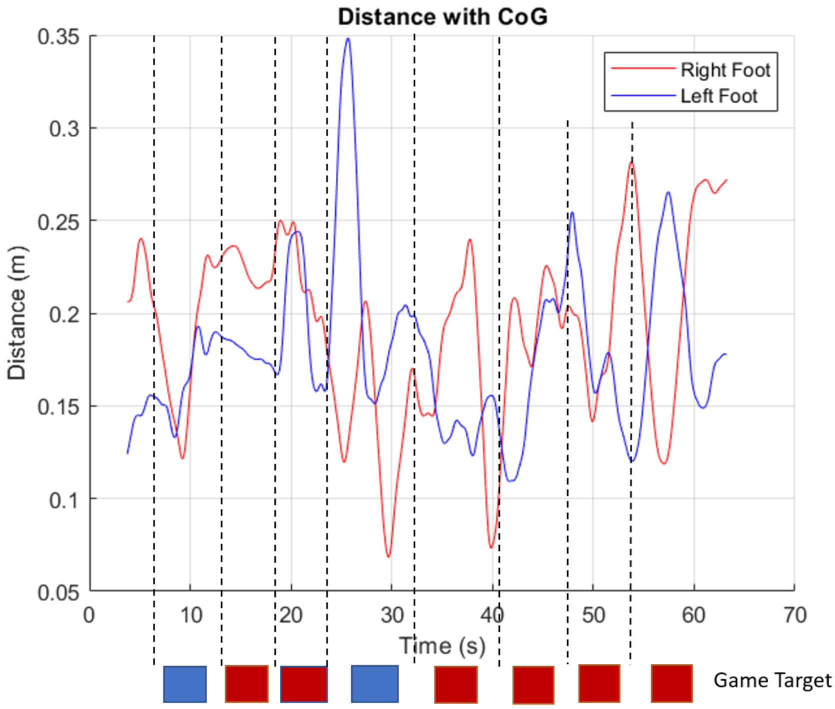

Figure 39 – Feet movements performed by child 2 during Left-Right game (first session).

In the last session held by child 2, it is possible to see that there is only one error in the movements required by the game, achieving noticeable improvement in its laterality, as shown in Figure 40. Figure 41 shows the child's foot velocity in the first (a) and last (b) sessions, showing an increment in the average velocity. In addition, in the overall game, the child was more active at the end of the intervention.

To analyze the improvement of each child with the Left-Right game for feet, the average success rate of each session was calculated. The progress during all sessions of children 1, 2 and 3 is shown in Figures 42, 43 and 44, respectively. Comparing the first and last session, it is possible to affirm that all children showed an increase of the lateralization in lower limbs, where the children 1, 2 and 3 have an improvement rate of 20,63%, 45,30%, and 35,64%, respectively, as shown in Table 13.

Table 13 – Comparison between first and last session in left-right game (feet) for all children.

User	**Session**	**Success rate**	**Improvement**
Child 1	First	$65\% \pm 21,21\%$	20,63%
	Last	$78,41\% \pm 4,82\%$	
Child 2	First	$65\% \pm 21,21\%$	45,30%
	Last	$94,44\% \pm 7,86\%$	
Child 3	First	$58,57\% \pm 2,02\%$	35,64%
	Last	$79,44\% \pm 13,36\%$	

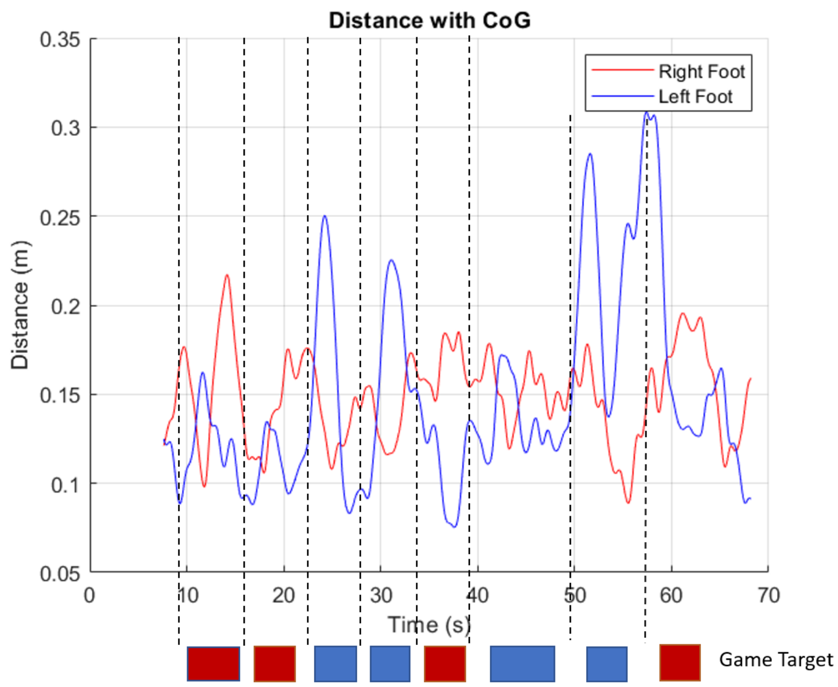

Figure 40 – Feet movements performed by child 2 during Left-Right game (last session).

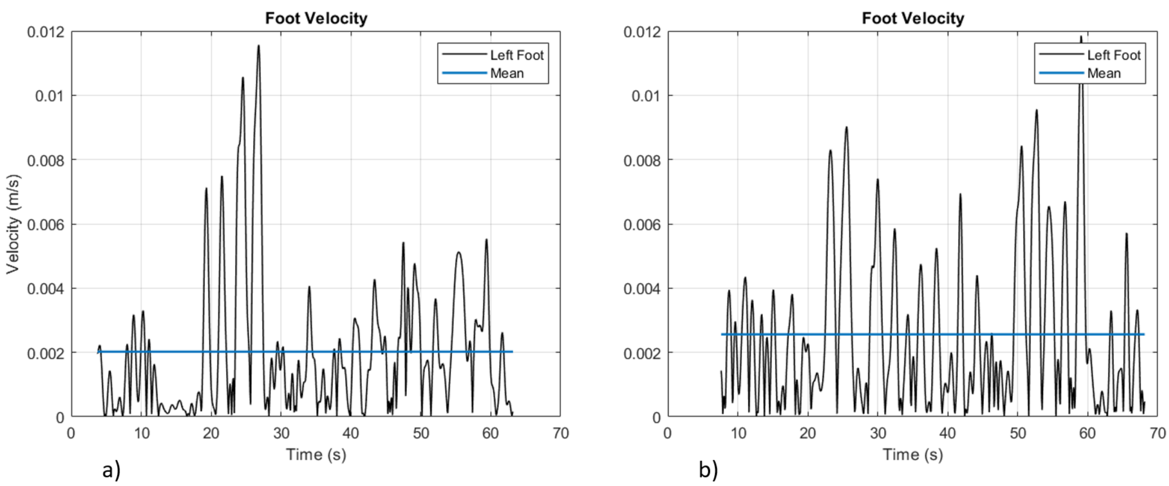

Figure 41 – Feet movements performed by child 2 during Left-Right game (last session).

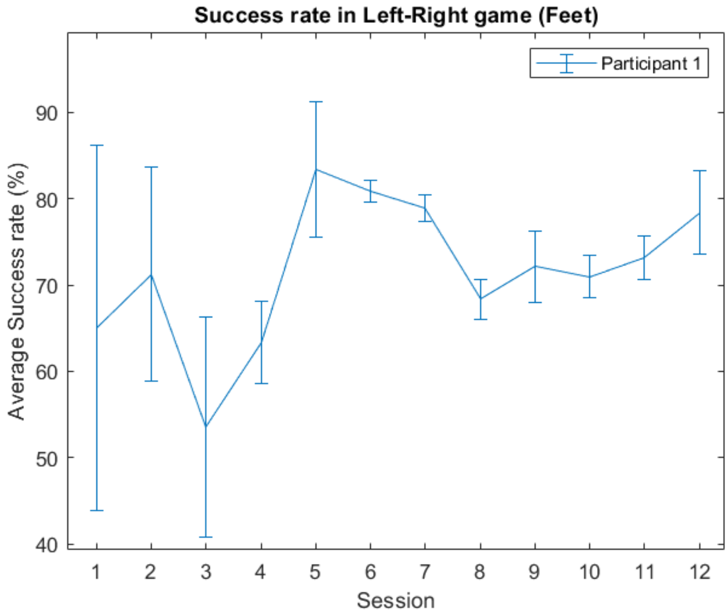

Figure 42 – Progress of child 1 during the intervention with the Left-Right game for feet.

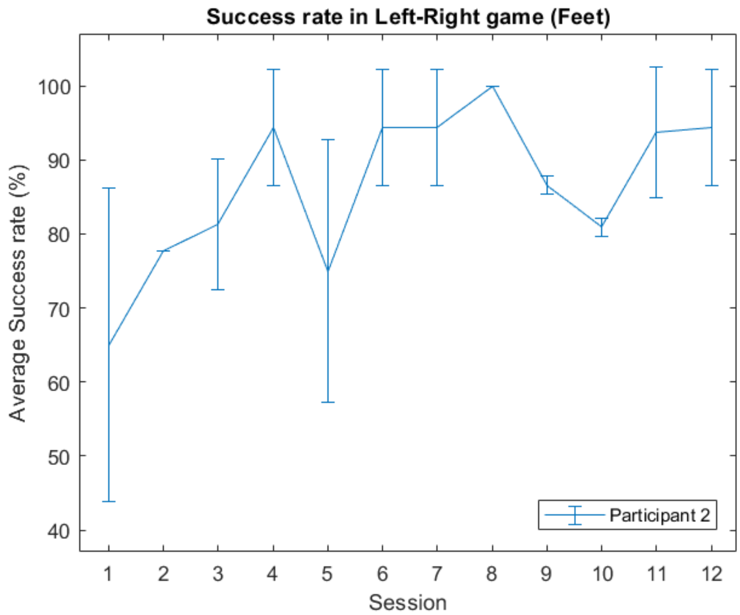

Figure 43 – Progress of child 2 during the intervention with the Left-Right game for feet.

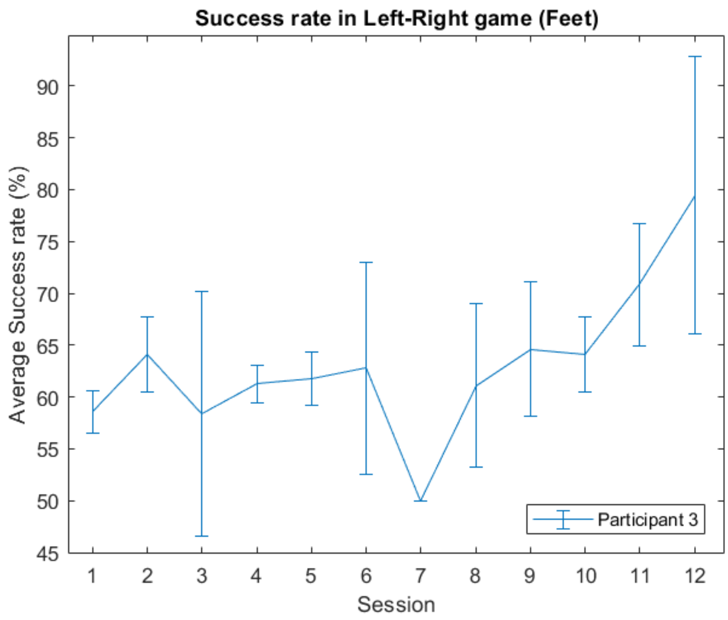

Figure 44 – Progress of child 3 during the intervention with the Left-Right game for feet.

5.4.1.3 The Catcher game

In this game, each child controls the movements of the game character with his/her own body displacement movement. Due to the children's cognitive and motor characteristics, the game was configured to be played without bombs and a slow food falling velocity.

The child's center of gravity was analyzed to observe the children' movements inside the room during The Catcher game. The movements are seen from the top of the room perspective, where the room's Y axis is parallel to the wall with the projection of the game, as can be noted in Figure 45. Child 2 shows very small movements in the Y-axis (required game movements) during the first session compared to the last one, where a wide movement around the room is shown, managing to catch more snacks that are falling in the game. Similarly, the velocity performed by child 2 is very small at the beginning of the intervention compared to the last session of the intervention, confirming a greater displacement, as shown in Figure 46. This velocity increase indicates confidence in her movements, possibly due to her balance improvement and/or due to, her better game understanding.

Figure 47 shows the inclination of the trunk. In the first session the child was trying to reach the game objectives without moving through the room, but performing trunk flexion to control the avatar, as shown in Figure 47.a. In the last session it is possible to observe that the inclination of the trunk is much smaller, because the control of the avatar was performed with the lateral displacement through the room, as shown in Figure 47.b.

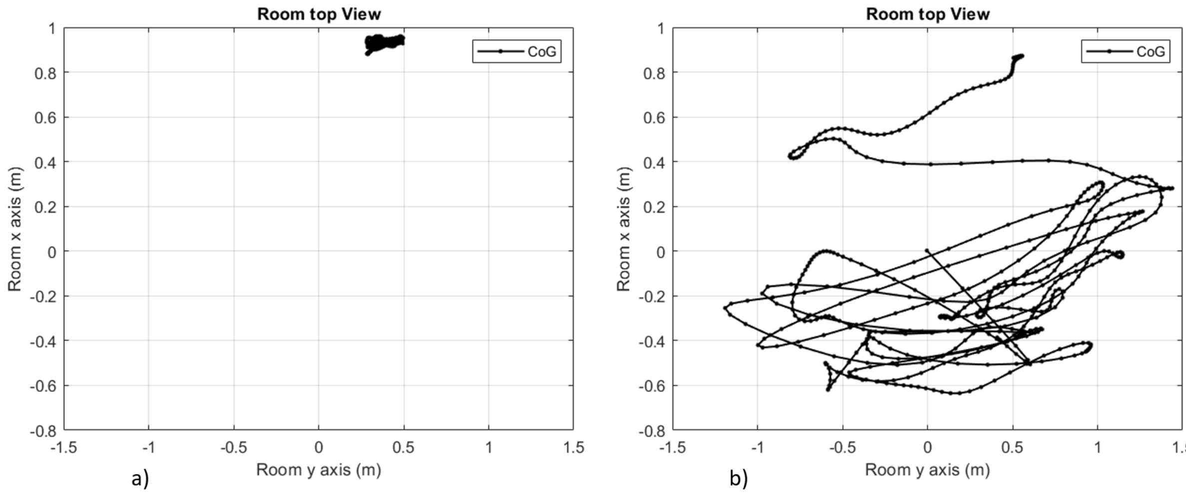

Figure 45 – Center of gravity path during The Catcher game for child 2. a) First session. b) Last session.

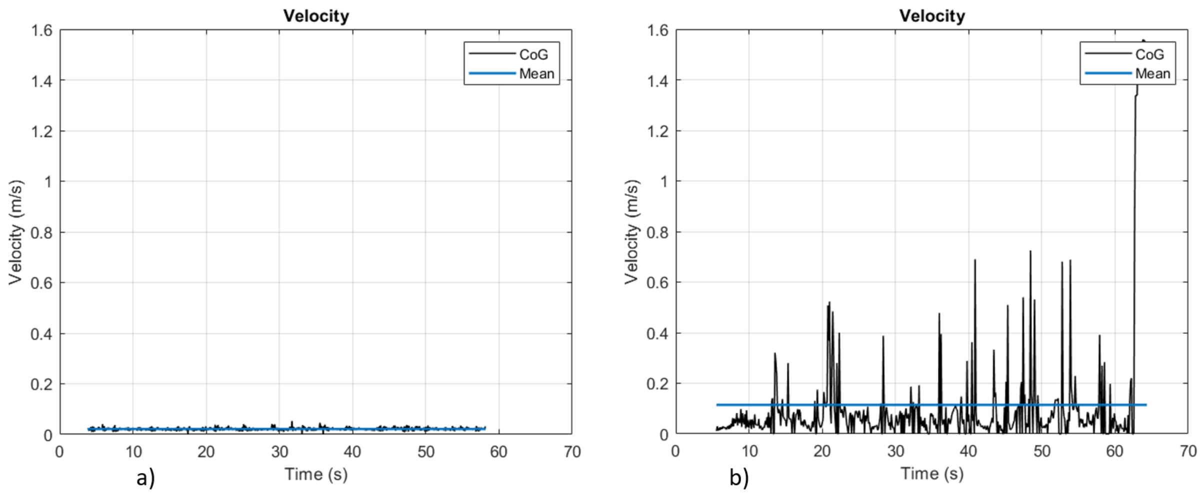

Figure 46 – Velocity of Center of gravity during The Catcher game for child 2. a) First session. b) Last session.

To analyze the improvement of each child with The Catcher game, the hit average of each session was measured. The progress during all sessions for children 1, 2 and 3 is shown in Figures 48, 49 and 50, respectively. Comparing the first and last session, all children showed an increase in their game understanding and gross-motor skills, where the children 1, 2 and 3 have an improvement rate (see Equation 5.4.1.1) of 366,67%, 121,21%, and 44,44%, respectively, as shown in Table 14. This Table shows the amount of points earned (caught food) during the game, comparing the first and last session for all children. A particular case is shown with the child 1 (Figure 48), who do not show responses or movement during the first five sessions. For that reason this child had an considerable improvement.

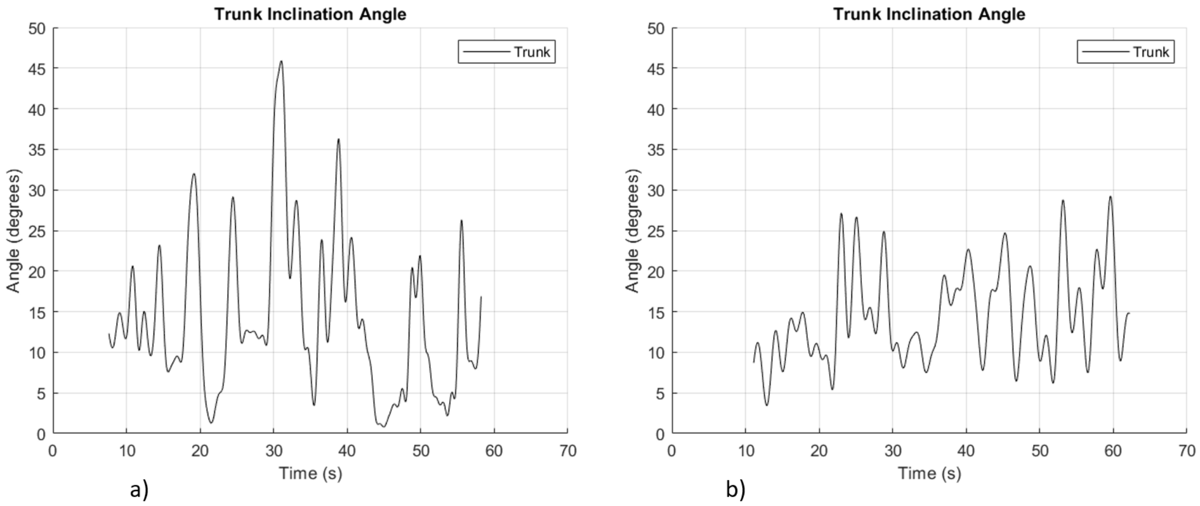

Figure 47 – Trunk inclination during The Catcher game of child 2. a) First session. b) Last session.

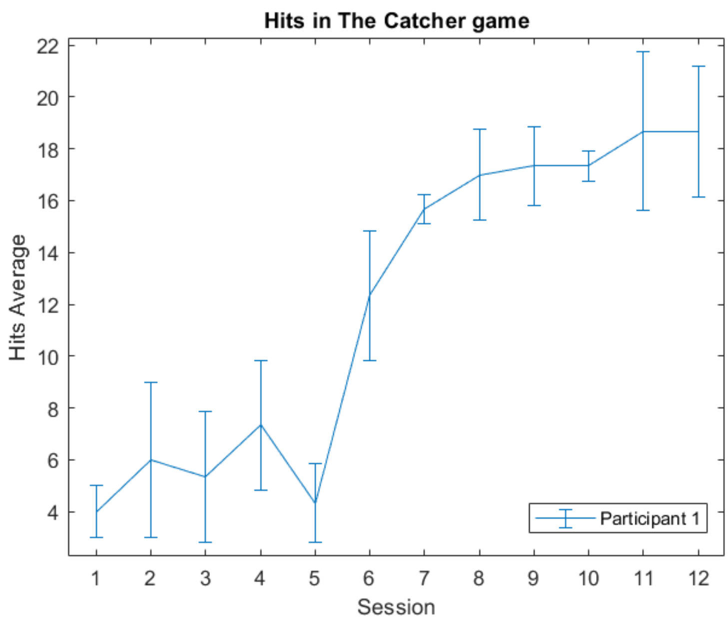

Figure 48 – Progress of child 1 during the intervention with The Catcher game.

Table 14 – Comparison between first and last session in The Catcher game for all children.

User	First Session	Last Session	Improvement rate
Child 1	4 ± 1	$18,67 \pm 2,52$	366,67%
Child 2	11 ± 4	$24,33 \pm 0,58$	121,21%
Child 3	12 ± 1	$17,33 \pm 1,53$	44,44%

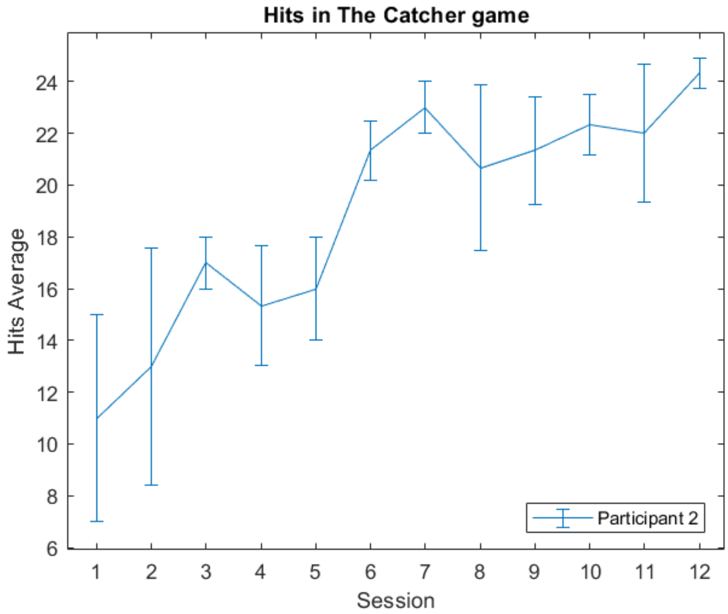

Figure 49 – Progress of child 2 during the intervention with The Catcher game.

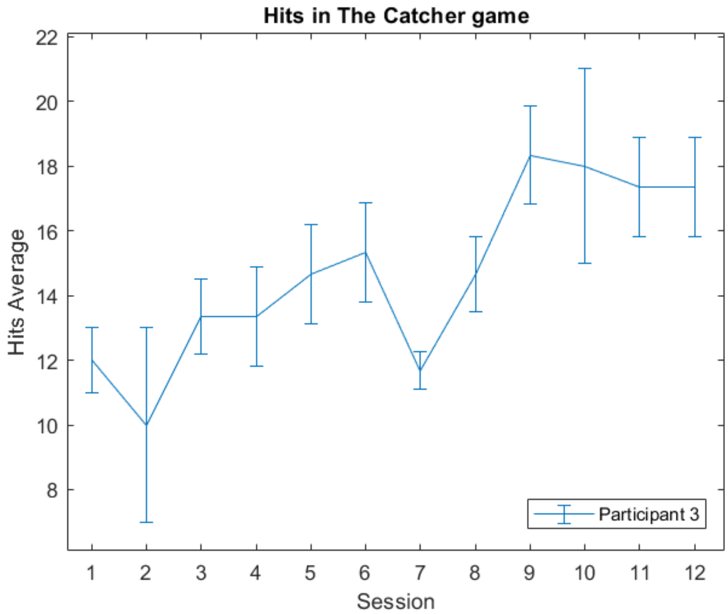

Figure 50 – Progress of child 3 during the intervention with The Catcher game.

5.4.1.4 Whack-a-Mole game

Due to the interface of this game, it was the most engaging for all children. The game was configured to show one whack at the same time, and 7.5 s of maximum exhibition time for each whack if the child does not step over it.

Three specific movements are analyzed in the Whack-a-mole game: the child displacement in the room; the angular amplitude in knees performed to step on the moles that appear at specific times; and the trunk inclination performed during body balance looking for moles. Figure 51 shows the position path of the center of gravity of child 3 during the game, comparing the beginning (a) and the end of the intervention (b). In the Figure 51.b the child shows a larger position path than in Figure 51.a, evidencing an increase in the activity interaction after 12 sessions.

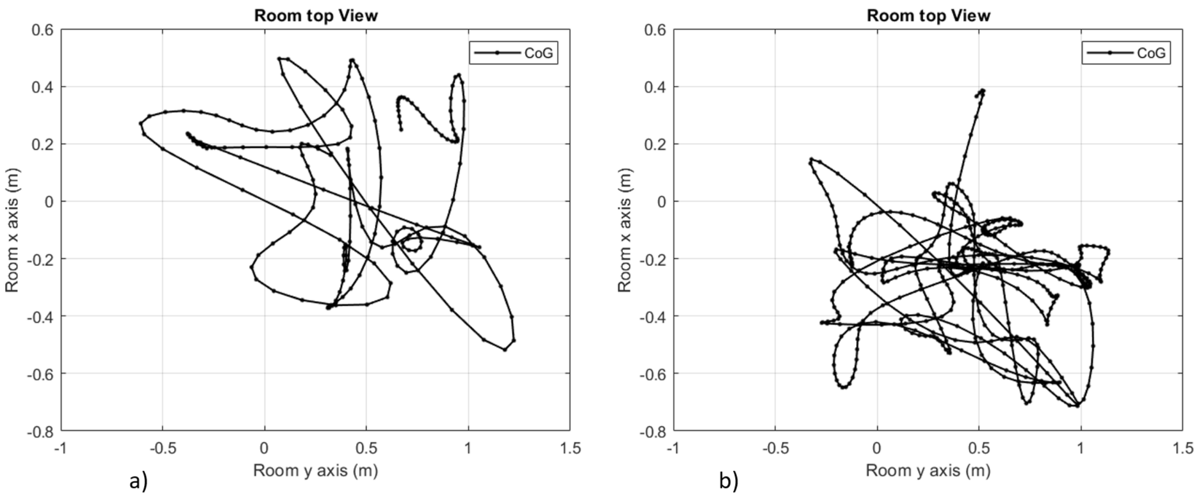

Figure 51 – Center of gravity path during the Whack-a-mole game, performed by child 3. a) First session. b) Last session.

Figure 52 shows the differences between the way the child stepped on the moles at the beginning and the end of the intervention. Analyzing the angular range at the knees, it is possible to see that in the last session the child performed much more activity comparing with the first session. In the same way, in Figure 53 the trunk inclination performed by child 3 is presented. The last session (b) shows a greater angular variability, compared to the first session(a), interpreted as greater variation and confidence in her movement.

To analyze the improvement of each child with the Whack-a-mole game, the hit average of each session was measured. The progress during all sessions of children 1, 2 and 3 is shown in Figures 54, 55 and 56, respectively.

The skill improvements are explained with the result shown in Table 15, showing that the child 1 stepped on $10,33 \pm 4,51$ moles in the first session of the game, and in the last session stepped on $19,67 \pm 1,53$, an increase (see Equation 5.4.1.1) of 90,32% in the

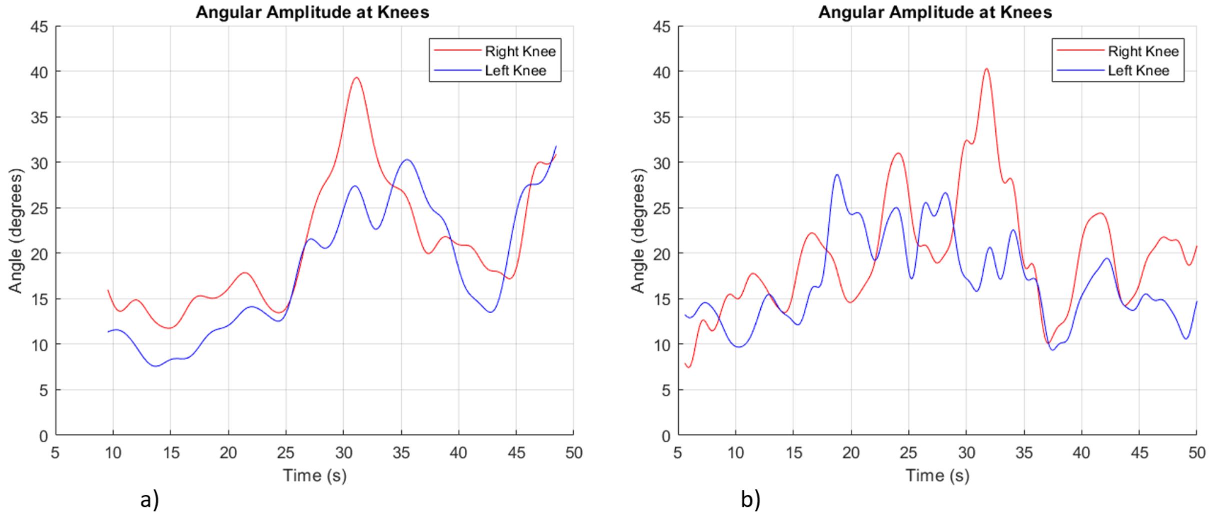

Figure 52 – Angular amplitude at knees during the Whack-a-mole game, performed by child 3. a) First session. b) Last session.

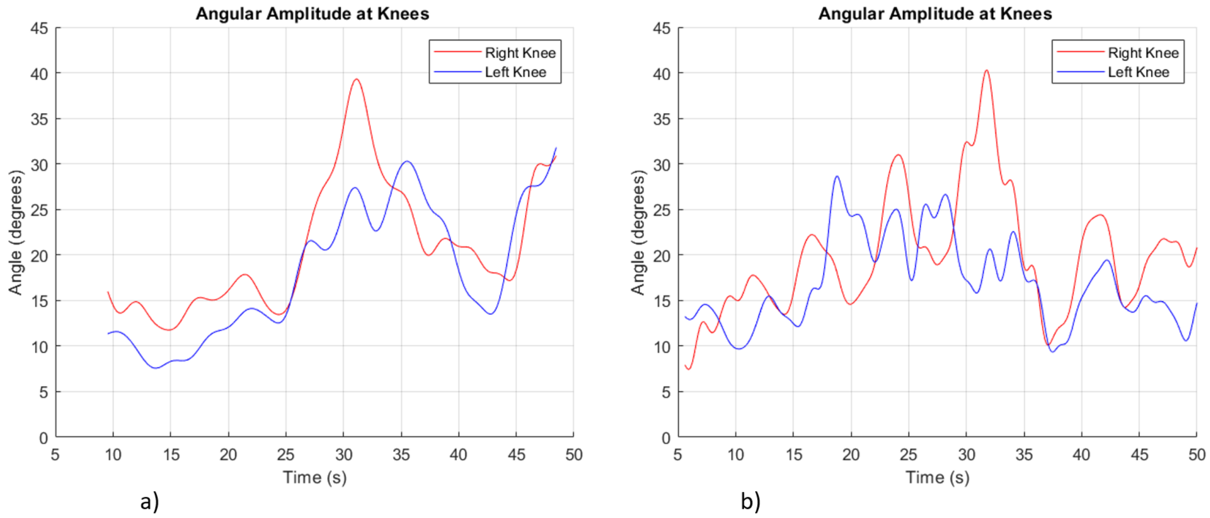

Figure 53 – Trunk inclination angle during the Whack-a-mole game, performed by child 3. a) First session. b) Last session.

performance. These results show an improvement for child's capabilities. The same table shows the results for children 2 and 3, whose increase was 60,98% and 33,33%, respectively.

Table 15 – Comparison between first and last session in Whack-a-mole game for all children.

User	First Session	Last Session	Improvement rate
Child 1	$10,33 \pm 4,51$	$19,67 \pm 1,53$	90,32%
Child 2	$13,67 \pm 1,15$	$22 \pm 2,65$	60,98%
Child 3	14 ± 1	$18,67 \pm 1,53$	33,33%

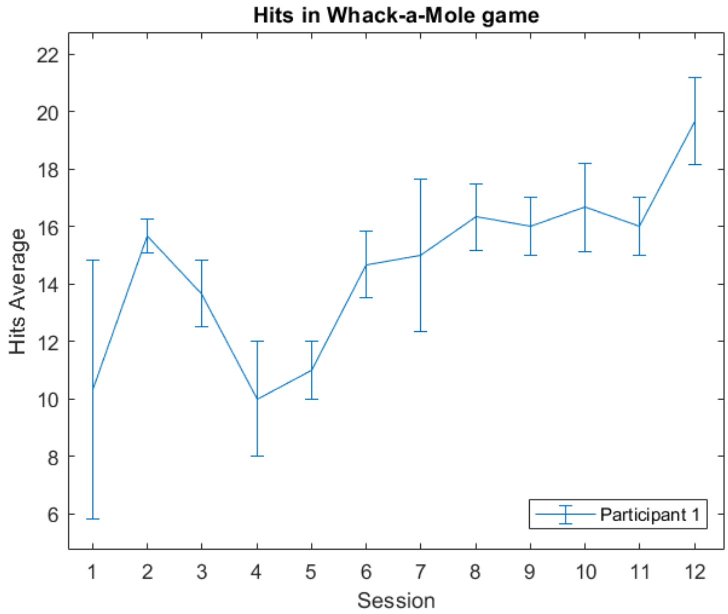

Figure 54 – Progress of child 1 during the intervention with the Whack-a-Mole game.

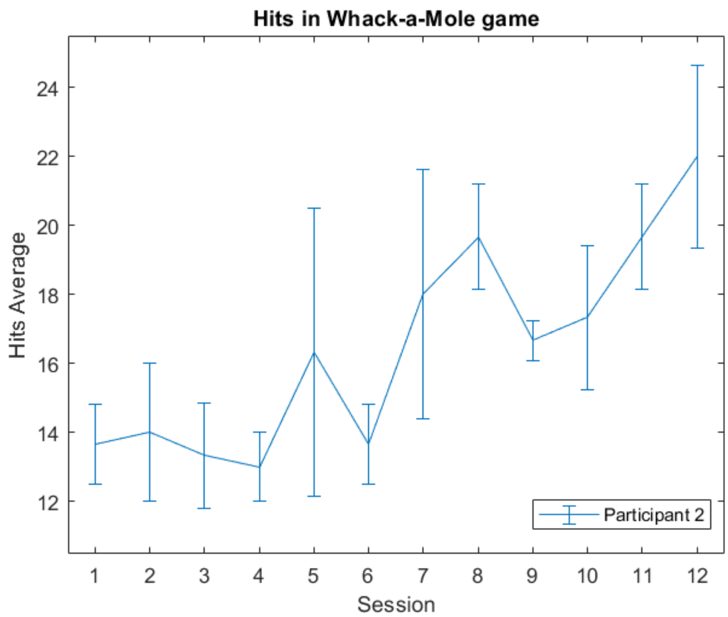

Figure 55 – Progress of child 2 during the intervention with the Whack-a-Mole game.

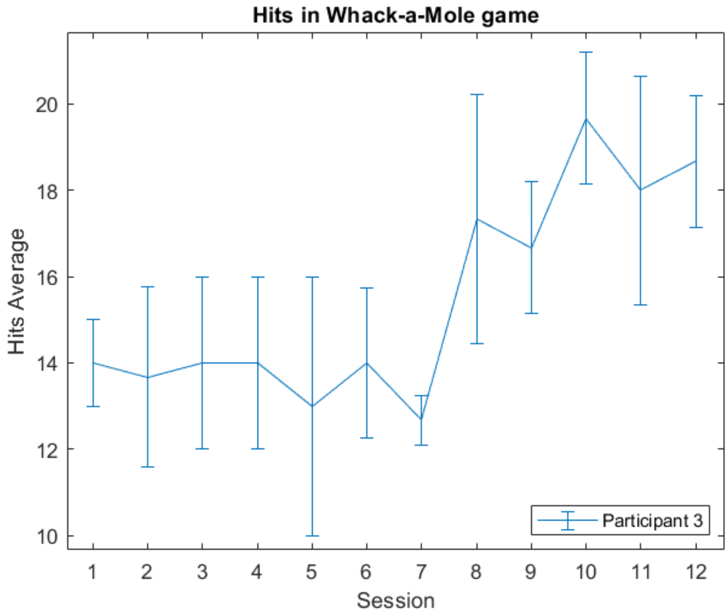

Figure 56 – Progress of child 3 during the intervention with the Whack-a-Mole game.

5.4.2 Psycomotor profile analysis

To complete the analysis it is necessary to modify the focus and observe the results of each child involved in the intervention developed through the MSE. As it was shown in Section 5.3.2, two evaluations were carried out to the children, in the first and the last session of the intervention, by means of two different tools: the Berg scale and the BPM by Fonseca. The results of comparing these two evaluations are presented in the next sections.

5.4.2.1 Participant 1

The child 1 has a moderately severe hearing loss and respective aid device. His audition issue could have induced a negative incidence in his performance. However, he showed an important improvement in their movements after 12 sessions of intervention during 88 days. The child's mother accompaniment, helping with the physiotherapist verbal commands during the intervention, was very important to the intervention progress.

Through the Fonseca BPM an increase in the scores of all the factors was found, except "spatiotemporal structuring" and "fine praxis" factors, which remain equal to in the first evaluation, as shown in Table 16. The initial evaluation score was 11,03 points, implying a classification of dyspraxic psychomotor profile (between 9-13 points). After performing the proposed intervention, the score increased to 16.34 points, putting the child's psychomotor profile as normal (between 14-21 points). The increase in the factors score may indicate that the therapy has stimulated the psychomotor maturation of the child, showing a better motor control compared to the initial assessment.

Table 16 – Comparison of Fonseca psychomotor factors before and after application of the game therapy protocol, applied to child 1.

Factor	Parameter	Before intervention	After intervention
Tonicity	Average score	3.2	3.6
	Psycomotor profile	Eupraxia	Hyperpraxia
Balance	Average score	1.43	2.14
	Psycomotor profile	Apraxia	Dispraxia
Laterality	Average score	2	4
	Psycomotor profile	Dispraxia	Hyperpraxia
Body sense	Average score	1.2	2.4
	Psycomotor profile	Apraxia	Dispraxia
Spatiotemporal structuring	Average score	1	1
	Psycomotor profile	Apraxia	Apraxia
Global praxis	Average score	1	2
	Psycomotor profile	Apraxia	Dispraxia
Fine praxis	Average score	1.2	1.2
	Psycomotor profile	Apraxia	Apraxia
Total	**Sum of Average score**	**11.03**	**16.34**
	Psycomotor profile	**Dispraxic**	**Normal**

Paralleling to the balance factor of BPM, an assessment with the Berg Scale was made. In the initial evaluation the child achieved a score of 45 points, and in the final assessment the score was increased to 51 points, both indicating a safe locomotion as shown in Table 17. This increase occurred due to the improvement presented by the child in the accomplishment of different tasks, like stand on just one leg at time or pick up an object from the ground, from a standing position.

Table 17 – Comparison of Berg Scale scores before and after application of the game therapy protocol, applied to child 1.

Berg Scale	Score	Indication for use of walking aid
Before the virtual environment intervention	45	No
After the virtual environment intervention	51	No

5.4.2.2 Participant 2

The child 2 shows an important improvement in her movements after 12 sessions of intervention over a period of 71 days. Through the Fonseca BPM an increase in the scores of all the factors was found, as shown in the Table 18. The initial evaluation score was 11.78 points, implying a classification of dyspraxic psychomotor profile (between 9-13 points). After performing the intervention, the score increased to 18.1 points, rising the child's psychomotor profile as normal (between 14-21 points). The increase in this factor score may indicate that the therapy has stimulated the psychomotor maturation of the child, showing a better motor control compared to the initial assessment.

Table 18 – Comparison of Fonseca psychomotor factors before and after application of the game therapy protocol, applied to child 2.

Factor	**Parameter**	**Before intervention**	**After intervention**
Tonicity	Average score	3.2	3.43
	Psycomotor profile	Eupraxia	Eupraxia
Balance	Average score	1.36	2
	Psycomotor profile	Apraxia	Dispraxia
Laterality	Average score	2	4
	Psycomotor profile	Dispraxia	Hyperpraxia
Body sense	Average score	1.4	2.8
	Psycomotor profile	Apraxia	Eupraxia
Spatiotemporal structuring	Average score	1.25	2
	Psycomotor profile	Apraxia	Dispraxia
Global praxis	Average score	1.17	1.67
	Psycomotor profile	Apraxia	Dispraxia
Fine praxis	Average score	1.4	2.2
	Psycomotor profile	Apraxia	Dispraxia
Total	**Sum of Average score**	**11.78**	**18.1**
	Psycomotor profile	**Dispraxic**	**Normal**

In the initial evaluation with the Berg Scale the child achieved a score of 46 points, and in the final assessment the score was increased to 51 points, both indicating a safe locomotion as shown in Table 19. This increase occurred due to the improvement presented by the child in the accomplishment of different tasks, like keeping stand without support with one foot forward, assessing balance compensation, or stand on just one leg at a time.

Table 19 – Comparison of Berg Scale scores before and after application of the game therapy protocol, applied to child 2.

Berg Scale	**Score**	**Indication for use of walking aid**
Before the virtual environment intervention	46	No
After the virtual environment intervention	51	No

5.4.2.3 Participant 3

The child 3 showed the greatest improvement among all children in their movements after 12 sessions of intervention over a period of 84 days. Through the Fonseca BPM an increase in the scores of all the factors was found, where the "laterality" and "body sense" factors presented the greatest advances, as shown in the Table 20. The initial evaluation score was 8.48 points, implying a classification of deficitary psychomotor profile (between 7-8 points). After performing the intervention proposed, the score increased to 14.88 points, rising the child's psychomotor profile as normal (between 14-21 points). The increase in this factor score may indicate that the therapy performed has stimulated the psychomotor maturation of the child, showing a better motor control compared to the initial assessment.

Table 20 – Comparison of Fonseca psychomotor factors before and after application of the game therapy protocol, applied to child 3

Factor	Parameter	Before intervention	After intervention
Tonicity	Average score	2.34	3.22
	Psycomotor profile	Dispraxia	Eupraxia
Balance	Average score	1.14	2.14
	Psycomotor profile	Apraxia	Dispraxia
Laterality	Average score	1	3
	Psycomotor profile	Apraxia	Eupraxia
Body sense	Average score	1	2.4
	Psycomotor profile	Apraxia	Dispraxia
Spatiotemporal structuring	Average score	1	1.25
	Psycomotor profile	Apraxia	Apraxia
Global praxis	Average score	1	1.67
	Psycomotor profile	Apraxia	Dispraxia
Fine praxis	Average score	1	1.2
	Psycomotor profile	Apraxia	Apraxia
Total	**Sum of Average score**	**8.48**	**14.88**
	Psycomotor profile	**Deficitary**	**Normal**

According to Tables 21, it can be observed that the intervention protocol using the game therapy was able to promote body balance improvement in the child. The Berg Scale score presented an increase from 37 to 46, modifying the classification from “assistance recommendation with walking aids” to a “safe gait without help”, corroborating the child's mother report of no-falls in the last 40 days after the beginning of the protocol application.

5.5 Discussion and Remarks

This multisensory system was implemented to achieve the requirements of the medical community to obtain objective parameters for the analysis of CwDS movements,

Table 21 – Comparison of Berg Scale scores before and after application of the game therapy protocol, applied to child 3.

Berg Scale	**Score**	**Indication for use of walking aid**
Before the virtual environment intervention	37	Yes
After the virtual environment intervention	46	No

as also made by Garzotto et al. (2019), Macias et al. (2018), Capio et al. (2018). With the results obtained by our multisensory system, we can highlight that all required tasks performed by the children, and the corresponding kinematic parameters acquired by the platform, are a powerful tool. In addition, the generated information can be analyzed to get more medical information to generate training, therapies and diagnosis.

The game platform has the characteristic of adaptability, fitting each child's improvement. The clinical professional can use the platform to evaluate the children's performance and determine whether the level of difficulty should be increased or decreased. In the same way, the system can challenge their static and dynamic postural control during the training, based on recommendations from the clinical staff.

The "Left-Right" game trains laterality recognition and stimulates postural balance when requesting movements of the lateral body segments. The implemented game for upper limbs shows the most relevant results, where child 2 went from a success rate surrounding 50% to results of 100% of correct left-right recognition. The same child (2) presented the best improvement rate in the results (45,30%) with the game oriented to lower limbs. It is important to highlight similar progress for all children in upper and lower limbs (Tables 12 and 13), proving a proprioceptive upgrade and the cognitive link (Grouios, Ypsilanti e Koidou (2013), Elliott, Weeks e Chua (1994)). The ranking is the first place to child 2, second place to child 3 and third place to child 1.

The Catcher game stimulates postural balance when requesting corporal displacement in the transverse axis. The key was that the child was required to do movements focusing on the screen projection and forgetting the floor. All children showed an interesting improvement rate in the game score, where child 2 showed the highest increase (121,21%), and children 1 and 3 rates are 51,35% and 44,44%, respectively. The recollected data showed how the children gained spatial awareness from each session to the next one, expanding their movements in the room and improving their velocity and body balance (Jones (2000), Tam, Gelsomini e Garzotto (2017), Abellard (2017)).

The "Whack-a-mole" game stimulates movement perception and improves body balance when asking the child to step on the mole that appears randomly in each burrow.

In this game, the children feel a haptic control to interact with the game, showing more activity, since the first session, and an understanding of the game functioning. At the final of the intervention with this game, the child 1 showed the major increase in the improvement rate (90,32%), and children 2 and 3 a rate of 60,98% and 33,33%, respectively. The inclination data of children showed more variation in the final sessions, proving the balance improvement due to the child felt more comfortable looking for the whacks in the floor projection. Another interesting parameter sensed was the knee angular amplitude, which shows much more variability in the final stages of the intervention in all children. Other works, as Macias et al. (2018), Scapinelli, Laraia e Souza (2016), Capio et al. (2018), show different interventions with commercial exergames and interesting results in terms of task-efficacy and selective attention, but without movements identification and proprioceptive analysis.

The implemented BPM of Fonseca is an indicator of specific psychomotor learning difficulties or capacities. The CwDS evaluated in this research had an average proprioception score established by Fonseca of (m=10.43) before the beginning of the intervention, showing deficient and dyspraxic profiles among the children. A final score showing an average of (m=16.44) indicates a normal profile for all the children. This finding corroborates several studies, suggesting a developmental improvement in these children (Garzotto et al. (2019), Bonarini et al. (2014), Tam, Gelsomini e Garzotto (2017), Agosta et al. (2015)), indicating that with this kind of tool is possible to develop proprioceptive skills in a CwDS population.

Different factors of the children, as environmental, familiar, emotional and physics could change the results of interventions or specific sessions. For example, the specific auditive situation of child 1 could cause interference in the understanding of different tasks, as related to The Catcher game, where the child does not show movements in the first five sessions.

We can conclude, through this research, that the developed system, as well as the protocol applied to the children, were determinant to improve their specific indices related to their motor and balance behavior. The games requested from the CwDs a great movement amplitude in both the upper and lower limbs, which required the use of trunk to generate weight transfers and jumps. This interaction with the virtual environment challenged the children's motor abilities, improving their body balance and cognitive skills. The results show that our multisensory environment (MSE) can be used to stimulate visual feedback, aiming to generate conflicts between visual, somatosensory and vestibular information, as a way of training different sensory systems, such as also addressed by several kinds of research (Adamovich et al. (2009), Franciulli et al. (2016), Abellard (2017), DEL RIO GUERRA et al. (2019)).

The data presented in this chapter confirm the use of multisensory environments

(MSEs) as a promising tool to be incorporated into the rehabilitation, diagnosis and training processes of CwDS to improve their motor development and body balance skills or related conditions, allowing them to grow in a more independent way.

The small sample size for the development of the intervention, did not allow us to generate a statistical analysis of the results. The good results obtained for the children could help as advertising to families and institutions, in order to have more participants for future experiments and interventions.

To generate a pervasive tool and increase the scope of the multisensory environment (MSE), it is necessary to continue with the development of different kind of games and interactions. For instance, smart toys and robots could improve the motor behavior and cognition in children with different pathologies, dysfunctions and syndromes.

6 Conclusion

This research presented a multisensory environment (MSE) for proprioception improvement in children with down syndrome to assist and enhance conventional intervention practices, helping clinical studies. The designed framework combines a vision system with an automated analysis of children's movements through a game platform, based on physiotherapeutic recommendations. This research contributes to the state-of-the-art of clinical technologies focusing on CwDS, with an innovative, flexible and scalable architecture capable of following the movement progress (interpreted as proprioceptive), balance or lateralization improvement. A detailed analysis of the results presented in the three main chapters, as well as some remarks and conclusions are described below.

6.1 Remarks on Contributions

The main contribution of this Ph.D. thesis was the development of an intervention through a multisensory environment (MSE) for proprioception improvement in children with Down syndrome, as well as a clinical relevance analysis of the movement parameters performed during a focused intervention with a game platform.

In addition, the research and design procedures conducted here, reaffirmed in an ethically responsible sense, addressed literature findings regarding the use of technological tools to strengthen Down syndrome intervention, therapies and diagnosis. In particular, the research presented here can open an additional chapter concerning how this new technique might be used to empower and leverage the clinical staff skills, and directly benefit the performance of therapies and diagnosis focused on Down syndrome.

There are some important remarks to mention:

1. An exploratory study was developed here with a Smart Mirror Environment (SME) platform to provide visual feedback and a proprioception assessment to CwDS. The discussion of the data warns that body experiences may be fundamental for motor and self-perception aspects. CwDS implicitly have a developmental deficit, therefore, it was found that they should be provided with sensory and bodily experiences in order to promote their neuropsychomotor development.

2. Those findings led us to develop a markerless camera-based system to measure body movement parameters. The proposed markerless system uses two RGB-D cameras in order to reduce errors and inaccuracies related to self-occlusion issues, generating parameters as positions, joints angular amplitudes, velocities and accelerations of fifteen

body joints.

3. The development of a clinical intervention based on a game platform that uses parameters of the markerless camera-based system contributes to generating a new scenario in aid technological tools focused on the Down syndrome population.

6.2 Findings

The results obtained in this research are promising, given that they allow exhibiting a series of useful findings to identify CwDS movement factors associated mainly with their hypotonia, cognitive and health conditions. This research shows some common signs in CwDS that turned more evident when they interacted with a game-based platform.

Thanks to the analysis of results of twelve CwDS with the assessment platform, and of three with the intervention platform, it was possible to identify different motor patterns as proprioception, left-right discrimination and gross motor skills of those children

Through the assessment platform (Smart Mirror Environment) developed here, different aspects in the proprioception and gross motor skills of CwDS was found. For example, it was found that CwDS have serious difficulties to distinguish the hemispheres of the body. Considering each BPM factors, the results show that the recurring practice using an interactive tool like SME can improve the motor understanding of the body, as well as laterality and proprioceptive skills, suggesting a necessary tool for training different abilities.

The multicamera system proposed here attached to the gaming platform developed in this work, generate multiple sensorial stimuli in the CwDS, providing them with significant interaction with the environment, expanding their motor experience.

The multicamera system can capture parameters of 15 joints simultaneously in the body, storing position data with temporal reference. Through that data, it is possible to acquire and analyze movements developed in articulations of arms, legs, hips or any other body segments required by the evaluator. Parameters as angular amplitude, linear and angular velocities and accelerations, as well as user pathways or positions, are part of the information required to the system.

Systems such as the developed here can provide CwDS with more significant interaction with the environment, stimulating and expanding their several senses. With the results obtained so far, we can highlight that all task and kinematic parameter performed by the children, measured by our virtual immersion system, can be further analyzed to get more parameters of interest. In fact, our system is able to analyze movements carried out in articulations of legs, torso, hip or any other body segments required by the evaluator.

This system was developed to meet the requirements of professionals in Psychology and Physiotherapy, with the purpose of understanding and analyzing basic motor tasks in CwDS. The information obtained by the system can be also used to develop more kinds of serious games applied to multisensory environments, thus expanding the contributions to the psychomotor development of CwDS.

To improve the results, it is necessary to carry out more tests with CwDS, including a platform of different serious games to stimulate different abilities in these children, based on recommendations from the physiotherapy staff.

6.3 Future works

The system could be used also by children with other pathologies or cognitive disabilities, being an innovative tool to generate objective data to analyze and record, which can be useful for future therapies and training for health professionals. Concepts such as telemedicine and pervasive healthcare can also be used with the developed system.

The next step of this research is to carry out more experiments with CwDS, including a new group of different serious games to stimulate different abilities of these children, based on recommendations from the clinical staff.

Currently, a study of Human Activity Recognition (HAR) (from the multicameras system) is currently being carried out in our lab to determine movement patterns during the games. This study aims to improve and automate the detection of tasks by the game platform, allowing to find relevant parameters for clinical staff. Motor actions like clapping, hand waving, jump up or shake head could be recognized. Other approach is to find emotions in actions like cheer up, nod head, or cross hands in front (saying stop).

6.4 Publications

The research developed in this Ph.D. thesis allowed the publication of the following works:

1. (Journal paper) Valencia-Jimenez, N.; Da Luz, S.; Santos, D.; Souza, M.; Bastos, T.; Frizera, A. The Effect of Smart Mirror Environment on Proprioception Factors of Children with Down Syndrome. Research on Biomedical Engineering 2020. <https://doi.org/10.1007/s42600-020-00041-3>. (Manuscript Accepted for publication)

2. (Journal paper) Valencia-Jimenez, N.; Leal-Junior, A.; Avellar, L.; Vargas-Valencia, L.; Caicedo-Rodríguez, P.; Ramírez-Duque, A.A.; Lyra, M.; Marques, C.; Bastos,

T.; Frizera, A. A Comparative Study of Markerless Systems Based on Color-Depth Cameras, Polymer Optical Fiber Curvature Sensors, and Inertial Measurement Units: Towards Increasing the Accuracy in Joint Angle Estimation. Electronics 2019, 8, 173. <https://doi.org/10.3390/electronics8020173>

3. (Book Chapter) Valencia, Nicolás; Cardoso, Vivianne; Frizera, Anselmo; Freire-Bastos, Teodiano. Serious Game for Post-stroke Upper Limb Rehabilitation. Biosystems & Biorobotics. 1ed.: Springer International Publishing, 2017, v., p. 1445-1450. <https://doi.org/10.1007/978-3-319-46669-9_237>

4. (Conference Proceeding) Schreider, S. ; Bastos, T. F. ; Lyra, Mariana ; Valencia, Nicolás ; Frizera Neto, A. . Proposta de Ambientes Virtuais para a Intervenção na Propriocepção de Crianças com Síndrome de Down: Protocolo de Aplicação. In: 2nd INTERNATIONAL WORKSHOP ON ASSISTIVE TECHNOLOGY (IWAT2019), 2019, Vitoria. Proceedings IWAT 2019, 2019.

5. (Conference Proceeding) Lyra, Mariana ; Valencia, Nicolas ; Ramírez-Duque, Andrés ; Frizera Neto, A. ; Bastos, T. F. . Development of a Game Platform for Motor Rehabilitation of Children with Poor Balance Control and Proprioception Skills. In: 2nd INTERNATIONAL WORKSHOP ON ASSISTIVE TECHNOLOGY (IWAT2019), 2019, Vitoria. Proceedings IWAT 2019, 2019.

6. (Conference Proceeding) Hernandez-Ossa, K. A. ; Valencia, Nicolás ; Souza, M. D. P. ; Leal, C. K. N. ; Delisle-Rodriguez, D. ; Souza, M. L. ; Ferreira, A. ; Frizera Neto, A. ; Bastos, T. F. . Considerações Práticas na Aquisição de Sinais de EEG para Aplicações em Psicologia. In: 2nd INTERNATIONAL WORKSHOP ON ASSISTIVE TECHNOLOGY (IWAT2019), 2019, Vitoria. Proceedings IWAT 2019, 2019.

7. (Conference Proceeding) Cremasco, E. ; Silveira, M. ; Valencia, Nicolás ; Bastos, T. F. . Proposta de Jogo Sério e Uso de Sensores de Força, Sensores Inerciais e Leap Motion para Reabilitação Motora Fina de Crianças com Déficits Motores. In: 2nd INTERNATIONAL WORKSHOP ON ASSISTIVE TECHNOLOGY (IWAT2019), 2019, Vitoria. Proceedings IWAT 2019, 2019.

8. (Conference Proceeding) Baiocco, T. ; Valencia, Nicolás ; Santos, Dayse ; Frizera Neto, A. ; Bastos, T. F. . Development Of Game-Based System For Improvement Of The Left-Right Recognition Ability In Children With Down Syndrome. In: Congresso Brasileiro De Engenharia Biomédica (Cbeb 2018), 2018, Búzios, RJ. Anais Congresso Brasileiro De Engenharia Biomédica (Cbeb 2018), 2018.

9. (Conference Proceeding) Valencia, Nicolas; Santos, Dayse; Frizera Neto, Anselmo; Souza, Mariane; Bastos, Teodiano. Ambientes Virtuais Como Ferramenta De Avaliação Da Autopercepção Corporal Em Crianças Com Síndrome De Down. In: Con-

gresso Brasileiro de Eletromiografia e Cinesiologia (COBEC) e o Simpósio de Engenharia Biomédica (SEB) COBECSEB, 2018, Uberlândia. Anais do V Congresso Brasileiro de Eletromiografia e Cinesiologia e X Simpósio de Engenharia Biomédica. Uberlândia: Even3, 2017. http://dx.doi.org/10.29327/cobecseb.78886

10. (Conference Proceeding) Valencia, Nicolás; Silva, D. K. S.; Souza, M. L.; Bastos, T. F.; Frizera Neto, A. Sistema De Inmersión Virtual Para Desempeño Funcional: Evaluación En Niños Con Síndrome De Down. In: Ii International Congress on Technology and Tourism for All, 2017, Málaga, Espanha. II Congreso Internacional De Tecnología Y Turismo Accesibilidad 4.0 Para Todas Las Personas, 2017.

11. (Conference Proceeding) Valencia, Nicolás; Silva, D. K. S.; Frizera Neto, A.; Souza, M. L.; Bastos, T. F. Ambiente Virtual Como Herramienta De Evaluación De La Propiocepción De Niños Con Síndrome De Down. In: IX Congreso Iberoamericano De Tecnología De Apoyo A La Discapacidad - Iberdiscap 2017, 2017, Bogotá. Memorias Congreso Iberoamericano De Tecnologías De Apoyo A La Discapacidad, 2017.

Bibliography

ABDEL RAHMAN, S. Efficacy of Virtual Reality-Based Therapy on Balance in Children with Down Syndrome. *World Applied Sciences Journal*, v. 10, n. 3, p. 254–261, 2010. ISSN 1818-4952. 22, 30, 34

ABELLARD, A. Serious Games Adapted to Children with Profound Intellectual and Multiple Disabilities. In: *9th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games)*. [S.l.: s.n.], 2017. p. 183–184. ISBN 9781509058129. 21, 32, 33, 91, 92

ADAMOVICH, S. V. et al. Sensorimotor training in virtual reality: A review. *Neurorehabilitation*, v. 25, n. 1, p. 29–44, 2009. ISSN 10538135. Disponível em: <https://www.medra.org/servlet/aliasResolver?alias=iospress{&}doi=10.3233/NRE-2009-0>. 45, 59, 92

AGOSTA, G. et al. Playful supervised smart spaces (P3S)-A framework for designing, implementing and deploying multisensory play experiences for children with special needs. In: *Proceedings - 18th Euromicro Conference on Digital System Design, DSD 2015*. [S.l.: s.n.], 2015. p. 158–164. ISBN 9781467380355. 92

ALESII, R. et al. Short range wireless solutions enabling ambient assisted living to support people affected by the Down syndrome. In: *IEEE EuroCon 2013*. [S.l.: s.n.], 2013. p. 340–346. ISBN 9781467322324. 20, 30, 33

ALMEIDA, M. D. de; MOREIRA, M. C. d. S.; TEMPSKI, P. Z. Physiotherapeutic intervention in the outpatient care of persons with Down syndrome at the Institute of Physical Medicine and Rehabilitation at HC FMUSP. *Acta Fisiátrica*, 2013. ISSN 0104-7795. 26

ALT, F.; GEIGER, S.; HÖHL, W. ShapelineGuide – Teaching mid-air gestures for large interactive displays. In: *PerDis 2018 - Proceedings of the 7th ACM International Symposium on Pervasive Displays*. [S.l.: s.n.], 2018. ISBN 9781450357654. 29

AMADO SANCHEZ, V. L. et al. BeeSmart: A Gesture-Based Videogame to Support Literacy and Eye-Hand Coordination of Children with Down Syndrome. In: DIAS, J.; SANTOS, P. A.; VELTKAMP, R. C. (Ed.). *Games and Learning Alliance*. Cham: Springer International Publishing, 2017. p. 43–53. ISBN 978-3-319-71940-5. 21, 26, 34

ARYA, R.; KABRA, M.; GULATI, S. Epilepsy in children with Down syndrome. *Epileptic.Disord.*, v. 13, n. 1, p. 1–7, 2011. Disponível em: <http://www.ncbi.nlm.nih.gov/pubmed/21398208>. 19

AVELLAR, L. M. *Development and Evaluation of Camera-based System for Analysis of Dual-task in Older Adults: Gait combined with Prehension*. 78 p. Tese (Doutorado) — Universidade Federal do Espirito Santo, 2019. 32

BARGAGNA, S. et al. Educational Robotics in Down Syndrome: A Feasibility Study. *Technology, Knowledge and Learning*, 2019. ISSN 22111670. 20, 29

BEQAJ, S. et al. Contribution of Physical and Motor Characteristics to Functional Performance in Children and Adolescents with Down Syndrome: A Preliminary Study. *Medical science monitor basic research*, 2018. ISSN 23254416. 26

BERG, K. O. et al. Measuring balance in the elderly: Validation of an instrument. In: *Canadian Journal of Public Health*. [S.l.: s.n.], 1992. ISSN 00084263. 68, 69, 70

BERG, P. et al. Motor control outcomes following nintendo Wii use by a child with down syndrome. *Pediatric Physical Therapy*, 2012. ISSN 08985669. 34

BERNARDINI, S.; PORAYSKA-POMSTA, K.; SMITH, T. J. ECHOES: An intelligent serious game for fostering social communication in children with autism. *Information Sciences*, v. 264, p. 41–60, 2014. ISSN 00200255. 21, 30, 33

BONARINI, A. et al. Integrating human-robot and motion-based touchless interaction for children with intellectual disability. In: *Proceedings of the 2014 International Working Conference on Advanced Visual Interfaces - AVI '14*. [s.n.], 2014. p. 341–342. ISBN 9781450327756. Disponível em: <http://dl.acm.org/citation.cfm?doid=2598153.2600054>. 92

BORK, F. et al. Empirical Study of Non-Reversing Magic Mirrors for Augmented Reality Anatomy Learning. *2017 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, p. 169–176, 2017. Disponível em: <http://ieeexplore.ieee.org/document/8115415/>. 20, 30, 33

BRANDÃO, A. et al. Jecripe: Stimulating cognitive abilities of children with Down syndrome in pre-scholar age using a game approach. In: *ACM International Conference Proceeding Series*. [S.l.: s.n.], 2010. ISBN 9781605588636. 29

BRANDÃO, A. et al. Semiotic inspection of a game for children with Down syndrome. *Proceedings - 2010 Brazilian Symposium on Games and Digital Entertainment, SBGames 2010*, p. 199–210, 2011. ISSN 2159-6654. 21, 30, 33

BRODIN, J. Play in Children with Severe Multiple Disabilities: Play with toys - a review. *International Journal of Disability, Development and Education*, v. 46, n. 1, p. 25–34, 1999. ISSN 1034-912X. Disponível em: <http://www.tandfonline.com/doi/abs/10.1080/103491299100704>. 30

BRULE, E. et al. MapSense: Multi-Sensory Interactive Maps for Children Living with Visual Impairments. In: *CHI '16*. [S.l.: s.n.], 2016. p. 10. ISBN 978-1-4503-3362-7. ISSN 0270-6474. 30

BUNDY, A. C.; LANE, S. J.; MURRAY, E. A. *Sensory Integration: Theory and Practice*. [S.l.: s.n.], 2002. 496 p. ISSN 0-8036-0545-5 (Hardcover); 978-0-8036-0545-9 (Hardcover). ISBN 0803605455. 20

CABIBIHAN, J. J. et al. *Why Robots? A Survey on the Roles and Benefits of Social Robots in the Therapy of Children with Autism*. 2013. 593–618 p. 20

CABREIRA, A. T.; HWANG, F. An analysis of mid-air gestures used across three platforms. In: *ACM International Conference Proceeding Series*. [S.l.: s.n.], 2015. ISBN 9781450336437. 29

CAMEIRAO, M. S. et al. Neurorehabilitation using the virtual reality based Rehabilitation Gaming System: methodology, design, psychometrics, usability and validation. *Journal of NeuroEngineering and Rehabilitation*, v. 7, n. 1, p. 48, 2010. ISSN 1743-0003. Disponível em: <http://jneuroengrehab.biomedcentral.com/articles/10.1186/1743-0003-7-48>. 22, 31, 33, 47, 68

CAPIO, C. M. et al. Fundamental movement skills and balance of children with Down syndrome. *Journal of Intellectual Disability Research*, 2018. ISSN 13652788. 19, 28, 91, 92

CARTER, M.; STEPHENSON, J. The Use of Multi-Sensory Environments in Schools Servicing Children with Severe Disabilities. *Journal of Developmental and Physical Disabilities*, v. 24, n. 1, p. 95–109, feb 2012. ISSN 1056-263X. Disponível em: <http://link.springer.com/10.1007/s10882-011-9257-x>. 20, 30

CARVALHO DOS SANTOS, J. et al. REALIDADE VIRTUAL E FACILITAÇÃO NEUROMUSCULAR PROPRIOCEPTIVA COMO ABORDAGEM PARA FUNCIONALIZAÇÃO DO TEMPO DE REAÇÃO VISUAL, EQUILÍBRIO DINÂMICO E FORÇA MUSCULAR. *Revista Pesquisa em Fisioterapia*, 2016. ISSN 2238-2704. 60

CARVALHO, T. L. *Sistema para Análise da Marcha Humana Baseado em Múltiplos Sensores Kinect v2*. Tese (Doutorado) — Universidade Federal do Espirito Santo, 2018. 32, 49, 51

CASAMASSIMA, F. et al. A wearable system for gait training in subjects with Parkinson's disease. *Sensors (Switzerland)*, 2014. ISSN 14248220. 47

CHEN, P. J. et al. Development of an upper limb rehabilitation system using inertial movement units and kinect device. In: *Proceedings of the IEEE International Conference on Advanced Materials for Science and Engineering: Innovation, Science and Engineering, IEEE-ICAMSE 2016*. [S.l.: s.n.], 2017. ISBN 9781509038695. 38, 51

CLARK, R. A. et al. *Three-dimensional cameras and skeleton pose tracking for physical function assessment: A review of uses, validity, current developments and Kinect alternatives*. 2019. 7, 32, 33

CLARK, R. A. et al. Reliability and concurrent validity of the Microsoft Xbox One Kinect for assessment of standing balance and postural control. *Gait and Posture*, 2015. ISSN 18792219. 32

CLARK, T. et al. Autistic symptoms in children with attention deficit-hyperactivity disorder. *European Child and Adolescent Psychiatry*, v. 8, n. 1, p. 50–55, 1999. ISSN 10188827. 20

COPPEDE, A. C. et al. Desempenho motor fino e funcionalidade em crianças com síndrome de Down. *Fisioterapia e Pesquisa*, 2012. 26

CORTES, M. Y. et al. Study of the usability in applications used by children with Down Syndrome. *2013 8th Computing Colombian Conference, 8CCC 2013*, 2013. 19, 29, 30

COVACI, A. et al. Assessing Real World Imagery in Virtual Environments for People with Cognitive Disabilities. In: *Proceedings - 2015 International Conference on Intelligent Environments, IE 2015*. [S.l.: s.n.], 2015. p. 41–48. ISBN 9781467366540. 20, 22, 32, 34

DAVIS, A. S. Children With Down Syndrome: Implications for Assessment and Intervention in the School. *School Psychology Quarterly*, v. 23, n. 2, p. 271–281, 2008. ISSN 10453830. 27

DE MELLO MONTEIRO, C. B. et al. Short-term motor learning through non-immersive virtual reality task in individuals with down syndrome. *BMC Neurology*, BMC Neurology, v. 17, n. 1, p. 1–8, 2017. ISSN 14712377. 19, 29

DE TROYER, O. Towards effective serious games. In: *2017 9th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games)*. IEEE, 2017. p. 284–289. ISBN 978-1-5090-5812-9. Disponível em: <http://ieeexplore.ieee.org/document/8056615/>. 21, 29, 33

DEL CIELLO DE MENEZES, L. et al. Motor Learning And Virtual Reality In Down Syndrome - A Literature Review. *International Archives of Medicine*, 2015. ISSN 1755-7682. 30

DEL RIO GUERRA, M.; Martin Gutierrez, J.; ACEVES, L. Design of an interactive gesture measurement system for down syndrome people. In: *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*. [S.l.: s.n.], 2018. ISBN 9783319920511. ISSN 16113349. 20, 29

DEL RIO GUERRA, M. S. et al. Hand gestures in virtual and augmented 3D environments for down syndrome users. *Applied Sciences (Switzerland)*, v. 9, n. 13, p. 1–16, 2019. ISSN 20763417. 20, 21, 29, 45, 92

DJAOUTI, D. Classifying Serious Games: the G/P/S model. *Serious games: Mechanisms and effects*, 2011. ISSN 1431-6730. 7, 34

EL-GOHARY, M.; MCNAMES, J. Shoulder and elbow joint angle tracking with inertial sensors. *IEEE Transactions on Biomedical Engineering*, 2012. ISSN 00189294. 53

ELLIOTT, D.; WEEKS, D. J.; CHUA, R. *Anomalous cerebral lateralization and down syndrome*. 1994. 43, 91

FELIX, V. G. et al. A pilot study of the use of emerging computer technologies to improve the effectiveness of reading and writing therapies in children with Down syndrome. *British Journal of Educational Technology*, 2017. ISSN 14678535. 29

FONSECA, V. *"Manual de observação psicomotora: significação psiconeurológica dos fatores psicomotores"*. [S.l.: s.n.], 2012. ISBN 9788578541750. 11, 39, 40, 44, 68, 69, 70

FRANCIULLI, P. M. et al. Balance and antecipatory postural adjustments in elderly fallers: effects of kinesiotherapy and virtual rehabilitation. *Acta Fisiátrica*, v. 23, n. 4, 2016. ISSN 0104-7795. Disponível em: <http://www.gnresearch.org/doi/10.5935/0104-7795.20160036>. 59, 92

GALLI, M. et al. The effects of low arched feet on foot rotation during gait in children with down syndrome. *Journal of Intellectual Disability Research*, v. 58, n. 8, p. 758–764, 2014. ISSN 13652788. 26

GALLI, M. et al. Postural control in patients with Down syndrome. *Disability and Rehabilitation*, v. 30, n. 17, p. 1274–1278, 2008. ISSN 09638288. 19, 20, 26, 68

GARZOTTO, F. et al. Engaging children with neurodevelopmental disorder through multisensory interactive experiences in a smart space. In: *Internet of Things*. [S.l.: s.n.], 2019. p. 167–184. ISBN 9783319946597. 20, 21, 30, 91, 92

GEERSE, D. J.; COOLEN, B. H.; ROERDINK, M. Kinematic validation of a multi-Kinect v2 instrumented 10-meter walkway for quantitative gait assessments. *PLoS ONE*, 2015. ISSN 19326203. 32

GHIANI, G. et al. End-user personalization of context-dependent applications in AAL scenarios. In: *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services Adjunct - MobileHCI '16*. [s.n.], 2016. p. 1081–1084. ISBN 9781450344135. Disponível em: <http://dl.acm.org/citation.cfm?doid=2957265.2965005>. 20

GLEGG, S. Virtual Rehabilitation with Children: Challenges for Clinical Adoption [From the Field]. *IEEE Pulse*, v. 8, n. 6, p. 3–5, nov 2017. ISSN 2154-2287. Disponível em: <http://ieeexplore.ieee.org/document/8110871/>. 21, 29, 33

GONZÁLEZ-FERRERAS, C. et al. Engaging Adolescents with Down Syndrome in an Educational Video Game. *International Journal of Human-Computer Interaction*, 2017. ISSN 15327590. 34

GROUIOS, G.; YPSILANTI, A.; KOIDOU, I. Laterality Explored: Atypical Hemispheric Dominance in Down Syndrome. In: *Down Syndrome*. [S.l.: s.n.], 2013. 43, 91

HASHIMOTO, K. et al. Ability for basic movement as an early predictor of functioning related to activities of daily living in stroke patients. *Neurorehabilitation and Neural Repair*, 2007. ISSN 15459683. 47

HERRAN, A. Muro-de-la; GARCÍA-ZAPIRAIN, B.; MÉNDEZ-ZORRILLA, A. *Gait analysis methods: An overview of wearable and non-wearable systems, highlighting clinical applications*. 2014. 47

HOUGLUM, P. A. *Therapeutic Exercise for Musucloskeletal Injuries*. [S.l.: s.n.], 2015. 25

HOVORKA, R. M.; VIRJI-BABUL, N. A preliminary investigation into the efficacy of virtual reality as a tool for rehabilitation for children with Down syndrome. *International Journal on Disability and Human Development*, 2006. ISSN 21910367. 30

HUO, Z. et al. Examining the feasibility of a microsoft kinect TM based game intervention for individuals with anterior cruciate ligament injury risk. In: *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS*. [S.l.: s.n.], 2015. ISBN 9781424492718. ISSN 1557170X. 32

HURST, A.; TOBIAS, J. Empowering individuals with do-it-yourself assistive technology. In: *The proceedings of the 13th international ACM SIGACCESS conference on Computers and accessibility - ASSETS '11*. [s.n.], 2011. p. 11. ISBN 9781450309202. ISSN 10984275. Disponível em: <http://dl.acm.org/citation.cfm?doid=2049536.2049541>. 20

IAROCCI, G.; MCDONALD, J. Sensory integration and the perceptual experience of persons with autism. *Journal of Autism and Developmental Disorders*, v. 36, n. 1, p. 77–90, 2006. ISSN 01623257. 20, 30

IBGE, B. I. o. G.; STATISTICS. *Censo Demográfico 2010*. [s.n.], 2013. v. 55. 2003 p. ISSN 0101-4234. ISBN 8524037237. Disponível em: <http://www.bcb.gov.br/pec/GCI/PORT/readout/readout.asp>. 19

ILG, W. et al. Video game-based coordinative training improves ataxia in children with degenerative ataxia. *Neurology*, 2012. ISSN 1526632X. 32

JONES, L. Kinesthetic sensing. *Human and Machine Haptics*, 2000. 25, 91

JUNG, H.-K.; CHUNG, E.; LEE, B.-H. A comparison of the balance and gait function between children with Down syndrome and typically developing children. *Journal of Physical Therapy Science*, Society of Physical Therapy Science (Rigaku Ryoho Kagakugakkai), v. 29, n. 1, p. 123–127, jan 2017. ISSN 0915-5287. Disponível em: <https://www.jstage.jst.go.jp/article/jpts/29/1/29{_}jpts-2016-808/{_}a>. 28

KAENCHAN, S. et al. Automatic multiple Kinect cameras setting for simple walking posture analysis. In: *2013 International Computer Science and Engineering Conference, ICSEC 2013*. [S.l.: s.n.], 2013. ISBN 9781467353243. 32

KETCHESON, L. et al. Physical Activity Patterns in Infants with and Without Down Syndrome. *Pediatric Physical Therapy*, v. 29, n. 3, p. 200–206, 2017. ISSN 1538005X. 19, 28

KIRTLEY, C. *Clinical Gait Analysis: Theory and practice*. [S.l.: s.n.], 2006. ISSN 00943061. ISBN 9780323048842. 56

KONSTANTINIDIS, E. I. et al. The interplay between IoT and serious games towards personalised healthcare. *9th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games)*, p. 249–252, 2017. Disponível em: <http://ieeexplore.ieee.org/document/8056609/>. 20, 22, 32, 34

KUMIN, L.; LAZAR, J.; FENG, J. *Expanding job options: potential computer-related employment for adults with Down syndrome*. 2012. 28

LANCIONI, G. E.; CUVO, A. J.; O'REILLY, M. F. *Snoezelen: An overview of research with people with developmental disabilities and dementia*. 2002. 175–184 p. 20, 30

LEAL JUNIOR, A. G.; FRIZERA, A.; PONTES, M. J. Analytical model for a polymer optical fiber under dynamic bending. *Optics and Laser Technology*, 2017. ISSN 00303992. 52, 54

LENT, R. *Neurociência da mente e do comportamento*. Guanabara Koogan, 2008. ISBN 9788527713795. Disponível em: <https://books.google.com.br/books?id=Zp6HPgAACAAJ>. 45

LIZETH, V. et al. Games and Learning Alliance. v. 10653, p. 43–53, 2017. ISSN 16113349. Disponível em: <http://link.springer.com/10.1007/978-3-319-71940-5>. 20, 21

LOPES, J. et al. P 115 - Brain activity after transcranial stimulation combined with virtual reality training in children with Down Syndrome: Case Report. *Gait and Posture*, 2018. ISSN 18792219. 30

MACEDO, I. et al. Observed interaction in games for down syndrome children. *Proceedings of the Annual Hawaii International Conference on System Sciences*, v. 2015-March, p. 662–671, 2015. ISSN 15301605. 19, 30

MACIAS, A. et al. Exergames in Individuals with Down Syndrome: A Performance Comparison Between Children and Adolescents. In: *Lecture Notes of the Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering, LNICST*. [S.l.: s.n.], 2018. ISBN 9783319761107. ISSN 18678211. 28, 91, 92

MALAK, R. et al. Delays in Motor Development in Children with Down Syndrome. *Medical Science Monitor*, v. 21, p. 1904–1910, 2015. ISSN 1643-3750. Disponível em: <http://www.medscimonit.com/abstract/index/idArt/893377>. 19, 20, 26

MARTÍN-GUTIÉRREZ, J. et al. Virtual technologies trends in education. *Eurasia Journal of Mathematics, Science and Technology Education*, 2017. ISSN 13058223. 28

MARTÍN-SABARÍS, R. M.; BROSSY-SCARINGI, G. La realidad aumentada aplicada al aprendizaje en personas con Síndrome de Down: Un estudio exploratorio. *Revista Latina de Comunicacion Social*, 2017. ISSN 11385820. 34

MAZUREK, D. et al. Down Syndrome – Genetic and Nutritional Aspects of Accompanying Disorders. *Rocz Panstw Zakl Hig*, v. 66, n. 3, p. 189–194, 2015. ISSN 0035-7715. Disponível em: <http://wydawnictwa.pzh.gov.pl/roczniki{_}p>. 19, 28

MCMAHON, D. D. et al. Augmented reality for teaching science vocabulary to postsecondary education students with intellectual disabilities and autism. *Journal of Research on Technology in Education*, 2016. ISSN 19450818. 30

MENEZES, R. C. et al. Development of a complete game based system for physical therapy with kinect. *SeGAH 2014 - IEEE 3rd International Conference on Serious Games and Applications for Health, Books of Proceedings*, p. 1–6, 2014. 22, 31, 32, 34

MIYAUCHI, M.; KIMURA, T.; NOJIMA, T. A tongue training system for children with Down syndrome. In: *UIST 2013 - Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*. [S.l.: s.n.], 2013. ISBN 9781450322683. 29

MOON, S. et al. Multiple Kinect Sensor Fusion for Human Skeleton Tracking Using Kalman Filtering. *International Journal of Advanced Robotic Systems*, v. 13, n. 2, p. 65, mar 2016. ISSN 1729-8814. Disponível em: <http://journals.sagepub.com/doi/10.5772/62415>. 51

MOUSAVI HONDOR, H.; KHADEMI, M. *A review on technical and clinical impact of microsoft Kinect on physical therapy and rehabilitation*. 2014. 32

MÜLLER, B. et al. Validation of enhanced Kinect sensor based motion capturing system for gait assessment. *PloS one*, p. 1–18, 2017. 31, 32, 36

NACHER, V. et al. Examining the Usability of Touch Screen Gestures for Children with Down Syndrome. *Interacting with Computers*, 2018. ISSN 09535438. 20, 29

NAITO, M. et al. Gait analysis in Down syndrome pediatric patients using a sheet-type gait analyzer: Pilot study. *Pediatrics International*, v. 57, n. 5, p. 860–863, 2015. ISSN 1442200X. 19, 20, 27

NATIONAL DOWN SYNDROME SOCIETY. *What Is Down Syndrome? - National Down Syndrome Society*. 2018. Disponível em: <https://www.ndss.org/about-down-syndrome/down-syndrome/>. 7, 19, 26, 27, 28

NGUYEN, V. V.; LEE, J. H. Full-body imitation of human motions with kinect and heterogeneous kinematic structure of humanoid robot. In: *2012 IEEE/SICE International Symposium on System Integration, SII 2012*. [S.l.: s.n.], 2012. ISBN 9781467314961. 51

NORRIS, C. M. *Managing Sports Injuries: Fourth Edition*. [S.l.: s.n.], 2011. ISBN 9780702034732. 25

PALERMO, E. et al. Experimental evaluation of accuracy and repeatability of a novel body-to-sensor calibration procedure for inertial sensor-based gait analysis. *Measurement: Journal of the International Measurement Confederation*, 2014. ISSN 02632241. 53

PARÉS, N. et al. Achieving dialogue with children with severe autism in an adaptive multisensory interaction: The "MEDIATE" project. *IEEE Transactions on Visualization and Computer Graphics*, v. 11, n. 6, p. 734–742, 2005. ISSN 10772626. 21, 31

PFISTER, A. et al. Comparative abilities of Microsoft Kinect and Vicon 3D motion capture for gait analysis. *Journal of Medical Engineering and Technology*, 2014. ISSN 1464522X. 7, 31, 32

PIRIYAPRASARTH, P.; MORRIS, M. E. *Psychometric properties of measurement tools for quantifying knee joint position and movement: A systematic review*. 2007. 58

RADÁK, Z. Fundamentals of Strength Training. In: *The Physiology of Physical Training*. [S.l.: s.n.], 2018. 25

RAMIREZ DUQUE, A. A. *From Robot-Assisted Intervention to New Generation of Autism Screening : An Engineering Implementation Beyond the Technical Approach*. 120 p. Tese (Doutorado) — Universidade Federal do Espirito Santo, 2019. Disponível em: <http://repositorio.ufes.br/jspui/handle/10/11376>. 32

RAMLI, R.; ZAMAN, H. B. Designing usability evaluation methodology framework of Augmented Reality basic reading courseware (AR BACA SindD) for Down Syndrome learner. In: *Proceedings of the 2011 International Conference on Electrical Engineering and Informatics, ICEEI 2011*. [S.l.: s.n.], 2011. ISBN 9781457707520. 30

REDDY, V. et al. Engaging with the self. *Autism*, v. 14, n. 5, p. 531–546, sep 2010. ISSN 1362-3613. Disponível em: <http://www.ncbi.nlm.nih.gov/pubmed/20841341http://journals.sagepub.com/doi/10.1177/1362361310370397>. 44

RINGLAND, K. E. et al. SensoryPaint: A Multimodal Sensory Intervention for Children with Neurodevelopmental Disorders. In: *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing, Seattle, WA, USA*. [s.n.], 2014. p. 873–884. ISBN 9781450329682. ISSN 1463-5771. Disponível em: <http://doi.acm.org/10.1145/2632048.2632065>. 30

RODENBUSCH, T. L. et al. Effects of treadmill inclination on the gait of children with Down syndrome. *Research in Developmental Disabilities*, v. 34, n. 7, p. 2185–2190, 2013. ISSN 08914222. 19, 26

SACKS, B.; BUCKLEY, S. What do we know about the movement abilities of children with Down syndrome ? *The Down Syndrome Educational Trust. Down Syndrome News and Update*, v. 2, n. 4, p. 131–141, 2003. 21, 26

SALAH, J.; ABDENNADHER, S.; ATEF, S. Galaxy shop: Projection-based numeracy game for teenagers with down syndrome. In: *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*. [S.l.: s.n.], 2017. ISBN 9783319701103. ISSN 16113349. 34

SALTER, T.; DAVEY, N.; MICHAUD, F. Designing & developing QueBall, a robotic device for autism therapy. In: *Proceedings - IEEE International Workshop on Robot and Human Interactive Communication*. [S.l.: s.n.], 2014. v. 2014-Octob, n. October, p. 574–579. ISBN 978-1-4799-6765-0. ISSN 1944-9445. 21

SCAPINELLI, D. F.; LARAIA, É. M. S.; SOUZA, A. S. de. Evaluation of functional capabilities in children with Down Syndrome. *Fisioterapia em Movimento*, v. 29, n. 2, p. 335–342, 2016. 44, 92

SCHMITZ, A. et al. Accuracy and repeatability of joint angles measured using a single camera markerless motion capture system. *Journal of Biomechanics*, 2014. ISSN 00219290. 57

SEEL, T.; RAISCH, J.; SCHAUER, T. IMU-based joint angle measurement for gait analysis. *Sensors (Switzerland)*, 2014. ISSN 14248220. 53

SHAMS, L.; SEITZ, A. R. Benefits of multisensory learning. *Trends in Cognitive Sciences*, v. 12, n. 11, p. 411–417, 2008. ISSN 13646613. 21, 30

SHOTTON, J. et al. Real-time human pose recognition in parts from single depth images. In: *CVPR 2011*. IEEE, 2011. p. 1297–1304. ISBN 978-1-4577-0394-2. ISSN 10636919. Disponível em: <http://ieeexplore.ieee.org/document/5995316/>. 48

SHULL, P. B. et al. *Quantified self and human movement: A review on the clinical impact of wearable sensing and feedback for gait analysis and intervention*. 2014. 47

SILVA, M. et al. Functional assessment of psychomotor development and family environment of children with down syndrome. *Rev. Interinst. Bras. Ter. Ocup. Rio de Janeiro*, v. 1, n. 2, p. 186–201, 2017. Disponível em: <https://revistas.ufrj.br/index.php/ribto/article/viewFile/4818/pdf>. 34

SILVEIRA, M. et al. Development of a Game Platform for Motor Rehabilitation of Children with Poor Balance Control and Proprioception Skills. In: *IWAT2019: International Workshop on Assistive Technology*. [S.l.: s.n.], 2019. 29, 60

SILVEIRA, M. L. *Plataforma Interativa Multimodal para Reabilitação de Déficit Motor em Crianças com Desabilidades Desenvolvimentais*. Tese (Dissertação de Mestrado.) — UFES, 2019. 8, 32, 62, 66, 67

SINAGA, P.; PRANANTA, M. S.; FADLYANA, E. Score of Fine Motor Skill in Children with Down Syndrome using Nintendo Wii. *Althea Medical Journal*, 2016. ISSN 2337-4330. 34

STARANOWICZ, A. N.; RAY, C.; MARIOTTINI, G. L. Easy-to-use, general, and accurate multi-Kinect calibration and its application to gait monitoring for fall prediction. In: *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS*. [S.l.: s.n.], 2015. ISBN 9781424492718. ISSN 1557170X. 32

STONE, E. E.; SKUBIC, M. Fall detection in homes of older adults using the microsoft kinect. *IEEE Journal of Biomedical and Health Informatics*, 2015. ISSN 21682194. 32

SUGIMOTO, D. et al. *Effects of Neuromuscular Training on Children and Young Adults with Down Syndrome: Systematic Review and Meta-Analysis*. [S.l.]: Elsevier Inc., 2016. 197–206 p. 45

SVENDSEN, J.; ALBU, A. B.; VIRJI-BABUL, N. Analysis of patterns of motor behavior in gamers with down syndrome. In: *CVPR 2011 WORKSHOPS*. IEEE, 2011. p. 1–6. ISBN 978-1-4577-0529-8. ISSN 21607508. Disponível em: <http://ieeexplore.ieee.org/document/5981673/>. 20, 27, 30, 31, 33

TAM, V.; GELSOMINI, M.; GARZOTTO, F. Polipo - a Tangible Toy for Children with Neurodevelopmental Disorders. In: *Proceedings of the Tenth International Conference on Tangible, Embedded, and Embodied Interaction - TEI '17*. [s.n.], 2017. p. 11–20. ISBN 0957-4174. ISSN 09574174. Disponível em: <http://dl.acm.org/citation.cfm?doid=3024969.3025006>. 21, 91, 92

TANNOUS, H. et al. A new multi-sensor fusion scheme to improve the accuracy of knee flexion kinematics for functional rehabilitation movements. *Sensors (Switzerland)*, 2016. ISSN 14248220. 54

TAYLOR, J. *Encyclopedia of Neuroscience*. Elsevier, 2009. 1143–1149 p. ISBN 978-0-08-045046-9. Disponível em: <http://www.sciencedirect.com/science/article/pii/B9780080450469019070>. 25

TETTEROO, D. et al. Lessons Learnt from Deploying an End-User Development Platform for Physical Rehabilitation. In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI '15*. [s.n.], 2015. p. 4133–4142. ISBN 9781450331456. Disponível em: <http://dl.acm.org/citation.cfm?doid=2702123.2702504>. 21

TOFFALINI, E. et al. Environment learning from virtual exploration in individuals with down syndrome: the role of perspective and sketch maps. *Journal of Intellectual Disability Research*, v. 8276017, p. 1–11, 2017. ISSN 09642633. Disponível em: <http://doi.wiley.com/10.1111/jir.12445>. 19, 22, 34

TORRES-CARRIÓN, P.; GONZÁLEZ-GONZÁLEZ, C.; CARREÑO, A. M. Methodology of emotional evaluation in education and rehabilitation activities for people with Down Syndrome. In: *ACM International Conference Proceeding Series*. [S.l.: s.n.], 2014. ISBN 9781450328807. 29

TOVAR, Á. E.; WESTERMANN, G.; TORRES, A. From altered synaptic plasticity to atypical learning: A computational model of Down syndrome. *Cognition*, Elsevier, v. 171, n. October 2017, p. 15–24, 2018. ISSN 18737838. Disponível em: <http://dx.doi.org/10.1016/j.cognition.2017.10.021>. 19, 27

VAN DEN NOORT, J. C. et al. Gait analysis in children with cerebral palsy via inertial and magnetic sensors. *Medical and Biological Engineering and Computing*, 2013. ISSN 01400118. 47

VARGAS-VALENCIA, L. et al. An IMU-to-Body Alignment Method Applied to Human Gait Analysis. *Sensors*, v. 16, n. 12, p. 2090, 2016. ISSN 1424-8220. 52, 56

VERHAGEN, E. et al. The Effect of a Proprioceptive Balance Board Training Program for the Prevention of Ankle Sprains. *The American Journal of Sports Medicine*, v. 32, n. 6, p. 1385–1393, sep 2004. ISSN 0363-5465. Disponível em: <http://journals.sagepub.com/doi/10.1177/0363546503262177>. 25

VIMERCATI, S. L. et al. Clumsiness in fine motor tasks: Evidence from the quantitative drawing evaluation of children with Down Syndrome. *Journal of Intellectual Disability Research*, v. 59, n. 3, p. 248–256, mar 2015. ISSN 13652788. Disponível em: <http://doi.wiley.com/10.1111/jir.12132>. 44

WANG, Q. et al. Evaluation of pose tracking accuracy in the first and second generations of microsoft Kinect. In: *Proceedings - 2015 IEEE International Conference on Healthcare Informatics, ICHI 2015*. [S.l.: s.n.], 2015. ISBN 9781467395489. 32

WINDERS, P.; WOLTER-WARMERDAM, K.; HICKEY, F. A schedule of gross motor development for children with Down syndrome. *Journal of Intellectual Disability Research*, 2019. ISSN 13652788. 20, 26

WOLFF, P.; SHEPARD, J. Causation, Touch, and the Perception of Force. In: *Psychology of Learning and Motivation - Advances in Research and Theory*. [S.l.: s.n.], 2013. 25

WONG, C. et al. *Wearable Sensing for Solid Biomechanics: A Review*. 2015. 47

WU, G. et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - Part II: Shoulder, elbow, wrist and hand. *Journal of Biomechanics*, v. 38, n. 5, p. 981–992, 2005. ISSN 00219290. 31

WU, J. et al. Walking Dynamics in Preadolescents With and Without Down Syndrome. *Physical Therapy*, v. 95, n. 5, p. 740–749, 2015. ISSN 0031-9023. Disponível em: <https://academic.oup.com/ptj/article-lookup/doi/10.2522/ptj.20140210>. 20

WUANG, Y. P. et al. Effectiveness of virtual reality using Wii gaming technology in children with Down syndrome. *Research in Developmental Disabilities*, v. 32, n. 1, p. 312–321, 2011. ISSN 08914222. 20, 33

XU, Y. et al. Robot teaching by teleoperation based on visual interaction and extreme learning machine. *Neurocomputing*, 2018. ISSN 18728286. 38, 51

YANG, L. et al. Evaluating and improving the depth accuracy of Kinect for Windows v2. *IEEE Sensors Journal*, 2015. ISSN 1530437X. 32, 36

YONGBIN QI, Y. et al. A Novel Approach to Joint Flexion/Extension Angles Measurement Based on Wearable UWB Radios. *IEEE Journal of Biomedical and Health Informatics*, v. 18, n. 1, p. 300–308, jan 2014. ISSN 2168-2194. Disponível em: <http://www.ncbi.nlm.nih.gov/pubmed/24403428http://ieeexplore.ieee.org/document/6482576/>. 51

ZUBRYCKI, I.; KOLESINSKI, M.; GRANOSIK, G. A participatory design for enhancing the work environment of therapists of disabled children. In: *25th IEEE International Symposium on Robot and Human Interactive Communication, RO-MAN 2016*. [S.l.: s.n.], 2016. p. 781–786. ISBN 9781509039296. 68