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Master Thesis

DEVELOPMENT OF SOCIAL ASSISTIVE ROBOT FOR THERAPY WITH CHILDREN WITH AUTISM SPECTRUM DISORDER : CASTOR

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"While human ingenuity may devise various inventions to the same ends,
it will never devise anything more beautiful,
nor more simple,
nor more to the purpose than nature does,
because in her inventions nothing is lacking and nothing is superfluous."

Leonardo da Vinci

Acknowledgements

This work closes an essential stage in my life, a step that, far from being simple, brought me the possibility of discovering more about who I am and what I am capable of doing if I have a purpose. I think this is not the story of my process but the story of the beginning of a research group and of what was, in my opinion, one of the most beautiful stages of my life. This stage was full of new experiences and meeting incredible people with immense potential whom, to this day, I can call family. It is with this last concept that I want to end this stage. My most incredible gratitude today goes to my family. And when I refer to my family, I am talking about my parents, Alfonso and Martha, who have always been my unconditional support, to my sister, who every day shows me that we set our limits, to my brother, who with firmness and example showed me that the most excellent demonstration of love is not given with words, but with actions. And that the greater the demands and pressure, the greater the potential they see in you. But, on the other hand, I also talk about my academy parents, my directors Marcela Munera and Carlos Cifuentes. With I began this stage full of enriching experiences. They taught me the value of science as a community. To whom I attribute the consolidation of the laboratory where I worked the last years. And I had the opportunity to meet wonderful friends; Daniel, Sergio, Nathalia, Felipe, Luis, Pips, Alejo, Orion, Majo, and the one I consider more than a friend today, my brother, Miguel. He showed me that life with support is more straightforward. With this family, I understood that a laboratory is not the equipment or the spaces. But the people and the ideas that are born there to do science. I want to say to this laboratory that no matter how far away each one of them is, they will always be my family. And for all this, thank you very much!

Con este trabajo se cierra una gran etapa en mi vida, etapa que, lejos de ser sencilla, me trajo la posibilidad de descubrir más sobre quien soy y de lo que soy capaz de hacer, si tengo un propósito. Pienso que esta no es la historia de mi proceso, sino la historia del inicio de un grupo de investigación, y de lo que fue, en mi opinión, una de las etapas más bonitas de mi vida. Esta etapa estuvo llena de experiencias nuevas, conociendo personas increíbles y con un potencial inmenso, a quienes, al día de hoy, puedo llamar familia. Es con este último concepto que quiero terminar esta etapa. Mi más grande agradecimiento se lo doy hoy a mi familia. Y cuando me refiero a mi familia, hablo de mis padres, Alfonso y Martha, quienes siempre fueron mi apoyo incondicional, a mi hermana, que cada día me demuestra que los límites nos los ponemos nosotros mismos, a mi hermano que con firmeza y ejemplo me demostró que la mayor muestra de amor no se da con palabras, sino con actos. Y que a mayor sea la exigencia y la presión, mayor es el potencial que ven en ti. Pero, por otro lado, también hablo de mis padres de academia, mis directores Marcela Munera y Carlos Cifuentes. Con quienes empecé esta etapa llena de experiencias enriquecedoras. Quienes me enseñaron el valor de la ciencia como comunidad. A quienes atribuyo la consolidación del laboratorio en donde trabajé los últimos años. Y tuve la oportunidad de conocer amigos maravillosos; Daniel, Sergio, Nathalia, Felipe, Luis, Pips, Alejo, Orión, Majo, y a quien al día de hoy considero más que un amigo, como mi hermano, a Miguel, que me mostró que la vida con apoyo es más fácil. Con esta familia entendí que un laboratorio no son los equipos ni los espacios. Sino las personas y las ideas que de allí nacen para hacer ciencia. A este laboratorio, quiero decirle que sin importar que tan lejos se encuentre cada uno, siempre sarán mi familia. ¡Y por todo esto, mil gracias!

Abstract

According to WHO, 1 in 160 children suffers from Autism spectrum disorder (ASD), a neuroatypical disorder defined by a range of social behaviours. This disorder affects the subject's ability to interact with others, lack of attention, and sometimes language difficulties. Although there is no cure, the sooner the disorder is diagnosed, and a therapy process is started, the better the long-term results will be for the subject. Recently, various emerging technologies have been used to capture children's attention in therapy. This is why robotic agents have been implemented in therapies showing great potential in improving communication skills, recognition skills, and emotions and nonverbal expressions. However, many studies do not have robots specifically designed for this type of therapy. Some robots do not have the structural strength to maintain physical interaction with users, limiting the sessions. This work presents the proposal for a novel social robot specially designed to treat CwASD. For the development of this device, a process of selecting design criteria based on a participatory design (PD) methodology was carried out with caregivers, medical staff and parents. With this information, an outline of the robot design was made, and an ergonomic study was carried out to determine the optimal dimensions and proportions of the robot. The robot underwent an aesthetic design of appearance process, which was tested and evaluated through a study conducted with 21 children with ASD. The core of this work focuses on implementing mechanisms that maximize the physical interaction that the robotic agent can maintain with the user. Therefore, bio-inspired actuators based on elastic elements in series were implemented. Finally, a robotic device capable of withstanding long sessions over time was obtained, encouraging researchers and therapists to conduct long-term studies that will yield more significant results.

Keywords: Socially Assistive Robotics, Human-Robot Interaction, Social Interaction, Robot-Therapy, Autism Spectrum Disorder, Series elastic actuator, Soft Actuation .

Glossary

ADOS Autism Diagnostic Observation Scale.

AR Assistive Robotics.

ASD Autism Spectrum Disorder.

CASTOR CompliAnt SofT Robotics.

CwASD Children with Autism Spectrum Disorder.

ICD International Classification of Diseases.

LRF Laser Ranger Finder.

PD Participatory Design.

SAR Socially Assistive Robotics.

SEA Series Elastic Actuators.

SIR Socially Interactive Robotics.

UN United Nations.

WHO World Health Organization.

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Chapter 1

Introduction

Socially assistive robots (SAR) have reported advantages in the treatment of ASD (Autism Spectrum Disorder). These studies show improved social skills, such as increased eye contact, emotion recognition, and rapport with others [1–3]. This thesis focuses on developing a new socially assistive robot (SAR) for children with ASD (Autism Spectrum Disorder) (CwASD). Additionally, this thesis presents a validation study of the social robot conducted at the Howard Gardner clinic (Bogotá, Colombia), which is an institution focused on the treatment of autism spectrum disorder (ASD) in children. The intention of this work is to encourage the development of robotic platforms with lower costs and include novel mechanisms to improve physical interaction with users. This chapter presents the context that motivated this work and the research objectives. Finally, this thesis's main contributions, publications and structure are presented.

1.1 Motivation

Autism spectrum disorder (ASD) is a neurodevelopmental disorder that affects people, often from birth, and commonly manifests in the early years of life. Worldwide statistics estimate that one in 160 children has ASD and that most children are not diagnosed until after the age of four years [4, 5]. CwASD have difficulties with attention and concentration, deficits in social communication, social interaction and recognition of emotions, impairments in verbal and nonverbal social communication, restrictive interest, and atypical behaviour [6, 7]. Socially assistive robotics (SAR) is an established research area in robotics where robots support therapeutic and healthcare interventions. Promising results exist in therapeutic interventions for the elderly and children [8]. SAR has received considerable attention as a potential intervention tool for CwASD. In the context of ASD therapy, SAR has shown significant advances and potential benefits in the development and applications of therapies for CwASD [1–3, 9]. Specifically, SAR has been used to assist the diagnostic process and practice and improve social skills, such as eye contact and joint attention [10, 11], emotion recognition [12, 13], imitation [14], sharing simple activities. Increasing self-initiated interaction [15] to encourage basic verbal and nonverbal communication [16]. Although the evidence for the efficacy of SAR for ASD therapy is increasing [8, 16, 17], most robots used with CwASD are off-the-shelf robots (e.g., toy robots and social robots), which are not specifically designed for therapeutic ASD interventions [18, 19]. Thus, evidence supports that these robots could negatively influence the therapy's performance and lead both to an unpleasant experience or dangerous event [8, 20]. Therefore, there is still a lack of consensus on how the interactions should be addressed and which robot morphology might be most effective. Consequently, several design techniques have started to be explored, where participatory design (PD) ensures the acceptability and functionality of the robot [21]. Besides, PD methods have been adopted to develop interventions for populations with special needs.

Participatory design (PD) methods allow the integration of contributions from different populations (e.g., stakeholders community) who will be directly affected by the decisions made. This process intends to achieve products or services reflecting the real needs, desires, and expectations of the users, designers, and stakeholders [22]. In this sense, all project members are valuable contributors who play a crucial role in the political, social, and ethical development considerations. Thus, the target populations and their social environment (i.e., families, society, partner groups, and friends) are no longer seen as a source of information and requirements for producing results but rather as an experienced partner [23].

Thus, PD methodology has been used in the design of SARs for ASD [24]. Those SAR systems aim to induce tactile interactions to promote social relationships and mediate interactions between CwASD, peers, and adults [25, 26]. However, different needs remain that current robots do not meet. Thanks to PD processes, it has been possible to determine that physical interaction with users is essential in a cognitive therapy process. These needs in therapies open a line of research that starts from developing robotic tools that can support such physical interaction (i.e., hugs, handshakes, pushes, even blows). This allows the development of new robotic platforms that are more resistant and easier to manufacture, encouraging the development of replicable devices that can be used as therapy tools with children in developing countries.

1.2 Background

This work is part of the CASTOR project see Fig, 1.1, funded by the Royal Academy of Engineering of the United Kingdom and the Newton Fund (Grant: IAPP1/100126). The project's aim was to develop a low-cost SAR through Participatory Design for therapies for CwASD.

The CASTOR project seeks to develop a clinical tool for increased performance in conventional ASD therapies. In this performance, the robot's appearance, structure and behaviours have an important role. Therefore, one of the first steps throughout the CASTOR project involved the stakeholders in the participatory design (PD) design process. With this PD, it was possible to create guidelines for developing the CASTOR robot. This PD was carried out in the clinic Howard Gardner, see Fig, 1.2.

Figure 1.1: CASTOR project team.

Figure 1.2: Clinic Howard Gardner. The clinic where the CASTOR project was carried out.

1.3 Objectives

1.3.1 General objective

Development of a robotic platform for physical interaction with CwASD, based on flexible actuation mechanisms, reducing risks and encouraging interaction with the user.

1.3.2 Specific objectives

- To develop a Soft Actuation system aiming at a compliant device that enables physical interaction with the children.
- To design and assess a social soft robotic platform for clinical interventions with children with cognitive impairments.
- To design and develop the outfits that are part of the physical appearance of the social robot based on the PD method.
- To develop a validation study in a clinical setting with CwASD to evaluate the differences in attention and emotion recognition with different appearances of a robotic agent in therapy.

1.4 Contributions

The main contribution of this thesis is to present a novel tool for therapy with CwASD based on SAR. Specifically, this thesis highlights the importance of physical interaction in therapy and what is the mechanical features that this interaction requires in the design. On the other hand, this thesis presents the evaluation of the robot functionality directly in a study carried out in a clinical centre specialized in the treatment of CwASD. There are a series of technical and scientific contributions described below.

1. Design and implementation of a mechanical actuation system based on series elastic actuators (SEA) with the purpose to increase the useful life of the motors. The proposal to include SEA in the robot is to encourage physical interaction with users.
2. Design and implementation of a huggable structure with the purpose to keep the robot's integrity facing an external impact or hard physical interaction by users.
3. Development of a protocol for the quantitative evaluation of the motor load in conventional robots vs the CASTOR robot.
4. Validation of the robotic tool in a clinical setting.

1.5 Publications

The work presented in this thesis has been subjected to the following scientific publications

1. (Journal Article) **Casas, Diego**, Gomez Daniel, Pinto Maria.j, Maldonado Juan, Marcela Múnera,Villa Adriana, Stoelen Martin F, Tony Belpaeme, and Carlos A. Cifuentes. "An Open-Source Social Robot Based on Compliant Soft Robotics for Therapy with Children with ASD". Actuators. 2020
2. (Journal Article - under review) Maria Jose Pinto-Bernal, Sergio David Sierra Marín, Marcela Munera, **Diego Casas**, Adriana Villa-Moreno, Anselmo

Frizera-Neto, Martin F Stoelen, Tony Belpaeme and Carlos A Cifuentes. "¿Do Different Robot Appearances Change Emotion Recognition in Children with ASD?" Frontiers in Neurorobotics

Other publications

Other publications developed during the time of the master and related to other projects are:

1. M. Sánchez-Manchola, D. Gómez-Vargas, **D. Casas-Bocanegra**, M. Múnera and C. A. Cifuentes, "Development of a Robotic Lower-Limb Exoskeleton for Gait Rehabilitation: AGoRA Exoskeleton," 2018 IEEE ANDESCON, 2018, pp. 1-6, doi: 10.1109/ANDESCON.2018.8564692.

2. D. Gomez-Vargas, **D. Casas-Bocanegra**, M. Múnera, F. Roberti, R. Carelli y C. A. Cifuentes, "Variable Stiffness Actuators for Wearable Applications in Gait Rehabilitation", en Interfacing Humans and Robots for Gait Assistance and Rehabilitation. Cham: Springer International Publishing, 2021, pp. 193–212.

1.6 Document organization

This Master thesis document is structured as follows:

Chapter 2 presents the current state ASD services, describing the phases, components, and features of conventional programs. Additionally, this chapter shows advances in the use of robotic agents as social assistants in clinical contexts of rehabilitation and treatment of children with cognitive diversity.

Chapter 3 describes the process that was carried out as a conceptual basis for the development of the CASTOR social robot. In this chapter, design criteria for the robot were determined from a participatory design (PD) process. Additionally, it shows how the creative process was carried out for the development of the robot's appearance, and the guidelines that were extracted from the PD to schematize the prototype.

Chapter 4 presents the mechanical design process of the structural parts of the robot. As well as, the presentation of the SEA-based actuation, and the electronic integration process of the CASTOR robot.

Chapter 5 shows the validation of the CASTOR robot through a study conducted in a clinical environment with children with ASD. The study aims to evaluate the effect of the physical appearance of the robot in therapies with CwASD, through interaction based on emotion recognition.

Chapter 6 presents the conclusions and recommendations for future work.

Chapter 2

Socially Assistive Robotics for Autism Spectrum Disorder

The influence of new technologies has been encouraging health professionals and research teams to work together. This has led to developments in the therapies for the cognitively diverse population [8]. These developments have been increasing in recent years, both with the elderly and with children. This chapter introduces the concepts of Autism spectrum disorder (ASD) and the conventional therapies for its treatment, as a context for discussing Socially Assistive Robotics (SAR) and their implication in current therapy. The literature review goes through general topics of SAR application in dementia and rehabilitation, ending with an emphasis on the application of robotic agents in therapies for children with autism. In this context, the characteristics that these agents must meet to avail the essential needs of therapy with children are shown. The following sections of this thesis focus on the development of one of these robotic agents.

2.1 ASD and conventional therapy

ASD is a neurodevelopmental disorder with a range of different kinds of behaviours or symptoms that affect normal interaction with others [5]. The criteria to characterize Autism Spectrum Disorder (ASD) has had an evolution up to the one known today. The term autism was presented by Eugen Bleuler in a monograph written for the psychiatric treatise, published in Vienna in 1911 [27]. In this document, autism is described as a series of behavioural difficulties, which brings social consequences such as a closed mental world and difficulty in communicating with others [27]. Subsequently, the psychiatrist Minkowski defined autism as "the loss of contact of life with reality". Because there was no method of diagnosis, it was believed that autism began in adolescence or young adulthood, not including children in this disorder [28].

At the end of the Second World War, the first World Congress of Psychiatry was held in Paris in 1950, where autism was not included among the diseases to be diagnosed; however, at the sixth Congress in Honolulu in 1977, the aim was to include mental and behavioural disorders, where autism was separated from diseases related to schizophrenia [29].

In 1943, physician Kanner published an article on autism in children, where an observational study was conducted on 11 children with erratic behaviour, loneliness and a delay or absence of verbal language acquisition. In addition, Kanner introduced some terms such as typical and atypical autism [27], [30]. At the same time, Hans Asperger published in Vienna an article on the psychopathology of autism, where historically, the Nazi regime imposed death on the mentally ill who could inherit these pathologies from their children. Therefore, Asperger mentioned that these subjects sometimes had surprising intellectual endowments, for which he concluded that they did not suffer from mental retardation [30].

Due to these two simultaneous paths on the definition of autism, a meeting was held where both authors agreed that although the disorders they studied were different [29], they coincided in the psychopathology of autism and subsequently, other conditions were included in the definition of the International Classification of Diseases ICD-10, which covers the mental illnesses of the UN and the WHO [31]. Thus, the term ”autism spectrum” was created, which encompasses different disorders with similar psychopathology, including infantile autism, atypical autism, Rett syndrome, other childhood disintegrative disorder, hyperactivity associated with mental retardation and stereotyped movements, Asperger syndrome, and other unspecified pervasive developmental disorders [27], [31].

Due to the variety of disorders included in ASD, there are individuals with pronounced impairment and individuals with high intellectual performance with social disturbances. For this reason, classifications of functionality within the spectrum and classifications of social skills affected in ASD are made [28]. The most commonly used classification scales are based on the Autism Diagnostic Observation Scale (ADOS) [32].

- Level 1: is the most profound degree of ASD, where severe deficits in social, verbal and nonverbal communication skills are usually manifested.
- Level 2: presents notable difficulties in social, verbal and nonverbal communication and has problems initiating social interactions.
- Level 3: is mild in terms of its symptomatology; it does not prevent the child from leading an autonomous life. However, social skills are affected.
- Level 4: is the simplest degree of ASD, where there are situations of difficulty that do not remain over time.

Among the treatments included in autism are communication therapies, physiotherapies, speech therapies and psychology therapies [33]. In addition to these, there are additional treatments such as neurosensory therapies that help stimulate social interactions by identifying environmental factors through the senses [34], [35]. On the other hand, there are pharmacological treatments focused on ASD-related symptomatology. Among these drugs are antidepressants [36] and antipsychotics [37], which help with self-injurious behaviours, irritability, hyperactivity and stereotyped behaviours.

Sometimes treatments are generalized to all affected behaviours in ASD [33]. However, specific social skills are affected in each case, so some therapeutic treatments focus specifically on the affected skills of the patient. An example of these approaches is hygiene, for which therapy is performed to teach the correct hygiene actions [38], or in the case of attention, therapies focused on enhancing this social skill in children are performed [39]. Various emerging technologies such as assistive robotics have generated a new approach in therapies focused on improving social skills. For this reason, studies worldwide focus on the impact of including robotic social agents in therapies for children with ASD. Studies indicate advantages such as the replicability of the sessions with the children and the concept of novelty that a robotic agent generates for the child, increasing the user's interest in carrying out the therapy [40].

2.2 Socially assistive robotics

Socially Assistive Robotics (SAR) can be defined as the intersection of Assistive Robotics (AR) and Socially Interactive Robotics (SIR). AR is the robotic field that addresses the assistance of people with disabilities. This assistance is provided by means of physical interaction (i.e., generate physical contact for example devices that assist mobility such as exoskeletons or smart walkers) [41]. On the other hand, SIR is the area focused on the development of robots able to perceive human social behaviour, such as emotions, and present similar communicative skills using natural cues (e.g., gaze or gestures). These robots are conceived under the assumption that humans prefer to interact with machines similarly as they do with other people. Hence, SIR can be applied in a range of applications (research platforms, educational tools, and therapeutic devices) [42,43]. In this context, SAR combines both fields, as it is focused on assistance (the main objective of AR) implementing robots that exhibit social behaviour and interact socially with the users, which is the main approach of SIR. However, unlike SIR, the scope of SAR is limited to the applications on rehabilitation, assistance, and healthcare scenarios [41].

The main role of social robotic agents, or social robots, is to act as companions or assistants in specific tasks involving monitoring under certain conditions. In clinical and rehabilitation settings, social robots are considered assistants, coaches or motivating agents that help improve patient performance by increasing engagement and attention in therapy. With this in mind, robotic agents are required to contain a number of features that allow them to interact effectively, providing adaptability and flexibility in different environments. Social robots are designed to interact socially with humans, for this reason, they must exhibit similar behaviors with structured functionality so that humans can interpret and become familiar with them [42]. However, many of the robotic platforms commonly used in patient sessions are either very expensive, ranging in value from 10,000 to 30,000 USD. In addition, they are not specifically designed for the physical interaction that many activities with children require.

2.2.1 Physical embodiment

As mentioned above, a considerable property that enables effective social interaction is the *physical embodiment*. This feature allows the robot to be perceived and experienced in the physical world. Therefore, it will be able to interact with humans and participate in their activities in a more natural and intuitive way [44]. The *embodiment* is a term considered to refer to the fact that intelligence cannot merely exist in the form of an abstract algorithm but requires a physical body [45,46]. Different studies have demonstrated the effectiveness and benefits that embodiment attributes to robotic platforms over other types of social agents, such as virtual agents and on-screen avatars (i.e., an icon or figure representing a specific person or character), see Fig. 2.1.

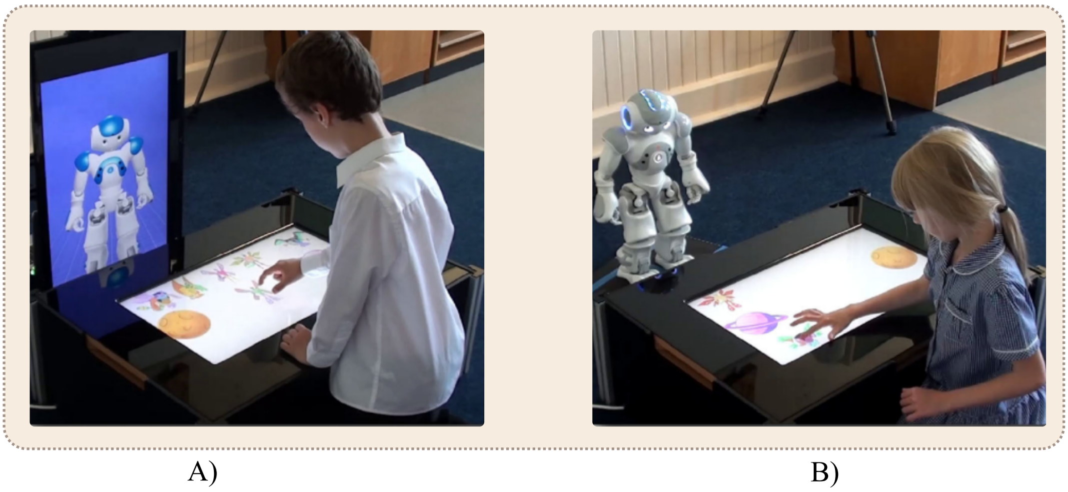


Figure 2.1: Comparison study. (A) child interacting with virtual agents, (B) a child interacting with a social robot. Image taken from Kennedy *et al.* [47].

Kennedy *et al.* [47] presented a study finding that physical robots would exhibit more advantages over virtual robots. However, they stated that it is unclear whether the real robot improves task performance, or distracts from a task. Moreover, a long-term study, carried out with children in school and hospital facilities, showed that children respond better to a robot which adapts its behaviour to the young user. Likewise, this study found that the robot, as a physically embodied agent, receives more attention than an on-screen avatar does [9]. Experimental data suggested that physically embodied interactions are favoured over virtual ones and that the first one can make a difference in a task-oriented setting [44]. Additionally, Powers *et al.* tested different hypotheses about the social impact of a robot agent, in which results showed that a robot would have more social impact than a computer agent [48]. In this study, the robots did not have a more social influence on health behaviour than the agents did, but robots were more engaging.

2.2.2 Social robots classification

Although all social robots are embodied (have a physical body that allows them to interact with the world), the degree of interaction may vary depending on their capabilities. Hence, a robot with more motor and sensor skills will present more capabilities to interact with the environment as it can establish more relationships with the world. Currently, there is a wide spectrum of design features that social robots have. In this chapter, it is considered the classification of social robots in two main categories: i) *Real-Abstract*, which indicates the degree of similarity that the platform has with nature (i.e. how similar the robot is to a living being), unlike the abstract design. ii) *Animal-Human* appearance describes their similarity to a human being or an animal creature. Fig.2.2 illustrates some robots that are conventionally used. As can be observed, these platforms vary in shape and appearance.

As shown in Fig. 2.2, JIBO is placed at the most abstract side of the graph since it does not exhibit any bio-inspired appearance. However, it has the ability to socially interact with human users using verbal and nonverbal communication [49]. In the same way, KEEPON presents similarities with JIBO regarding their physical appearance. However, it is located closer to the animal-like robots, as it counts with eyes that present similarities with natural creatures [50]. Animal-like robots such as AIBO [51] and PLEO [52] present high similarities with natural creatures. In addition, their range of movements and functionalities resemble natural behaviour. Finally, human-like robots such as PEPPER [53], NAO [54], ONO [55], and KASPAR [56] exhibit anthropomorphic features such as arms, head, and eyes. However, they differ in their appearance, where Pepper and NAO look more synthetic (i.e.,

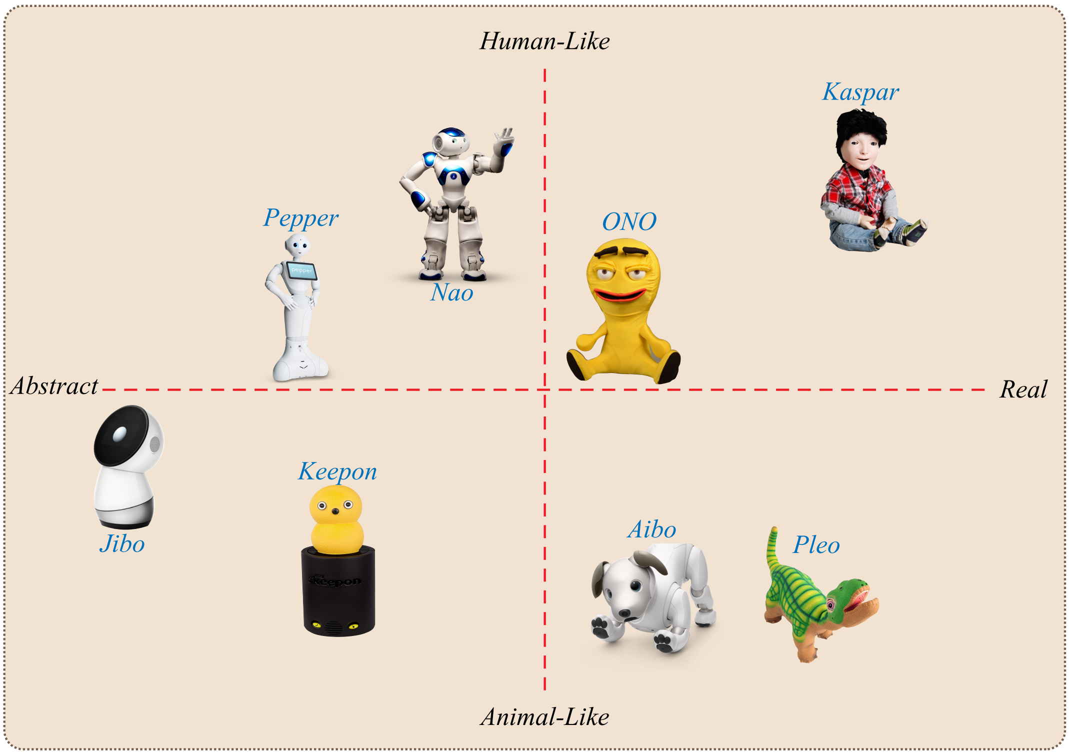


Figure 2.2: Socially Assistive Robots classification in two main categories: *Real/Abstract* and *Human/Animal*.

plastic), while ONO tends to be more realistic and KASPAR can be considered one of the most realistic and anthropomorphic social robots.

2.2.3 Robotic platform configurations

Different platforms can be regarded as social robotic agents. However, their functionalities and field of applications can diverge, as each robot can be suitable for a specific task and a specific degree of interaction depending on their configuration and degrees of freedom. As more robotic platforms are designed, the application spectrum of SAR is expanding in a similar way, covering multiple areas in healthcare and rehabilitation scenarios. This section describes four types of social robot configurations and the scenarios in which each of them is commonly used: table-top robots, wheeled robots, humanoid robots and mobile social robots.

Figure 2.3: Table-Top social robots. (A) ONO robot, (B) KASPAR robot. (C) KEEPON robot.

Table-Top Robots are usually placed on tables to interact with people, and in most cases do not count with locomotion to perform any displacement. Fig. 2.3 illustrates some examples of table-top social platforms. The robot ONO Fig.2.3(A) is an open-source social robot that has been mainly tested for children with autism due to its facial expressions. However, it presents a limited mobility of its body [55]. The major feature of this platform is the ability to express emotions, as it counts with several degrees of freedom on its face. Similarly, KASPAR Fig.2.3(B) is a child-sized humanoid robot designed as a social companion to improve the lives of children with autism and other communication difficulties [56]. Finally, KEEPON Fig.2.3(C) has been used in clinical and research environments to observe and study the development of social behaviours in children [50].

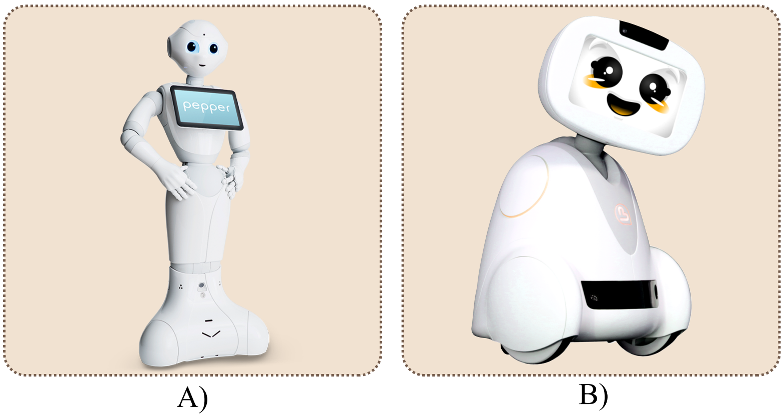


Figure 2.4: Wheeled social robots. (A) Robot PEPPER .(B) Robot BUDDY.

Wheeled Robots are robots that have a wheeled base that allow them to move freely in different spaces. This feature in combination with social behaviours provides them with a greater degree of interaction as they are able to share the same spaces with humans and interact in a more natural way. Two examples of these robotic platforms are illustrated in Fig. 2.4. Pepper Fig. 2.4(A) is a robotic platform with a high degree of impact due to its mobility, shape and size in social interactions. It has been created in order to communicate with its users in the most natural and intuitive way possible through gestures and voice [53]. Buddy Fig. 2.4(B) is a friendly companion robot designed for entertainment and education. This robot has the ability to interact with humans in home-based scenarios, where the robot is able to recognize all family members and provide assistance and companionship in their daily life [8].

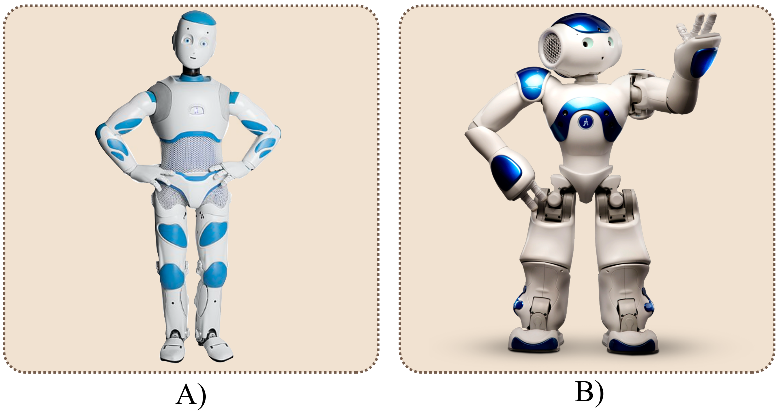


Figure 2.5: Humanoid social robots. (A) Robot ROMEO. (B) Robot NAO.

Humanoid Robots Are robotic platforms whose physical appearance is similar to humans. In other words, they have arms and legs and can move through gait. Although robots in other categories can have similarities with humans such as Pepper Fig. 2.4(A) or KASPAR Fig. 2.3(B), humanoid robots' classification was considered according to their anthropomorphism and human-like movement capabilities. Fig. 2.5 illustrates two examples of humanoid robots that are commonly known in rehabilitation and assistance contexts. Romeo Fig. 2.5(A) is a robotic platform that was designed to assist people with movement impairments and limited autonomy to carry out displacements [57]. Some studies aim to evaluate the ability of the robot ROMEO to create and maintain social bonds with people through cognitive processes. Furthermore, the NAO robot Fig. 2.5(B) is a humanoid robot that has been widely used in different scenarios that involve human-robot interaction due to its social capabilities [54]. This platform has several features such as artificial vision, speech and different sensors that allow the robot to recognize the environment. Due to its physical appearance, this platform is ideal for rehabilitation and training scenarios, since it can recreate human-like movements, which is useful when demonstrating exercises and providing appropriate instructions.

Mobile Social Robots This category comprises social robots that have been built on top of a robotic mobile platform. Platforms of these characteristics have been incorporated into research exploring different rehabilitation scenarios. Fig. 2.6(A), illustrates the robot CLARA, which was designed to play the role of a therapy assistant. As depicted in the figure, the robot comprises a mobile platform that allows the robot to move around the room. A camera and a screen are also installed to provide a social presence and recognize the patient. On the screen, there is a real therapist video displayed to interact with the patient and provide instructions to patients [58]. Similarly, there is a study with a robot composed of a mobile platform, a laser rangefinder (LRF) to navigate, and a camera to detect the patient and guide therapies [59] has been implemented. Similarly, there is a mobile robot with an anthropomorphic torso designed to aid the physical exercise of elderly patients.

2.3 SAR in clinical scenarios

SAR was initially explored in cardiovascular therapies with the development of CLARA, a hands-off physical therapy assistant whose aim was to reduce the effects of nursing shortages, provide motivation and aid patients through rehabilitation exercises such as spirometry therapies. With this study, researchers found high expectations over the robot's usefulness and an average overall satisfaction of the population of about 80% [58] see Fig. 2.6 (A). Furthermore, SAR has been used in several applications focused in elderly care [60], dementia and mental health treatments [61–63], physical and post-stroke rehabilitation [64], therapies with CwASD [65, 66], among many others.

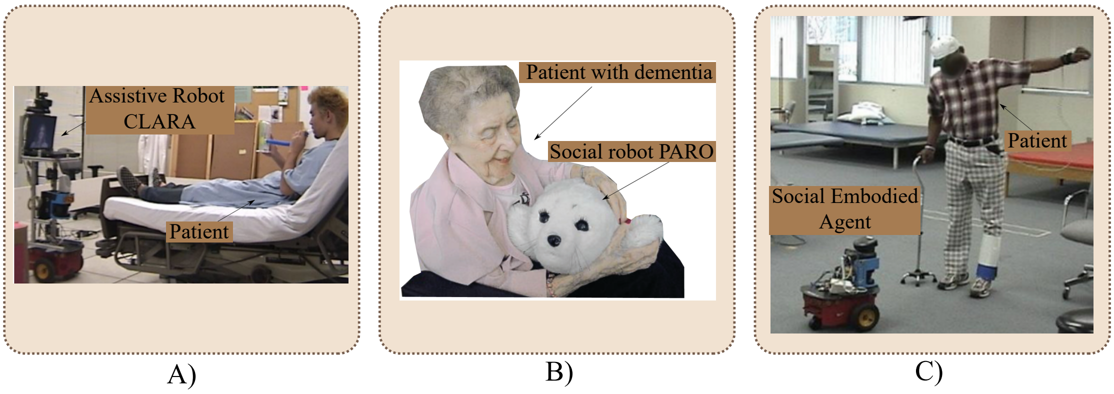


Figure 2.6: SAR in clinic Scenarios. (A) Spirometry therapy scenario assistive by social robot CLARA. Image is taken from Kang *et al.* [58]. (B) An elderly patient with dementia interacting with the social robot PARO. Image is taken from Calo *et al.* [63]. (C) Post-stroke therapy assisted by a social embodied agent. Image taken from Mataric *et al.* [64].

2.3.1 Elderly care

Elderly care is the service that provides assistance to older adults who present with disabilities or chronic issues. This service can be provided at home or geriatric centres. Among basic assistance that is provided, it is included basic medical care monitoring of vital signs, medication administering, exercise, and provision of emotional support. The main objective of this service is to provide independence and control over their illness in a familiar environment [67].

Within elderly care services, robots such as PARO see Fig. 2.6 (B) are used in therapeutic scenarios, in order to achieve social exchanges and encourage patients during exercises [63, 68]. Some studies open interesting perspectives about the use of robots as a non-pharmacological therapeutic aid, and it has been found that PARO was able to support the complexity of a clinical scenario in a flexible way allowing patient engagement and socio-relational exchanges. Also, effects such as the improvement of communication, and cognitive skills [69] and reduction of anxiety [70] in the elderly population have been observed demonstrating positive attitudes towards social robots.

2.3.2 Stroke rehabilitation

The main goal of stroke rehabilitation is addressed to help patients to relearn the skills lost after the event. This program helps improve quality of life and independence. One of the most relevant components of rehabilitation is associated with physical activities such as motor-skill exercises, mobility training, constraint-induced therapy to force the affected limbs to recover their function, and range-of-motion therapy that reduce muscle tension or spasticity [71].

This application has been widely approached by SAR. Where autonomous robots [64, 72], and embodied agents [73] have been explored to monitor and supervise post-stroke survivors during gait training and upper-limb exercises see Fig. 2.6 (C). The studies showed a positive impact on the users on their willingness to perform prescribed rehabilitation, changes in motor functioning and improvements in the average number of trials accomplished per minute.

2.4 SAR in ASD therapy

Social functions and skills are affected in children with ASD, therefore, different studies have been conducted focused not only on the population but also on treating and improving some of these skills with the use of SAR. Some of these skills that will be detailed are joint attention (JA), recognition and imitation of basic emotions, physical imitation, instructional follow-up and symbolic play.

2.4.1 Joint attention

Joint attention (JA) is the ability to share a focus of attention with someone in the midst of social interaction. JA in children with ASD can be improved through learning sessions with SAR [65], [66]. In the methodology of studies involving the treatment of JA with SAR, activities are performed through gaze focus, pointing to the target after looking at it, and verbal cues [65], [66]. Joint attention is performed in addition to musical therapies that allow teaching children with ASD, by means of the social robot, to play the xylophone by concentrating on colours and musical notes with JA [74].

In these studies, comparative analyses are carried out, such as the implementation in control groups without the use of the social robot and the robotic implementation [65], between groups of neuro-typical children and children with ASD [66], and the comparison of musical rhythmic therapies with robotic musical therapies [75]. Among the robots implemented in JA-focused therapies are the NAO robot [65] [66], [76], [75], and the CommU robot [77].

In the results of the implementation of SAR in JA, it was found that the implementation of explicit cues from the robot contributes to the development of JA in children with ASD [76]. On the other hand, the rhythmic therapies had better results in evaluating JA competencies in the long term than the robot-assisted group in musical therapies, where a decrease in the children's attention was evidenced [75].

2.4.2 Emotion recognition and imitation

Emotion recognition and imitation is a skill that is affected in children with ASD. This skill allows the subject to express emotions and to understand the emotions of others. The training of emotion recognition by using SARs is studied in several publications [66], [10], [78]. These publications show the great potential of implementing robotic agents in facial gesture recognition therapies. Mainly due to the fact that with robots, gestures can be simplified, so that they are more understandable for children and therefore, an easier recognition can be generated [78].

In some conventional therapies, images of facial expressions and moods [66] are implemented, as well as expressions simulated by robots [78], [10], in which the participants had to both identify the expressions and perform and imitate them. Additionally, studies have been conducted with physiological variables such as heart rate in emotion recognition activities [79]. Among the most commonly implemented emotions are happiness, sadness, anger, surprise, fear and neutrality, which are known as basic emotions [80]. Studies have seen evidence of improved emotion recognition ability with the NAO robot [66], as well as increased performance in the recognition activity with the use of the Probo robot and the ONO robot. In addition, the increasing display of emotional empathy was found spontaneously and unconsciously by children through nonverbal actions performed by the robot [79].

2.4.3 Imitation and instructional tracking

The skills of imitation and following instructions are also affected in children with ASD, this condition hinders normal development in a conventional educational environment [81]. For this reason, it is important to apply interaction strategies that reinforce these skills. In this sense, SARs represent a novel alternative, with which therapies are performed to encourage imitation and following instructions [82]. This is done through games pre-designed by the team of therapists and engineers and executed by the robotic agent. Several studies focused on physical imitation have been carried out [83], using different tools and objects for interaction. In these studies, JA and instructional tracking are encouraged by detecting objects and manipulating them. Activities such as imitating the jumping movement of a toy frog as a playful activity, and drinking glass by simulating the action of drinking water, as well as physical and verbal imitation in planned and evaluated tasks with therapeutic equipment, have been carried out [84]. Better results have been obtained in imitation activities in children with ASD than in children with typical development (TD), where they conclude that it could be due to the age difference between the two study groups or due to the therapies previously performed in children with ASD, in which imitation had already been treated [76]. Likewise, there has been found an evolution in the performance of physical and verbal imitation activities [83], [84]. Among the limitations found when evaluating this skill are the marked differences in performance between children in the same group, where some had great progress, while others had a constant performance in the activity after performing 5 interaction modules with the RERO robot [83].

2.4.4 Symbolic play

Different skills such as JA and recognition of instructions can be further contextualized through playful interaction strategies, which are referred to as symbolic play [85]. These strategies are intended to generate a therapy session where children understand their role in a playful activity. This activity has certain rules to be carried out but also encourages the child to take part in the activity [86].

Currently, the possibility of including robotic agents to guide the activity while the clinical staff observes the development of the activity has been studied [87,88]. An example is two studies performed with the PROBO robot, where eye contact is taken as the focus of attention to evaluating the interaction of the children with the activity and the robot. For these studies, role-playing activities were carried out, such as a doctor's game [87], and instructional recognition activities, such as the elaboration of a cooking recipe [88]. As a result, it could be evidenced that children with ASD had greater attention on the robotic agent throughout the activity, leaving aside the attention produced by other peers since it was a group activity. However, performance in the game did not improve in any case, and the variables evaluated had no significant differences. Despite this, there were differences in eye contact with the robot. Therefore, it can be concluded that there is great potential for more elaborated therapies in the long term in future applications [88].

2.4.5 ASD long-term studies with SAR

In this work, long-term studies are called those that exceed 10 sessions [89] or one month's duration [83]. This is because these studies are called long-term when they have a number of sessions that exceed those established in previous studies or a duration time in which a change can be evaluated over time, thus denominated as longer than one month. These studies have been implemented in therapeutic environments [90] and in uncontrolled environments [83], [91]. Game-based therapies have been performed to motivate children to perform therapies at home [83], [91], as well as implemented in a daycare centre for children with ASD. Daily therapies are performed with cause-and-effect games, where the robot's participation is evaluated by questionnaires to professionals (doctors, nurses, therapists). In addition, developmental scores are given for children with ASD managed in the institution [90] and paired games with the LEGO block game [92]. On the other hand, Cognitive Behavioral Therapy (CBT) protocols have also been evaluated, focusing on emotion-understanding skills and the ability to identify the correct emotion in relation to a context [89]. These therapies range from 10 to 19 sessions, one month, [91], 8 weeks [75], or up to 16 months [90]. In which the social robots that have been implemented are Kiwi [93], [91], NAO [89] [75] [92], JIBO [83], and KASPAR [90].

Within the evidence obtained, great potential is seen in therapies with participatory games [91] and following instructions in each of the assigned tasks [92]. On the other hand, there are also findings where a significant evolution over time was not found, showing that children lose interest in the robot after some time [75]. This could be attributed to the lack of dynamics of the activities proposed.

2.4.6 Mechanical characteristics of social robots

In studies conducted in therapies with CwASD, it has been possible to demonstrate different characteristics and structural needs that social agents must meet. Different reports of therapists highlight the fragility of some robotic agents, such as the NAO robot [8], in addition to their high cost. These reasons generate a bias on the part of the therapists because they focus their attention on protecting the robot from damage and diminish the attention on the therapy. In this context, one of the most notorious characteristics of therapies focused on physical interaction, such as joint attention or symbolic play, is the robot's ability to resist interaction by the children. It is known that some children with cognitive diversity may present episodes of hyperactivity and aggressive behaviours [6]. For this reason, the structure of the robotic agent must be designed to prevent damage to the structural integrity. At the same time, it must guarantee that the physical interaction with the user is not risky for the user.

On the other hand, the presence of big heads is also evident to emphasize the child's attention to facial gesticulation and nonverbal communication, encouraging the recognition of emotions. This is evident in robots such as PROBO [94] which has a trunk to increase expressiveness in some of the basic emotions. As well as the ONO robot [95], which has a large head and considerably large eyes and mouth in order to focus the user's attention on its gestural movements. Other applications also show evidence of degrees of freedom in the neck of the robots to promote eye contact and natural expressions. As well as degrees of freedom in the limbs to promote the following of instructions through symbolic play, or proprioception activities, pointing out parts of the body as in the case of the KASPAR robot [96]. In this sense, there is a marked need to develop more robust robotic platforms to meet the functional and safety needs of CwASD therapies.

2.5 Conclusions

This chapter contextualized the state of the art regarding robotic services for interaction with humans in clinical settings. It also emphasized how interventions are conventionally performed in therapies with children with autism, closing with the application of robotic agents in therapies with CwASD. This served as a first step to frame the problematic of this work, providing some needs that are evident in the literature regarding robotic agents. Also evident is the need to focus attention on the design of robotic platforms specifically for therapies with children. This is because the vast majority of studies in the literature are conducted with rigid robots, which do not meet the structural characteristics necessary for physical interaction with children. This problem could be addressed by thinking of mechanisms with flexible actuation and easily accessible materials to develop replicable, easy to manufacture and resistant devices. This in order to reach populations in developing countries, as well as research centers that want to contribute to the state of the art in SAR technologies using robotic agents already designed for specific applications.

Chapter 3

Dimensional and Appearance Design of CASTOR Robot

The CASTOR project was conceived from the need for robotic tools to be implemented in CwASD therapies in developing countries. In general, this development is based on three pillars which are the community to which the robotic platform is addressed, the mechanical functionality and design of the robot and finally, the replicability of the platform. This work describes the process of design and creation of the CASTOR robotic platform, which was built and designed based on the guidelines proposed by a PD process. This PD process was a previous work done to actively include all the stakeholders in the creation of this robot [97]. In this way, it was possible to materialize in a qualitative way concept from different points of view to reach established mechanical criteria. This chapter presents the link between the participatory design and the design criteria on which this robot was based.

3.1 Participatory design

As mentioned in the previous chapter, different robotic platforms have been designed and tested. However, the conventional therapy development and the stakeholders were rarely considered when developing a tool to accompany health professionals in their therapies. Participatory design (PD) is a vital information-gathering mechanism to carry out a design in which its success as a product lies in its acceptance and not only in its functionality [98]. To guarantee the best possible result, it is necessary to include all those involved, even more so when children are involved. For this reason, the PD is carried out with parents, caregivers, and health professionals and the perspective of the CwASDs was also considered [97]. The objective of this process was to collect basic information on the needs of the target population. To understand and answer different doubts of this population in the face of prejudices regarding the use of robotics with children, and to clarify and inform that the robot is just another tool for health professionals and not a substitute [99].

This section aims to describe the previous work carried out in the PD to contextualize the bases of this project. The PD participatory design was divided into four stages which are i) sensitization, ii) Focus group with stakeholders, iii) CwASD intervention, and iv) validation and verification.

3.1.1 Sensitization

This stage of the process was based on generating a relationship between the CASTOR project work team and the clinic through different visits to see the reality of day-to-day therapy with CwASD. On the other hand, visits were made to inform health professionals about the basic concepts and the purpose of having a SAR in support of therapies. In addition, this first stage is meant to clarify some prejudices that are held about social robotics and the ethical aspects of its use. First, a three-question survey was carried out to determine what was their idea of a robot in therapy. In the first question, the stakeholders were asked what the concept they had of a robot was and to describe how they imagined it was. The second question was based on how a robot could provide therapy assistance at its own discretion, and the last question was on how they thought the robot could benefit CwASDs. Finally, this awareness stage ended with the presentation of the CASTOR project to the stakeholders [97].

3.1.2 Focus groups with stakeholders

The focus group phase generated a more cooperative work environment between researchers and the population. The groups carried out activities which served to materialize some concepts that would later be useful to determine the design criteria of the robot. The first activity was based on a questionnaire that described basic problems such as: (i) what are the positive and negative aspects of the therapies currently carried out? (ii) what is in your concept an ideal tool for treating ASD? and (iii) what do you think about having a robot in therapy? and what positive and negative aspects could you anticipate? In the second activity, groups were formed. First, they were asked to describe what the ideal robotic intervention in therapy would be like, employing a collage that was then exposed by each participant. The third activity consisted of making a model with recyclable materials that highlighted all the concepts discussed above. Finally, a final plenary discussion established the guidelines for researchers and designers. This last activity aimed to orient the project on the four most essential pillars in treating CwASD according to Huijnen *et al.* [24]. These are (i) occupational therapy, (ii) speech and language therapy; (iii) physical therapy; and (iv) psychology.

3.1.3 Intervention with CwASD

In this PD phase, the main objective is to make the CwASDs an active part, which can also give their position regarding the image they have of a robotic partner. The information that was collected from this part of the process was instrumental in giving an idea of what the CwASD really wanted to see in a robot. For this phase, cards with images of six types of commercial robots used in studies with the ASD population were presented. Two of these robots with an anthropomorphic shape, two biomimetics and two non-biomimetics. This is done to cover various morphologies and make modifications to some parts of each robot to show which were the interesting aspects of each morphology. In this way, the aim is to notice preferences in the form of the ideal robot for CwASD.

3.1.4 Validation and verification

In this last phase, the results obtained from the activities previously carried out were evaluated, and a final questionnaire was applied and shared with the community. On the other hand, through the networks, it was also shared with different centres specialized in ASD therapies. The questionnaire consisted of nine items related to the physical characteristics of the robot, 17 items related to the physical behaviour of the robot, one item about the use of sensory elements, six open questions about the role of the robot in therapy, and nine general questions.

3.2 Design criteria

The participatory design (PD) was carried out with the aim of providing tools to researchers and providing valuable information on the needs of the target population. However, it is not a process to impose limits but to trace a path with a focus defined by the filtering of guidelines extracted from this method. In this context, a series of guidelines were obtained and distributed in four main groups i) physical requirements, ii) mechanical and manufacturing characteristics, iii) technical characteristics, and finally iv) implementation in the intervention. From these previously named items, a series of parameters to be taken into account are derived, which forged the bases of this work, see Fig. 3.1. In this way, a requirements extraction process was carried out, and a design criterion described in this section was determined.

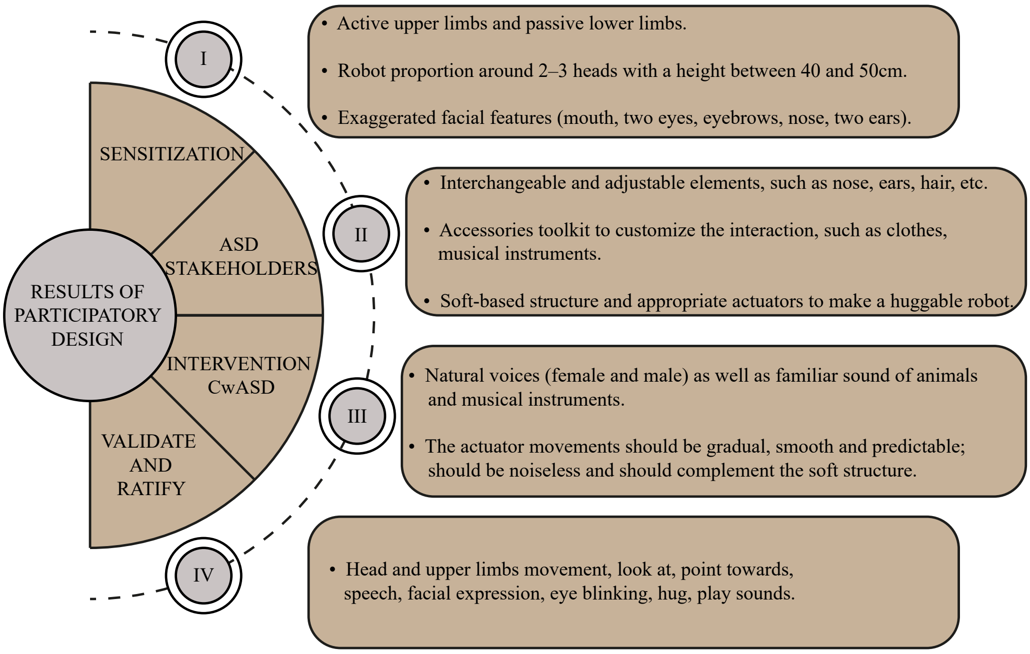


Figure 3.1: Guidelines for the robot design from the study based on the participatory design methodology.

These four groups of guidelines frame four approaches in the conceptual development of the robot. In the first group, dimensional and design characteristics were taken into account, in order to determine what the robot should have, without specifying how. The second group refers to characteristics of the how providing ideas of possible mechanisms and mechanical designs that represent a solution for the robot to comply with the functional characteristics of resistance. The third group frames the technical characteristics, such as the implementation of speakers and silent motors, to improve the user's experience with the robot. Finally, group four refers to the functional characteristics of therapy. That is to say that, already fulfilling the characteristics of the previous groups, the robot must now be able to perform tasks that satisfy the protocols carried out by the researchers. That is, the robot must have the ability to perform facial gestures, and trajectories in its arms to replicate proprioception therapies with children, among others. In this context, these four groups serve as a subdivision of the development of the robot, since each group leads to the development of a section of the project.

Different projects and products in the industry start from making a brief or a consensus that determines the design criteria of a product [22]. This design criterion is one of the most important steps for the creation of a product since it is the abstraction of a series of ideas and concepts that a client or target population has [100]. On the other hand, it collects and quantifies fundamental characteristics focused on solving a problem, whether it is a machine that fulfils a function or a product that meets a need.

3.2.1 Mechanical Functionalities

Based on the PD, first, it was determined that regardless of physical appearance, the robot must have actuation in the upper limbs such as the arms and neck. This is based on the importance of the upper limbs in contributing up to 60% of the ability to carry out non-verbal communication [101]. On the other hand, the need to include exaggerated facial features is also evident, that is eyes, nose, and mouth, with increased dimensions to increase attention in facial gestures that represent 40% of non-verbal communication. As well as the importance of having visual contact, for this reason, measures of around 50 cm are proposed to maintain the same line of sight between the robot and the child [97].

Regarding the guidelines of mechanical and manufacturing characteristics, some ideas were extracted, such as (i) easily interchangeable elements, (ii)a modular structure that is easy to assemble, (iii) and a structure that would allow additional degrees of freedom to make a huggable robot. As well as different interchangeable elements such as nose, ears, feet and other elements that make up the robot's outfit. Regarding the technical characteristics, it was considered to have audio systems that emulate a friendly but firm voice, due to the need to represent a voice of authority when carrying out therapy about following instructions [102]. Finally, one of the goals of therapies in CwASD is to improve communication skills and among these, one of the most important is the recognition of facial expressions. For this reason, the implementation of active eyes and mouth is proposed to emulate various expressions and a degree of freedom in the neck that allows direct visual contact with the patient.

Table 3.1: Design criteria grouped according to each design module (Arm, head, Huggable). And these in turn divided into the four fundamental guidelines provided by the PD

Module	Physical requirements	Mechanical and manufacturing characteristics	Technical characteristics	Implementation in the intervention
Arm	- 3 DOF for each arm - Measurements proportional to those of a child - Soft touch cover - Easy to assemble - Implementation of haptic systems for interaction	- Proximal to distal weight distribution - Flexible actuation - Sleek part design - Robust structure - Easy-to-fabricate parts (3D-PLA printing)	- Easy snap-on parts system - Easy to control actuators (Dynamixel) - Commercial materials (bearings, fasteners, printing material)	- Wide range of motion for (pointing, hugging, expressing...) - Hand that can point and interact - Easy to pre-program system to perform different choreographies.
Head	- Large proportions to attract attention - 1 DOF for moving the neck and maintaining eye contact - 5 DOF for generating facial gestures - Interactive digital eyes - Height from head to head approx. 50 cm	- Neck energy absorption system (aluminum bars) - Head design with slim parts - Robust and stable structure design to support the head weight - Mechanical mouth design with flexible materials	- Commercial bearings - Commercial electronic cards for eye control - OpsoroHAT board implementation for facial gesture control - Speaker implementation for audio generation	- Ability to generate eye contact - Ability to emulate facial gestures (basic emotions) - Ability to communicate verbally
Huggable	- Human-shaped torso - Torso deformation in the face of hugging or external interaction - User-safe hugging system	- Mechanical system that absorbs impact energy - Easy to assemble, sturdy and stable structure	- Implementation of pneumatic pistons - Ease of integration of absorption system by means of pistons	- A system that promotes safety and physical interaction. - Feels like hugging a person - Device that does not pose a risk to users

The design of the CASTOR robot was divided into three modules, which would have specific characteristics to meet the requirements mentioned above.

- **Arm module:** The first module refers to the upper extremities, in which it was determined that they should have at least 3 degrees of freedom to generate the necessary ranges of motion for pointing, proprioception activities and the ability to embrace. On the other hand, it was determined that being thin and long elements, they would be exposed to high loads, so they would require adequate motors and a mechanical system to absorb external loads. For this reason, the need to implement mechanisms that protect the structural integrity of the device becomes evident. This problem has been solved in the literature through the use of elastic mechanisms that absorb energy. Obtaining robust structures based on elastic actuators in series [103].
- **Head module:** This module is divided into two parts: i) functional aspects of the head, such as the mechanical and design characteristics of the neck joint. This joint had to be robust enough to support the weight of the head and at the same time had to have elastic systems to provide security to the structure. ii) The head contains the functional characteristics of the robot's face (facial gestures). These had to have the capacity to generate facial gesticulation to emulate emotions, maintaining a friendly and pleasant appearance.
- **Huggable module:** This module refers to the system that gives the robot the ability to hug and be hugged. Thus, the structure of the robot had to have an energy absorption system using pneumatic actuators. The objective was to emulate the behaviour of the human body by deforming its skeleton when physically interacting with a hug.

As a result of the parameter extraction, a table of design criteria was obtained, see 3.1. This table summarizes the general and specific criteria stated above. Furthermore, they are divided into these three modules, separating the criteria of each module and, in turn, each module is divided into the four groups of guidelines mentioned in chapter 2. In this way, better planning of the development of the CASTOR robot can be performed, focusing attention on the most relevant characteristics of each module and thus working in parallel, fulfiling each requirement raised and obtaining an optimal development of the project.

3.2.2 Ergonomic study

The second stage consisted of selecting the structural dimensions and determining the appropriate height of the line of sight between the robot and the user, employing an ergonomic analysis. This feature is vital because of the influence of eye contact in the child-robot interaction, which is essential in ASD therapy [104, 105] This analysis included two scenarios commonly used in ASD therapy [96, 106]. During the first scenario, a social robot was on the table in front of the child Fig. 3.2 A), whereas, in the second scenario, the robot and the child were on the floor Fig. 3.2 B). Moreover, the analysis included the anthropometric measurements of 5- and 10-year-old children (U1 and U2, respectively) who are part of the robot's potential range according to the clinic population. In Fig. 3.2, D refers to the distance between the child and the robot, H_{max} and H_{min} denote the maximum and minimum heights of the robot where the child can see all of it, and H_{ideal} represents the height where the line of sight between both the child and the robot is aligned. Concerning the impossibility of adjusting the robot dimensions for all scenarios and users, in Fig. 3.2 C) is showed that the analysis prioritized the line of sight of the older child in the second case (i.e., the robot and the child on the floor). However, to align the line of sight of U2 with the robot in the first scenario. Also, an adjustable chair would be desirable.

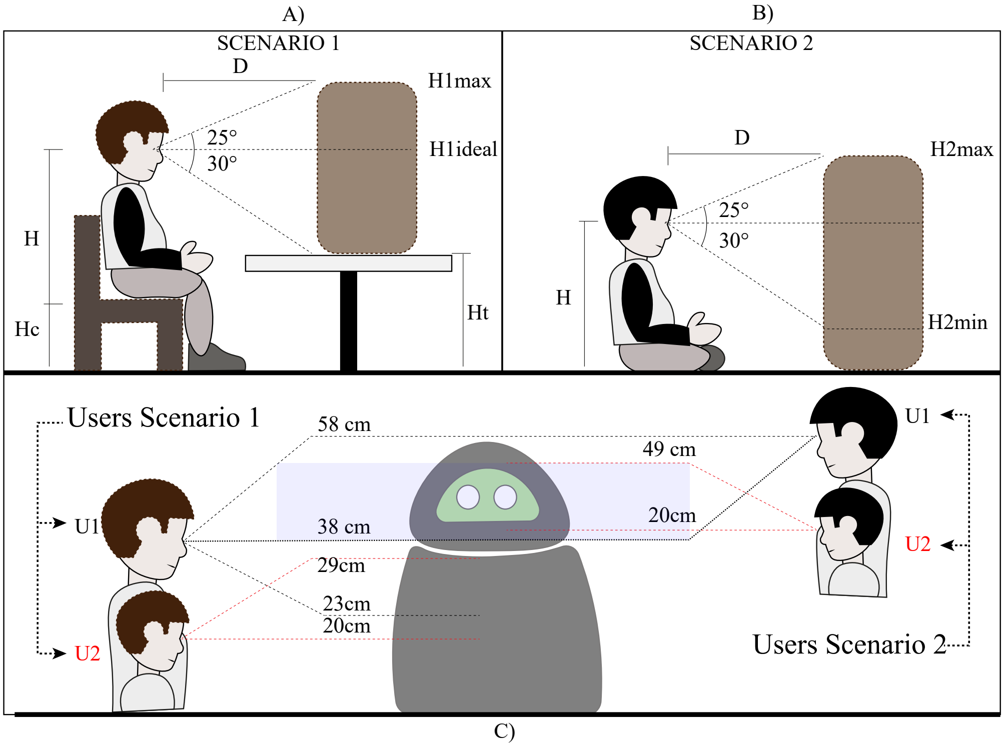


Figure 3.2: Experimental setup for the ergonomic analysis. (**A**) Sitting condition in a chair. (**B**) Sitting condition on the floor. (**C**) Children's range of vision for both scenarios, line of sight of the robot, and optimal height range of the robot. The variable U refers to the user involved in this analysis (U1: 10-year-old and U2: 5-year-old); H: distance between the sacrum and the user's line of sight; H_c: chair height; H_t: table height; $H_{1-2;max-min}$: maximum values in the visual range; $H_{n;ideal}$: child's line of sight; and D: distance between the child and the robot. The numerical values of these variables are given in Table 3.2.

Table 3.2 summarizes the range values of the robot height for both scenarios. In general terms, the optimal size of CASTOR is between 38 and 49 cm. This range integrates the minimum value of U1 in the first scenario (i.e., $H1_{min}$) and the maximum value of U2 in the second scenario (i.e., $H2_{max}$). This way, the robot can keep proper visual contact with children within the ranges included in this analysis, adjusting the chair height for smaller children, as previously mentioned. The ergonomic analysis information is relevant to the mechanical design of the CASTOR robot presented in the next chapter.

Table 3.2: Variables used and parameters estimated in the ergonomic analysis.

Variable	**Description**	**Range (cm)**
H	Height from the base to eyes	43–67
H_c	Chair height	30–40
H_t	Table height	63–76
H_{1max}	Maximum robot height Scenario 1	29–67
H_{1min}	Minimal height Scenario 1	20–38
H_{2max}	Maximum height Scenario 2	49–95
H_{2min}	Minimal height Scenario 2	38–40
D	Distance front face object	35–62

3.3 Physical appearance of CASTOR robot

This section describes the process by which the design and implementation of the physical appearance of the robot were carried out. This process was divided into two parts. The first part refers to the methodology that was used to determine what appearance would fit the needs of the CwASD. This process was carried out by means of a perception study of physical characteristics based on 2D sketches. The second part describes in a technical way the process that was carried out for the manufacture of the costumes that represent the appearances of the robot. The materials used, colours and method of manufacture and assembly, are described.

3.3.1 Appearances design process

The design of CASTOR's appearance was based on an inclusive and participatory design methodology that involved patients, therapists and caretakers, in order to make them an active part of the design of the robot's appearance. This methodology was carried out in several stages, in which different focus groups were used. Surveys were conducted to determine certain design parameters such as the size of the eyes, and mouth and the morphology that the robot should have was assessed.

Several sketches were elaborated on the obtained results, which are illustrated in Fig. 3.4a. In order to find the best appearances, two filters were performed. The first filter involved 44 persons among therapists, caregivers and parents, who voted for the sketch they considered the best. In the second filter, nine children participated in activities of adjectives association, to choose the best sketch. According to these two filters, five appearances were selected as shown in Fig. 3.4b.

For the final decision, a survey was carried out to identify the appearance that facilitated emotion recognition, facial expression portraying and gesture imitation. Likewise, physical interaction, friendliness and empathy were also assessed. These results revealed three appearances: human-like, fantastic-like and robot-like, See Figure 3.3. It is important to note, that according to this final decision the design of the mechanical structure was carried out, See Figure 3.4c). The implementation of the appearances was also done taking into account that the robot will be used in a clinical environment and that the appearances should be easily interchangeable.

Figure 3.3: Robot's appearances obtained from the participatory design process with the autism community.

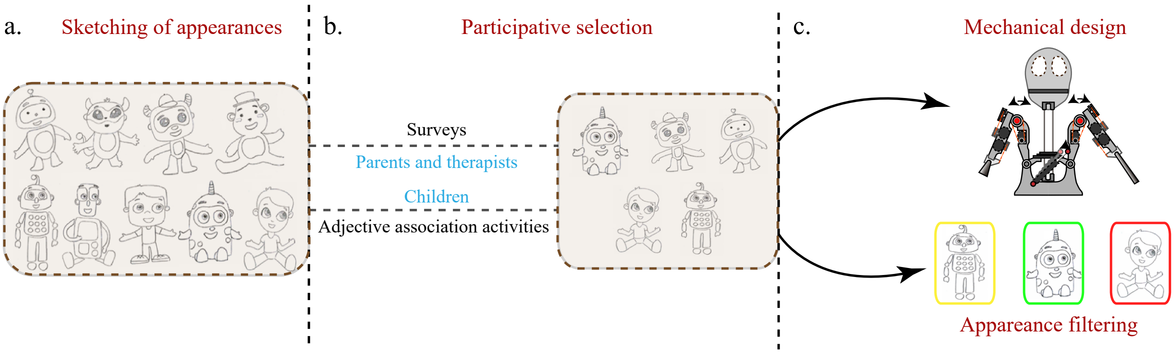


Figure 3.4: Selection process of the Robot's appearance.

3.3.2 Materials and fabrication method

Considering the results obtained from the PD and the appearance design process, a scheme was developed to show the main characteristics of the robot's attire. In this first stage, technical characteristics such as the dimensions of the mechanical structure, the space allocated for the electronics and the range of movements were taken into account. The functionality of the robot is the main feature that had to be preserved. For this reason, 3 points of high importance were determined. The first one refers to the range of motion of the arm joints. That is to say that the clothing must not obstruct the movement of the arm joints. However, this garment must cover the mechanical part in order to achieve the desired aesthetic and safety characteristics. To solve this problem, the robot's arms were covered with tube-shaped elastic lycra that functioned as sleeves covering the external part of the arm mechanisms, See Fig. 3.5 B). Being elastic and lightweight, this lycra adapts to the shape of the arms without obstructing movement and without overheating the motors.

The second focus was on the space for the electronics because of the need to protect the electronics from impacts in the head area. At the same time, it must be considered that the electronics require ventilation. For this reason, the garment must be able to cover the entire mechanical structure and at the same time allow air

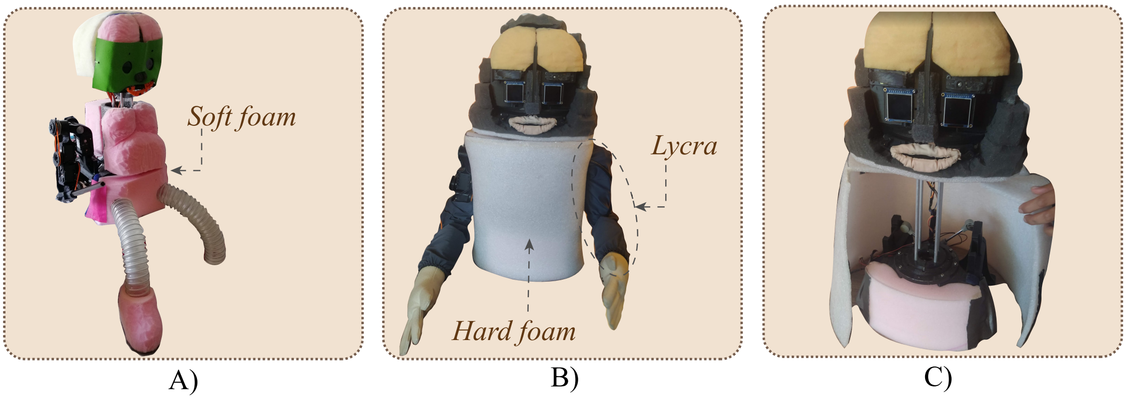


Figure 3.5: Inner parts of the robot outfit. A) inner part with soft foam for human appearance. B) inner part with hard foam for robot and fantasy appearance. C) inner part of the rigid cover to allow air circulation in the electronics compartment.

to circulate inside the electronics compartment. To achieve this, basic geometries were created to generate the necessary shape and volume. These volumes are divided into two parts: the head and the torso. These parts had variations with respect to each outfit. For the human-shaped outfit, a face was made with soft foam to give it the head shape, see Fig. 3.5 A), and for the other two (robotic shape and fantastic shape) a rounded cone geometry made of grey foam was used, see Fig. 3.5 B). This foam gave consistency to the shape without adding too much weight to the head. On the other hand, for the torso, a rigid foam body was used to shape the torso with a hollow centre to allow air to circulate inside the electronics housing. Finally, it was determined that another point of risk was the neck joint. As mentioned above, the head joint has a motor that acts from the back of the robot. The challenge at this point was to cover the device from the base to the head without obstructing the internal mechanism that allows the functioning of the SEA responsible for the movement of the head using a grey foam tube that allows separating the mechanism from the soft structure of the garment. Leaving a cylindrical space for its correct functioning, see Fig. 3.5 C).

On the other hand, it was necessary to ensure that the attire complied with the visual characteristics specified in the 2D sketches mentioned above. This process

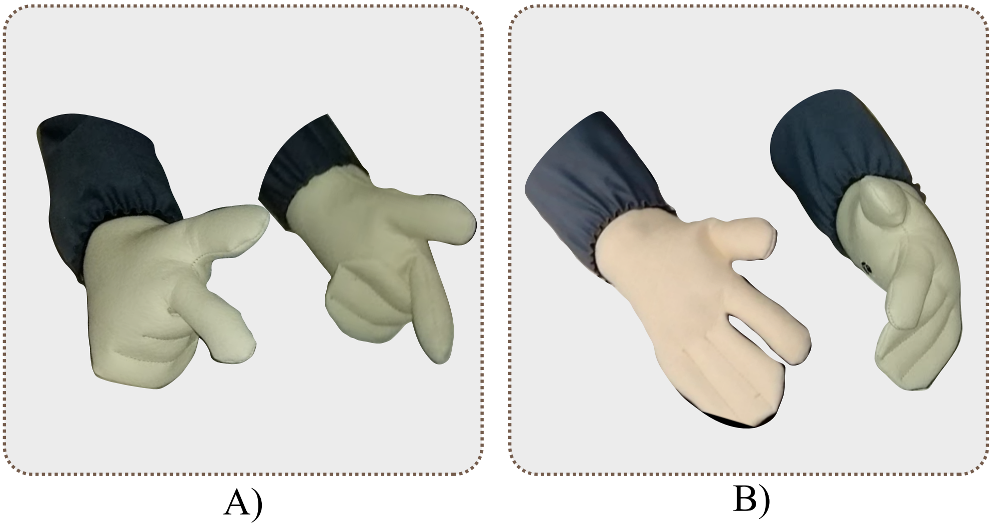


Figure 3.6: Soft hands made with synthetic leather and soft foam, with the ability to **A)** point out, **B)** or hand open.

was carried out at the facilities of the company (Tejido de sueños) which is one of the partnerships of the CASTOR project. It consisted first of the collection of possible materials to be used for each of the garments and how they were intended to be manufactured. Only for the human-shaped costume, we used a soft foam cube to represent the torso of the child-shaped robot, see Fig. 3.5 A). The rest of the materials to be used were leather of different colours and textures to suit the needs of each costume. The reasons why these materials were chosen were the ease of cutting, the variety of colours and shapes and the semi-impermeable coating that allows easy cleaning. The latter is important since the robot is intended to perform its functions in environments such as hospitals and clinics. Various textile and plastic materials were also used for the interchangeable accessories such as the legs, the child's clothing and the robot's hands. These hands were manufactured with skin-coloured leather with internal foam and functionality to saw off the fingers so that only the index finger remains extended, see Fig. 3.6. This functionality was developed with proprioception and environment identification tasks in mind, in order for the robot to have the ability to point.

3.4 Results

The dimensions of the robot represented a challenge for several reasons. Primarily, the robot had to be sized to interact with children in two of the most common scenarios (the robot sitting on a table and the robot sitting on the floor) [96, 106]. The challenge was to determine an optimal range that would work for both scenarios and at the same time have proportion between its limbs. The reference point taken to identify this range of measurement was the line of sight see Fig. 3.2. It is essential that it be aligned with the child's line of sight to encourage eye contact. On the other hand, the robot had to contain all the electronics and hardware necessary for its operation.

Taking into account the aforementioned characteristics, the standard measurements for the construction of the CASTOR robot structure were determined, which can be seen in Fig. 3.7. Where it can be seen that the measurements are in accordance with the proportions of a child, emphasizing the size of the head to focus attention on facial gestures, and thus encourage interaction in therapies.

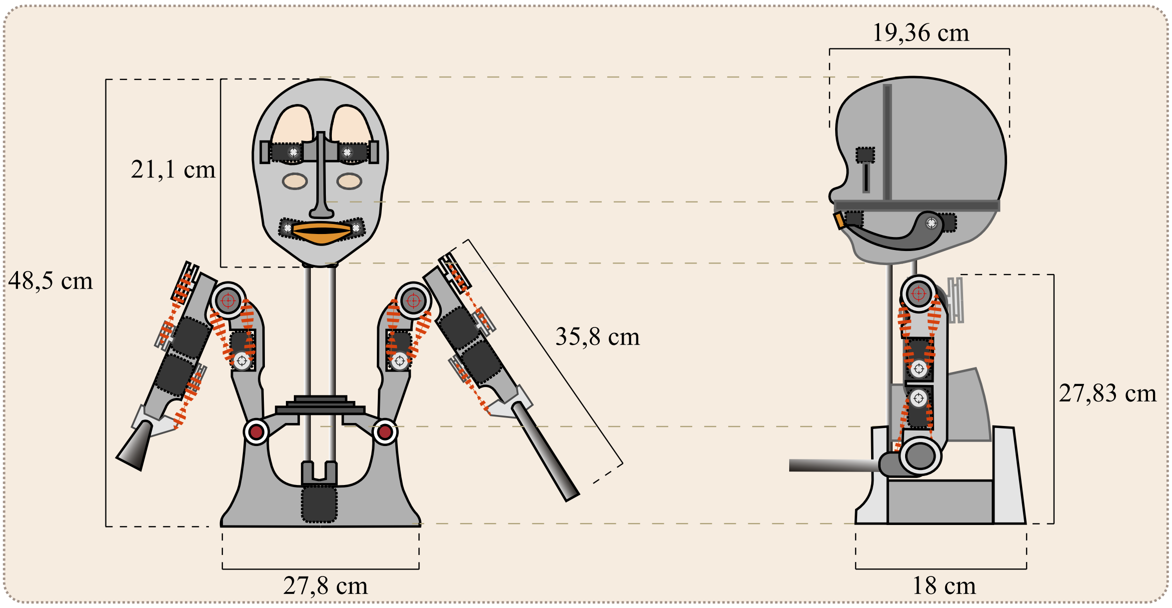


Figure 3.7: Final dimension of the CASTOR schematic design.

Finally, the results obtained from the manufacturing process of the robot's outfits will be shown. As mentioned above, the outfits were chosen and designed based on the results obtained by the PD and in collaboration with the Tejido de sueños company, see Fig. 3.8. Which is part of the CASTOR project. This section will show the purely aesthetic result of each of the outfits. This is because the validation of the outfits with children will be dealt with in the next chapter. In this context, the results are divided into three parts, one for each outfit.

Figure 3.8: Focus group session with stakeholders in a participatory design activity with the company (Tejido de sueños).

3.4.1 Fantastic like

For the materialization of this outfit, brightly coloured leather was used. In this case, the body and head were made with blue material, with some interchangeable spots to encourage some recreational processes such as the exchange of parts. A horn was also included, which was part of the 2D sketch made in the PD, see Fig. 3.9. Similarly, as shown in the 2D sketch, the feet for this outfit are two shoes that are attached with Velcro directly to the body of the robot. These were manufactured with foam to generate the shape of the foot and lined with green leather for aesthetic purposes and easy cleaning. Finally, an interchangeable red nose was added to generate greater contrast and thus attract the attention of the child.

Figure 3.9: Fantastic-like Robot

3.4.2 Human like

For the human-like robot, a pink foam base was used to emulate the robot's torso. For the face, a skin-coloured leather mask was made and a wig was made with fabric for coats, then it was combed and adjusted to the length to look like a haircut. For the outfit, specially designed clothes were made that were easy to put on and take off. Jeans pants which went over two plastic hoses that emulate the shape of the legs, with the aim of preserving the proportions of the robot. Giving him a length of legs according to the length of the arms and the head, see Fig. 3.10.

Figure 3.10: Human-like Robot

3.4.3 Robot like

Finally, we have the outfit of the robot. This one is based on a mixture of the bases of the other two outfits. That is to say that the inner part of the head and torso are the same as those of the fantastic outfit. The legs are the same plastic hoses and shoes used in the human outfit. For the outer outfit, silver-coloured leather was used to give it a metallic look. Interchangeable accessories were also added in order to provide interaction alternatives between the robot and the child figurine, see Fig. 3.11.

Figure 3.11: Robot-like Robot

Chapter 4

Technical and Functional Design of CASTOR Robot

This chapter describes the structural design and operating characteristics of each of the modules mentioned, including the design methods, fabrication and theoretical concepts of operation, as well as the electronic design and an explanation of the software that makes the robot's functionality possible.

4.1 Mechanical design

According to the design criteria, the robot had to be robust, but easy to assemble and reproduce. It also had to be transportable, which means that it had to be light. These criteria led to choosing materials that were within the reach of any team or research centre interested in replicating this robot. For this reason, 3D printing was used as the main method of manufacturing the entire robot, as it is one of the most efficient rapid prototyping methods in the industry today [107].

In order to optimize the robot development process, it was decided to divide the mechanical design into three modules, represented in Fig. 4.1. in which different mechanisms of action were proposed, which will be presented in detail below in each module.

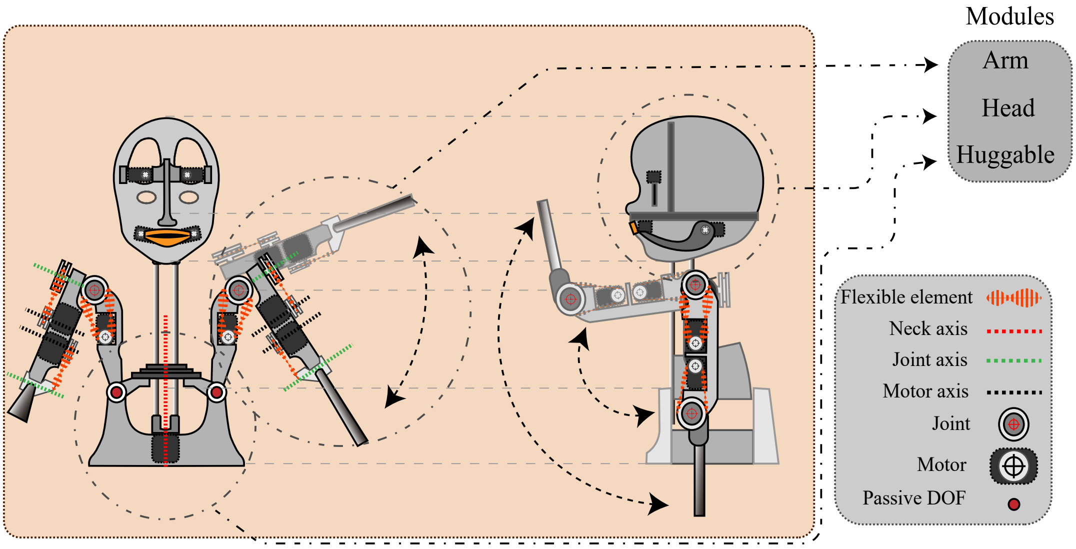


Figure 4.1: Mechanical structure and modules implemented in CASTOR. The right lower box summarizes the elements integrated into the mechanical structure. The right upper box presents the modules of the robot.

4.1.1 Head module

The CASTOR head module consists of two parts; the first is the design and operation mechanisms to perform or emulate facial emotions and gestures such as (anger, happiness, surprise and sadness) [80]. On the other hand, the second part is the neck joint that was implemented to follow eye contact and thus increase empathy between the child and the robot [8].

Structural design process

Generation of facial gestures: According to the literature, non-verbal communication is one of the most important learning skills, especially for children [101]. Furthermore, 40% of this non-verbal communication is represented by facial gestures [101]. For this reason, it was essential to include a pair of eyes and a mouth that could emulate gestures, and it would allow increased shared attention in communication, through eye contact [104].

For the development of facial gestures, a sketch of the face was made with the aim of defining a workspace to locate the different elements such as mouth, eyes and eyebrows. Two TFT (thin-film transistor) screens were implemented to represent the robot's eyes (Adafruit Animated Eyes Bonnet for Raspberry Pi, New York City, USA). These screens have three fundamental operating characteristics: (1) Control of the location of the eyes using Cartesian coordinates, (2) Control of the type, shape and colour of the eyes, and (3) Pupil size control to emulate some facial gestures. On the other hand, for the movement of the mouth and the eyebrows, mechanisms were chosen to generate gesticulation. In the case of the eyebrows, a servomotor was implemented for each of the eyebrows. These motors control the inclination of each eyebrow for the generation of gestures Fig. 4.2 A). In the case of the mouth, two basic functions were required. The first function is based on the ability to perform the gesture of happiness, sadness and neutral gesture. 3 DoF were implemented, of which two motors are responsible for moving the ends of the mouth in order to emulate the gesture of happiness and sadness. On the other hand, the second functionality is to emulate pronunciation gestures that involve opening and closing the mouth, for which an engine was implemented that performs this task in the lower part of the mouth, as shown in Fig. 4.2 B).

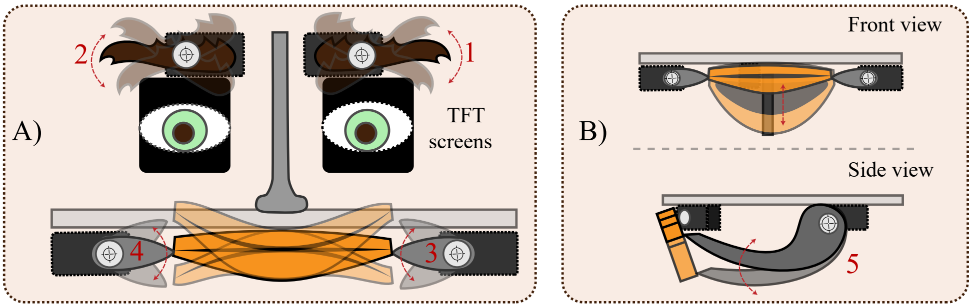


Figure 4.2: Mechanisms and actuators for the CASTOR robot's face. (**A**) elements (i.e., actuators, screens, and 3D-printed pieces) involved in the facial expressions. (**B**) illustrates in two views (i.e., front and side) the system for emulating the speech. The numbers represent the DOFs in this module.

These mechanisms are assembled in a container representing the robot's head. The structure of this head was made thinking of containing the hardware that controls the operation of the screens. In addition to providing protection to the internal elements of this system. The structure is designed in three removable parts that form a transverse structure that increases the rigidity of the assembly and allows the use of thin wall thicknesses. This structure is manufactured using the 3D printing process with PLA, a polymer that is easy to acquire and has mechanical properties that are adjusted to the needs of the design. On the other hand, it is a material that, although it is not completely flexible, does not have a high rigidity either, which makes it more resistant to impacts [108].

Neck joint: Having a joint in the neck represented a design challenge due to two fundamental factors. The first was that this joint should support the entire weight of the robot's head, which, as stated above, has various actuation mechanisms and embedded electronic systems. On the other hand, the second factor was that being such an exposed joint, it had to have the capacity to withstand external physical interactions. In other words, it had to withstand impacts and arbitrary handling by users. This fulfils one of the most important characteristics of this robot which is the ability to sustain physical interaction with users.

Thanks to the ergonomic study carried out, a range of measures was determined to generate a workspace, which delimited the maximum levels at which the design could be carried out, see table 3.2. The first step was to make a sketch locating the robot's head and torso and then make a diagram of how the structure should be distributed. The stability of the structure is a fundamental characteristic for a portable device to have physical interactions without affecting its integrity. Mechanically, this translates into having the centre of gravity of the entire structure as close as possible to the support point. For this reason, a structure that would start from the base and that in this base would contain all the elements for the robot's operation is used. Thinking of having an easy-to-program platform and having easily accessible commercial elements, it was decided to choose the Dynamixel motors (Robotis, Seoul, Korea) for the actuation of the degrees of freedom with more mechanical demands. With the motors selected to drive the neck, positioning the motor at the structure's base was considered. A structural scheme of this degree of freedom is made with the dimensions of both the workspace and the motor to be used. One of the innovative features of CASTOR in terms of its structure design is that it uses the structural casing of the motors as an active part of the robot structure itself. This means the structure needs to have the motors installed to join all its links. This makes the structure lighter and more modular; see Fig. 4.4. Once the location of the motor had been identified, the problem was how to transfer the movement of the motor to the robot's head, which would be more than 20 cm from its position. This turned out to be an advantage due to the wide space that there would be between the engine and the head position. Since it would be on the same axis of rotation as the degree of freedom, an elastic structural element that absorbs energy to protect the motor from damage is placed. Although the head-to-motor distance is considered an advantage, it is still challenging. This is because locating the head so far from the engine poses a risk to the engine's integrity. This is because these motors are designed to twist in a specific plane.

By transferring the movement so far from the said plane, loads fall on the motor shaft which can affect its operation see Fig. 4.3. To solve this problem, it was necessary to include structural support that would support the elastic element in series without obstructing the motor's rotational movement. For this reason, it was necessary to include a bearing with a diameter of 15 cm in the centre of the robot structure. This bearing is fixed on the outside of the robot structure and attached on the inside to the elastic element in series, which is exposed to the rotation of the motor to generate the degree of freedom of the neck. Fig. 4.5 shows the torque resultant T_M for each case. This resultant refers to the torque transmitted at the base of the motor in response to an external force F, where S is the support force generated by the bearing and X is the torque action distance of F. Making the T_M in the supported structure lower than the T_M in the unsupported structure.

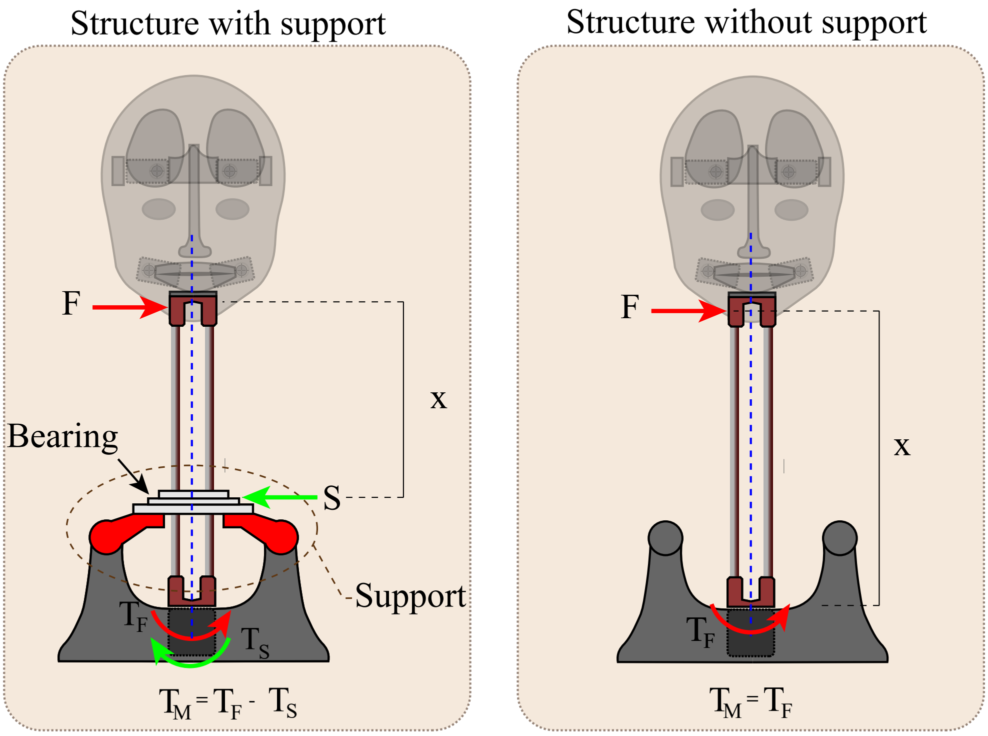
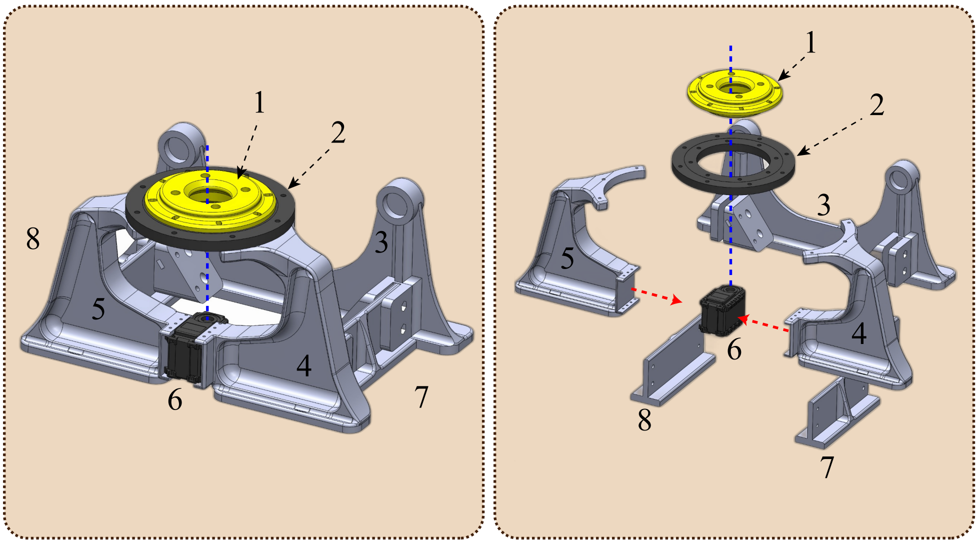


Figure 4.3: Comparison between the structure with support at the neck joint and the structure without support. Where T_M is the torque, F is the external force applied, S is the support force generated by the bearing and X is the torque action distance of F.



Isometric view Exploded isometric view

Figure 4.4: Exploded view of the structural base of the CASTOR robot and its assembly. Where the parts are listed and how the motor is an active part of the structural group. This base is composed of 6 pieces manufactured in 3D printing, which are (**1,3,4,5,7,8**); a motor piece **6** and a bearing, piece **2** that generates support to the neck joint

Actuation mechanisms

HRI physical interaction of commercial SAR is strongly restricted, due to the limited physical interaction that can be had between the robot and the user without producing damage to the robot structure. This is because the vast majority of commercial robots do not have a robust enough design for this interaction. Some robots like NAO [109], and Pepper [110] have gear-based joints. These joints, being rigid, do not allow certain activities to be carried out without running the risk of compromising the device.

Currently, various manipulators in the industry have solved this problem by means of a concept called (series elastic actuator) SEA. This concept is based on implementing an elastic element in series located between the end effector and the motor [111]. This elastic element acts and absorbs energy that would go directly to the engine, leaving it exposed. This mechanism is based on decoupling the movement from the degree of freedom and the motor, and depending on how this mechanism is resolved, the type of SEA is determined. In this section, it will be explained how the elastic element for the degree of freedom of the robot neck was designed and implemented. As mentioned before, the neck of the robot has a large space that was used to design a structural segment. This segment connects the head at the top of the robot with the motor, which is located at the bottom of the robot. This segment consists of four 6 mm diameter aluminium bars. Which are arranged around the axis of rotation of the degree of freedom. These bars are 4 cm apart and joined at their ends by two plastic structures. The upper structure is the base of the head and the lower structure is a part that is directly coupled to the motor, Fig. 4.5 A). This structural arrangement takes advantage of the bending properties of aluminium, as well as the geometry in which the bars are arranged. This means that when a torque is applied to the end of the elastic segment, the bars will bend, allowing a spiral to be generated in the structure. This allows said elongated structure to deform without affecting the axis of action that connects the axis of the motor and that of the end effector Fig. 4.5 B). The design of this piece based on aluminium bars allows its deformation, thus absorbing energy as if it were a spring. This configuration has the rigidity to move the head if the motor is engaged, yet has the ability to allow the motor not to lock up should the user apply an obstruction to the head.

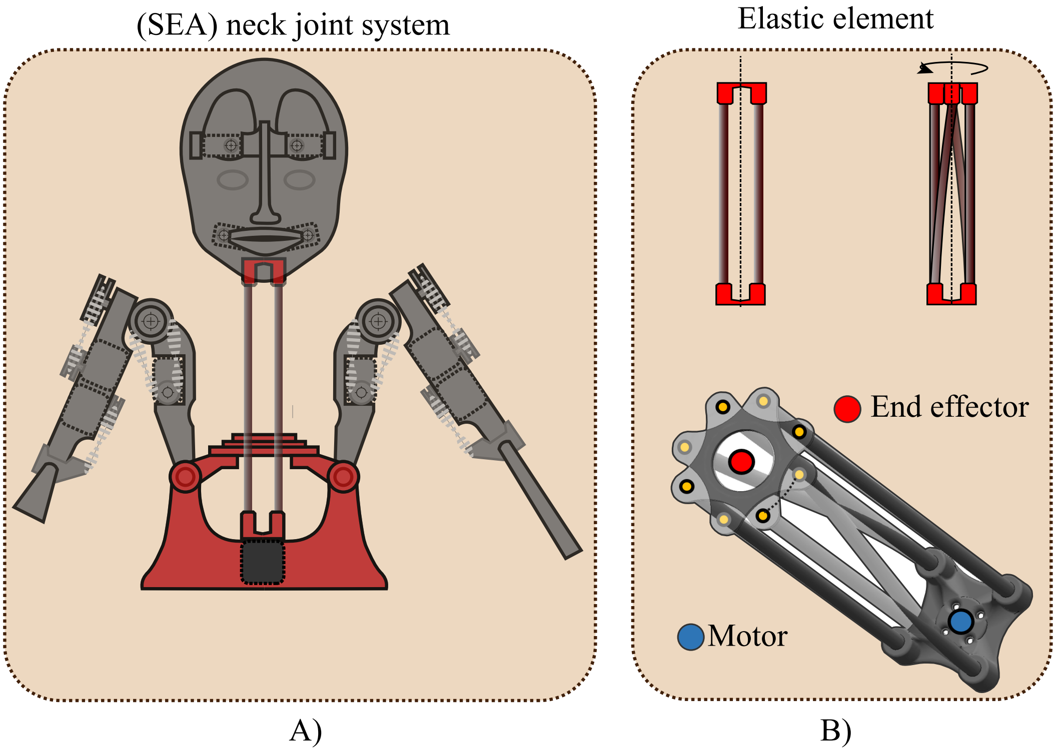


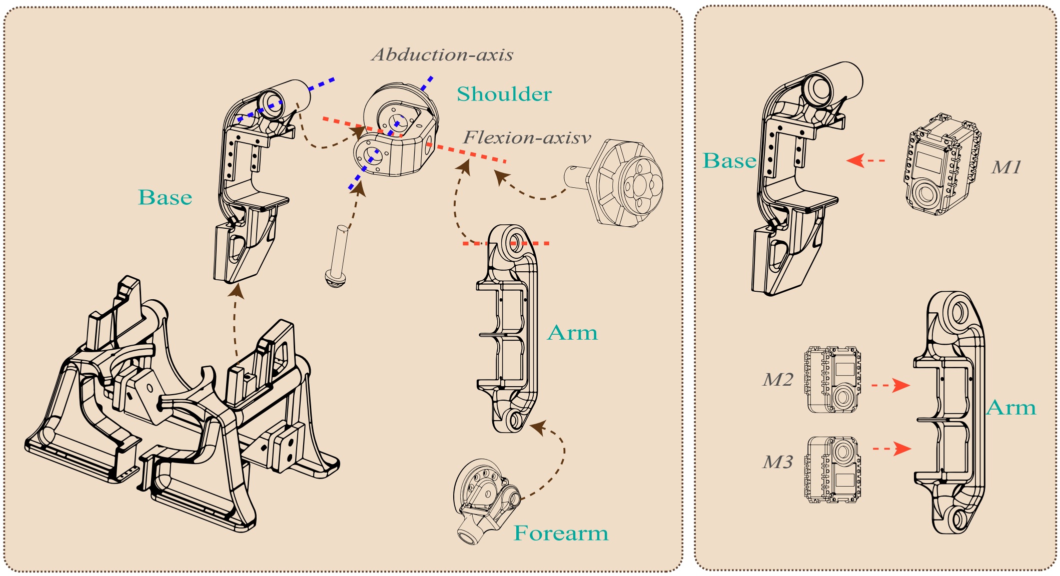
Figure 4.5: Neck mechanism based on series elastic actuators. (**A**) system attached from the motor in the robot base (black box) to the head. (**B**) the mechanism in two views and exhibits the elements involved (i.e., aluminium bars and 3D-printed pieces).

4.1.2 Arms module

As mentioned above, a high percentage of non-verbal communication is found in the upper extremities. This implies the ability to point, express emotions and generate gestures of greeting or farewell, among others. For this reason, the implementation of a pair of active arms was essential. CASTOR robotic arms consist of 3DoF per arm, which refers to elbow flexion, as well as shoulder flexion and abduction. Thanks to these three degrees of freedom, a wide range of movement were achieved in each arm.

Structural design process

One of the fundamental characteristics of the robot design is modularity, extracted from the PD process. Modularity is based on the need to have a structure that is easy to assemble, easy to replicate and easy to repair. These needs translate into a structure that allows the easy exchange of parts if required. In addition to providing an additional advantage by allowing the exchange of modules. Modularity improves the iterative design process by being able to improve the designs of each module separately if necessary.



A) B)

Figure 4.6: Exploded diagram of arm module assembly (**A**), emphasizing the actuation axes of each degree of freedom.(**B**) Location of the motors in the arm structure

The first step was to determine the workspace using a sketch Fig. 4.13. The module of each member is composed of 7 pieces see Fig. 4.6 A) that represent the base of the module, the robot’s shoulder, arm and forearm. In addition to three pieces that serve as the axis of rotation for each shoulder´s degree of freedom. The motors were located in the workspace to carry out the design of each piece where each motor would be located Fig. 4.6 B).

- The first piece was the base of the module where the N1 motor is located. This piece is built by placing three fixed aspects in the workspace: 1) The space for coupling to the base, which is based on a wedge-shaped part that fits into the base of the CASTOR robot. This wedge allows easy assembly of the entire arm module thanks to its geometry Fig. 4.7. 2) The axis of rotation for the degree of freedom of shoulder abduction, which is located thanks to the sketch made with the ergonomics study. This axis can be clearly seen in Fig. 4.6 in blue. 3) The third is the space where the motor is located, in order to leave enough space to implement the elastic mechanism that transmits the motor torque to the end effector.

- The second piece is the one that represents the shoulder. It is a U-shaped piece that is the mobile element driven by the motor M1. This piece, in turn, is attached to the axis of action of the degree of freedom of shoulder flexion. Said degree of freedom is activated by the motor M2 which is positioned in part 3 Fig. 4.6 B)

- The third piece is the one that refers to the robot arm where two motors are located. The M2 motor drives the movement of the shoulder in flexion and the M3 motor gives movement to the elbow flexion degree of freedom.

- The fourth piece is the one that refers to the forearm which is divided into three parts. The first is a printed part that transmits the movement of the M3 motor to the elbow. In addition to being the base to insert a 15 cm aluminium tube that gives the body to the forearm. The third part is a passive hand model, which is mounted on the end of the aluminium tube.

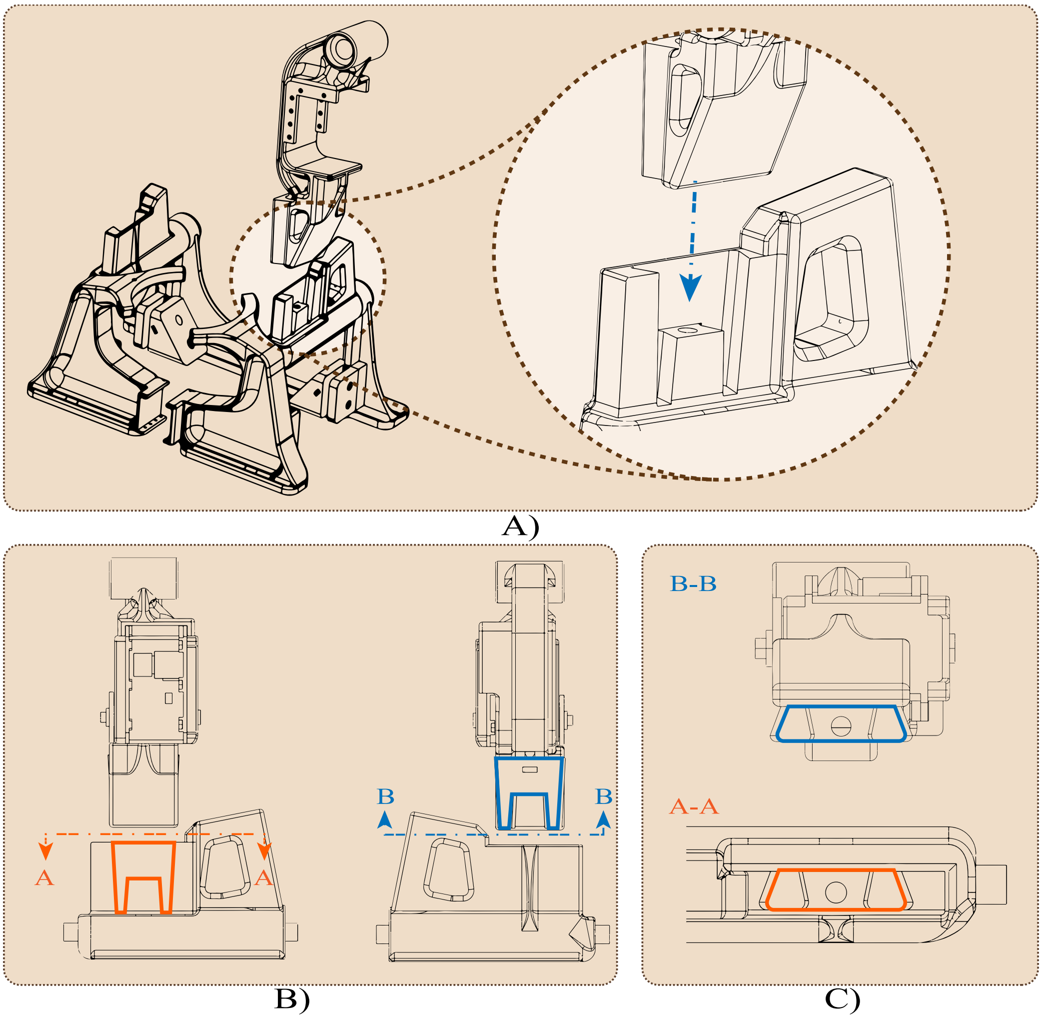
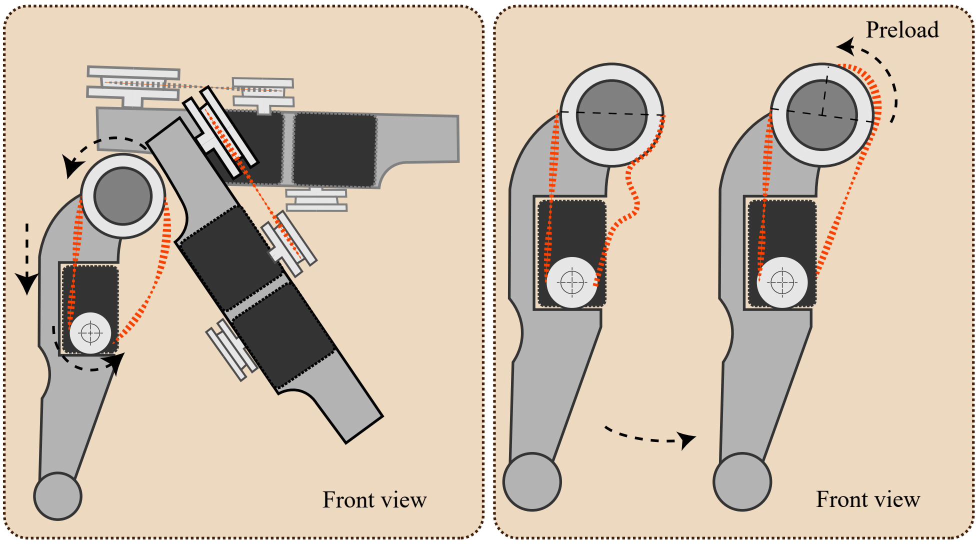


Figure 4.7: Diagram of dovetail design **A)**.**B)** shows the side views of the segments, emphasizing the trapezoidal geometry that reinforces the joint between the two pieces that interlock. **C)** shows the views of the **A-A** and **B-B** cuts representing the geometry of the top view of the socket, in the fitting pieces.

Actuation mechanisms

In the case of actuation by arm, a pulley system was implemented to transmit the movement of the motor to the final effector of each degree of freedom Fig. 4.8 A). This system is based on two fundamental elements: the first element is an elastic material that is responsible for transmitting loads. This is a TPU filament, an elastic polymer that works together with a stiff nylon filament. The joint work of these two materials acts as a tendon that allows energy to be absorbed at the beginning of the movement thanks to the elastic polymer and in the end, allows the transmission of loads thanks to the rigid filament. This composition of materials emulates the functioning of human tendons as seen in [112] . On the other hand, the second element is a pretension system for said elastic tendon and consists of two elements. The first is a disc fixed to the piece to which the load is transmitted, and the second is a mobile ring that allows the flexible filament to be pre-stressed to improve the transmission of movement. This design works by attaching one end of the tendon to the fixed disc. The tendon then loops around the engine pulley and reattaches the other end to the snap ring. This ring is concentric to the fixed disc, which allows a pretension of the composite element as seen in Fig. 4.8 B). After making the pretension, the mobile ring is blocked to transmit the loads as if it were a common pulley.



A) B)

Figure 4.8: Mechanical design of CASTOR's arm. (**A**) joint movement concerning the actuator. (**B**) adjustment process to change the system stiffness in the joint. The red lines represent the bioinspired elastic element.

4.1.3 Huggable module

One of the most relevant design features of the CASTOR robot is its ability to be hugged. This characteristic was extracted from one of the results obtained in the PD. When talking about a huggable robot, refers to the ability to maintain strong physical contact with the user. An example of a huggable item is a teddy bear, which not only encourages cuddling due to its soft stuffing [113] but also increases empathy and the desire to interact with the product. Therefore, it is thought that including this property in the structure provides greater comfort and will increase the user's empathy towards the robot. Currently, there are robots and studies that test these properties with patients, as is the case of the PARO robot [114]. In the case of the CASTOR robot, the characteristic of being huggable leads us to think of the design of a soft structure like that of a stuffed animal. But at the same time a rigid structure that supports all the structural elements mentioned above.

Therefore, the main source of inspiration was nature. A great example of a structure that allows for physical interaction and is both rigid and soft is the human body. It was observed that it made the body experience this type of interaction, like that of a strong hug. The answer is that, despite having a rigid structure made up of bones, it has the ability to deform. This deformation capacity is given thanks to multiple degrees of freedom that allow the structure to compress when experiencing a strong interaction: be it a hug, a collision with another body or even a fall [115]. This feature was specifically drawn from the degree of freedom provided by the clavicle. That allows such deformation. In the case of the CASTOR robot, a couple of additional degrees of freedom were added, which would not be actively driven. These degrees would only be activated in the aforementioned cases: a hug, an impact or a fall. This design is composed of a couple of pieces which contain the previously exposed arm modules, these pieces are mounted to the base structure of the robot by means of two bearings that allow the degree of freedom without obstructions. However, two unrestricted degrees of freedom would make the structure insufficiently rigid, which is why each of the pieces that allow the degree of freedom is restricted by a passive pneumatic piston. These 60N linear force pistons act in such a case if necessary absorbing the energy of external interactions as seen in Fig. 4.9. Giving the structure the ability to deform and return to its initial state smoothly since these pistons have a damping system and smooth action.

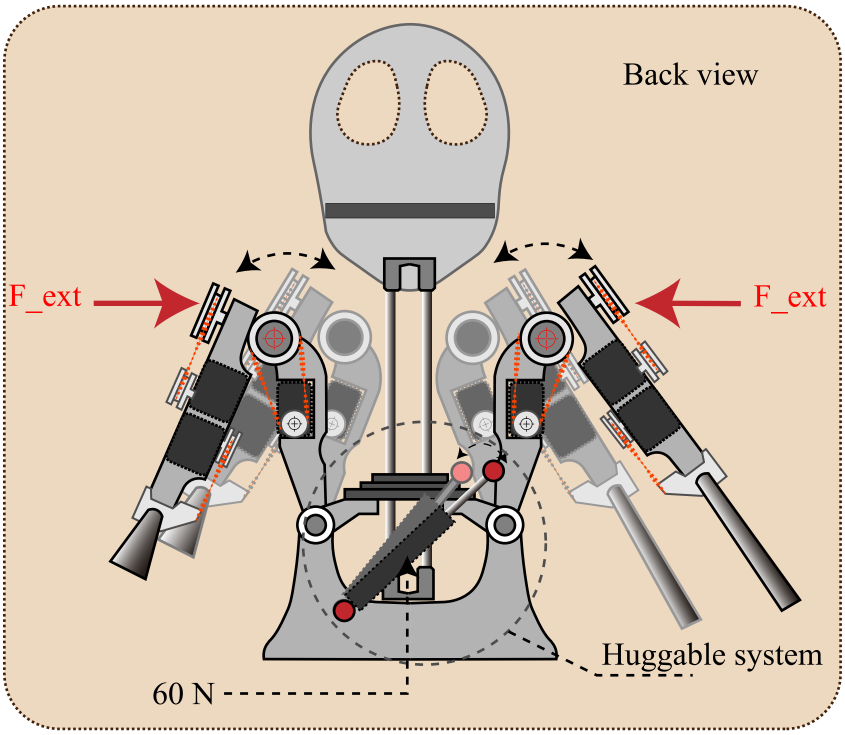


Figure 4.9: Mechanical design of the huggable structure. F_ext denotes external forces applied to the robot. The shaded drawing in the middle represents the movement performed by the system. The lower circle illustrates the pneumatic pistons for the huggable function.

4.2 Electronic architecture design

Considering CASTOR's modules, Figure 4.10 shows the electronic system and communication protocols implemented on the robot. For the hardware, the robot integrates a network of seven servomotors AX12 (Dynamixel, Seoul, Korea,) to move the arms and the neck. The actuators use a USB driver (U2D2, Dynamixel, Korea) for communication with the processing unit. In the face movements, the ROBOT has five low-cost servomotors (MG995, TowerPro, Taiwan) controlled by an OpsoroHAT board (OPSORO, Kortrijk, Belgium). This board also controls the speaker (Extra-bass, Sony, Japan) and the touch sensors (Velostat, Adafruit, USA) of the perception module. Moreover, an EyesBonet board (Adafruit, USA) connected to the main computer controls the eyes' aspect and functionality. In the processing context, the robot incorporates two Raspberry Pi 3 (i.e., the first board for the head and perception modules and the second for the arm module) running the Robot Operating System (ROS) under a Unix-based distribution. In terms of consumption, the robot requires a power supply of 12 V to 9.5 A in normal conditions (i.e., without blocking states).

For the software, the device uses IVONA Text To Speech for the perception module's robot voice. Moreover, CASTOR has a web interface to configure and control the different modalities and applications using any smart device. From the modularity and replicability aimed at in this project, the software (i.e., controllers, sensor acquisition modules, and the functionalities of the device) are ROS packages available in a public repository at `https://github.com/CastorProject/CASTOR_Robot/wiki`.

4.2.1 CASTOR robot functionalities

This section describes the functionality of the robot. Possible thanks to the joint design of the mechanics of each device and the design of the electronics mentioned above. This functionality is divided into two main groups. The first one refers to the functionality of the movements performed by the mouth and eyes, focused on the generation of facial expressions. On the other hand, the second group represents the functionality of the extremities, such as the arms and neck. These

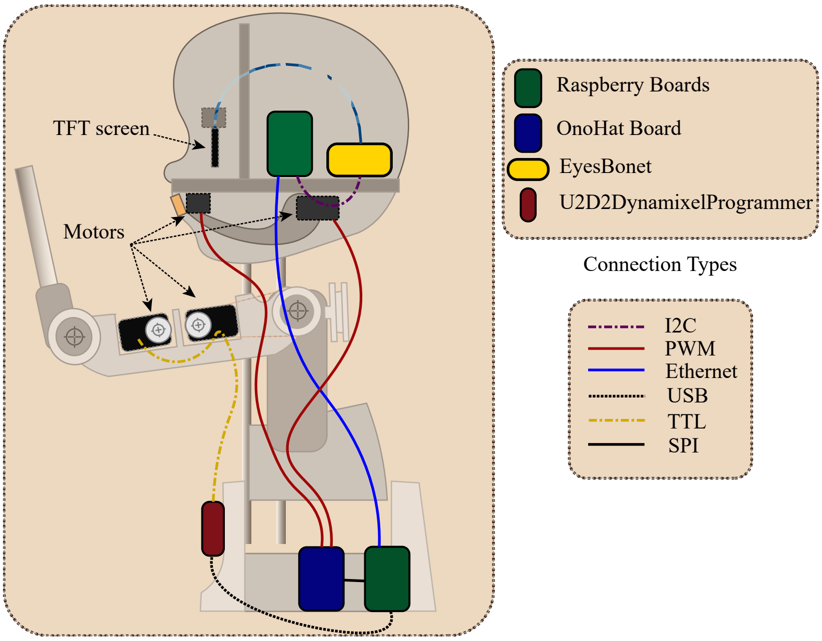


Figure 4.10: Electronic system, connections, and communication protocols of CASTOR. The right boxes summarize the elements (top) and connection types (bottom) of the robot.

systems are mainly focused on the realization of physical interaction with the user and encourage proprioception through physical activity.

4.2.2 Emotions and visual contact

As mentioned in the previous section, the actuators of the head (i.e., 2 DOFs for eyebrows and 3 DOFs for the mouth) and the screens can generate facial expressions such as surprise, happiness, sadness, and anger see Fig. 4.11. The integrated screens have three main characteristics: (1) control the eye movements using the Cartesian axes, (2) change the iris and eyelid colour through a design editor, and (3) modify the pupil size between contracted and dilated. For the face movements, CASTOR uses an OpsoroHAT board to establish the appropriate range of motion (ROM) of each motor to represent a specific emotion. Thus, the CASTOR robot has the necessary gestures for emotion recognition methods in therapy sessions [116].

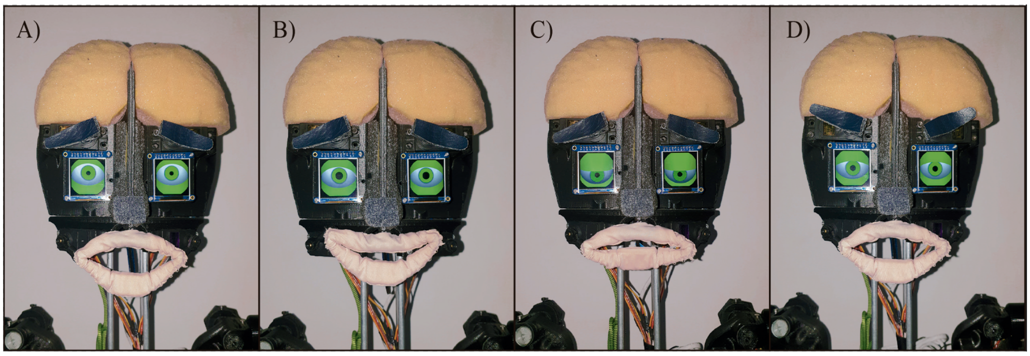


Figure 4.11: Emotions performed by CASTOR's face: (**A**) surprise, (**B**) happiness, (**C**) sadness, and (**D**) anger.

4.2.3 Cognitive interaction

Likewise, the arm and neck actuators allow movements such as waving/farewell, high-five, pointing to parts of the body, pointing to an object/place, and even dancing see Fig. 4.12. To this end, the CASTOR robot implements position controllers for each servomotor with characteristics such as initial position, actuation range, and movement speed. Moreover, the inclusion of a speaker gives the possibility to tell stories or play sounds. This way, the CASTOR robot can combine movements and sounds, for instance saying "hello" while performing a greeting or playing a song while the robot dances. Furthermore, the OPSORO board also allows the integrating of 12 tactile sensors, establishing the activation threshold of the sensor, and executing the facial movements or sounds associated with the interaction. Hence, the inclusion of these functionalities provides the robot with the capacity to respond to the child's stimulus. Therefore, CASTOR has the potential to be included in different therapy techniques such as imitation, proprioception, physical interaction, or following instructions.

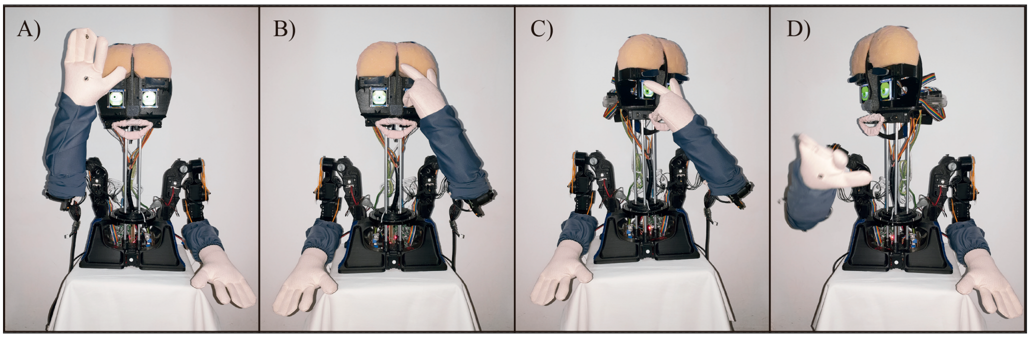


Figure 4.12: CASTOR robot functionalities for potential use in therapy scenarios. (**A**) greeting. (**B**) robot pointing to the head. In (**C**) robot points to the eyes, and (**D**) robot dancing.

4.2.4 Physical interaction system

Perception improves the interaction between the robot and the child [96], playing an important role in social development [117]. This way, different robotic platforms such as KASPAR, NAO, or Probo have integrated interactive modules composed of touch sensors, push bottoms, and touch screens to identify such haptic interactions. Several studies showed the relationship between the device's response to the stimulus of the child and the advancement in their spontaneous interaction [96]. Likewise, this capacity evidenced encouragement, motivation, and adherence to posterior sessions [96].

Therefore, CASTOR incorporates a system based on touch sensors made of Velostat (Adafruit, New York, NY, USA) to detect the interaction (see Figure 4.13). The sensors were placed in zones with a higher probability of physical contact (i.e., the antenna, head, hands, and shoes). Thus, this system identifies when the child has direct contact with the device, and hence, it responds with a programmed behaviour (e.g., movements or sounds). In this context, the robot uses a speaker to communicate verbally with the child, integrating text-speech software. Moreover, according to the circumstances and the therapy goal, the voice parameters (i.e., genre, type, or tone) can be modified.

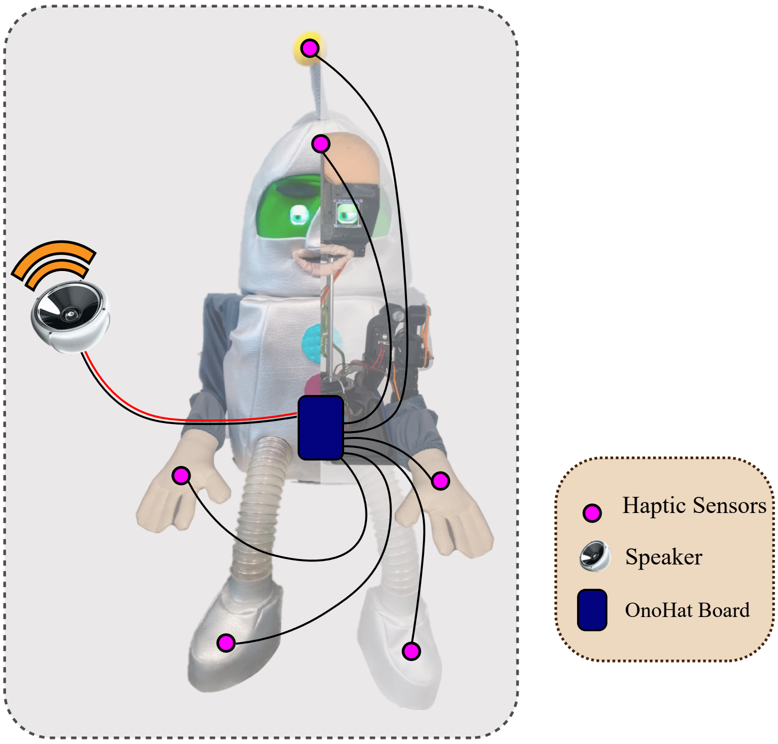


Figure 4.13: Sensors and the actuator involved in the perception module. The highlighted points represent the haptic sensors, located on the antenna, head, hands, and shoes. The other elements refer to the board and speaker placed on the lower part of the robot.

4.3 Mechanical test

In CASTOR's mechanical design, the mechanical test aims to show the device's capability to resist physical interaction. This test is presented in a published article [118]. This work assesses the most fragile parts (i.e., neck and arms) of the CASTOR robot. Specifically, the neck actuator has a high susceptibility to mechanical blocking, which is related to the child's reaction and curiosity during the therapy. Likewise, the arm actuators can suffer excessive forces because of both the inertia of the segments and external forces in an interaction scenario.

For the experimental procedure, a mechanical structure blocked the servomotors of the neck and the arm. The actuators received a signal of goal position commands, where the amplitude increased in each repetition. The maximum value of the set-point was the ROM of each joint (i.e., 180 degrees for the head rotation and 105 degrees for the arm flexo-extension). The speed of the actuators, during the trial, was configured as the maximum value (i.e., 55 rpm).

The servomotors attempted to execute the positions in stiff and flexible configurations. For that, in the neck, the 3D-printed piece's adjustment, coupled with the bar mechanism, allowed for modifying the stiffness level. In the arm actuators, the stretching of the elastic element achieved both configurations. The device's load response was acquired using the rosbag package on an external computer (Pavilion Intel i5, HP, Palo Alto, CA, USA). The data extraction and processing were performed in MATLAB (R2018b. MathWorks, Natick, MA, USA).

4.4 Results

This section presents the functional results of the robot, which can be classified into three parts: i) Robot motion ranges, ii) Facial expressions of the robot and iii) Physical interaction.

In the robot motion ranges, according to the information collected from the PD and the design criteria, the ability to move the upper extremities to encourage proprioception in therapy was one of the needs that the robot had to fulfil. The design process of the CASTOR robot resulted in a robot with arms of 3 DOF each one. This allows the generation of trajectories to perform basic sign interaction tasks (e.g., pointing to body parts, pointing to a target to perform an instruction, encouraging gestural interaction by shaking hands ...). see Fig. 4.12. This represents a favourable tool for the elaboration of experimental protocols focused on improving proprioception and instruction recognition skills. In addition to having an audio system that accompanies the instruction. Another focus of the functional features of the robot is the ability to emulate facial expressions. This need was successfully met by a combined system. It has a digital system in the eyes to emulate greater expressiveness and a mechanical system to increase the visual interaction with the child. This system makes it possible to emulate various facial expressions (e.g., happy, angry, surprised, sad). This represents an advantage for therapists and researchers because it is a versatile tool that can be used to interact with children and thus encourage them to improve their emotion recognition skills. At the same time increasing their eye contact in therapy. Finally, one of the most important features that represented the biggest challenge in terms of design and development was to give the robot the ability to physically interact with the user without affecting the integrity of both the robot and the user. This was achieved thanks to the implementation of SEA. These were able to absorb the energy of the external loads generated by the users. Throughout the development of the robot, mechanical tests were carried out in order to demonstrate the behaviour of a joint with SEA and a joint without the implementation of elastic elements. In other words, the joint is directly anchored to the actuator axis. In this mechanical test, see Fig. 4.14 shows the actuators' load response in terms of the percentage of the maximum set-point value. This value was normalized according to the ROM of each joint. The red lines represent the flexible configuration in the two joints in the graph, and the black colour denotes the load response for the stiff condition.

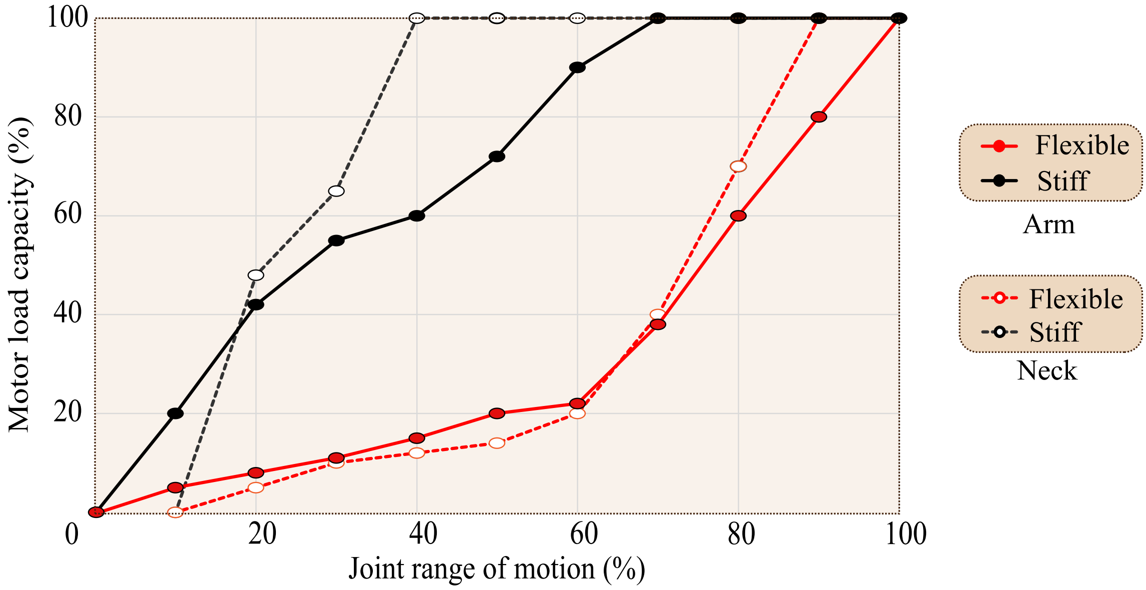


Figure 4.14: Motor load capacity for the neck and the arms in the blocking state. The X-axis represents the percentage of the total ROM of the element (i.e., 180 degrees for the neck and 105 degrees for the arm). The black lines represent the stiff condition of the neck (white point and segmented line) and arm (black point and continuous line). The red lines refer to the flexible condition for both parts in the same convention.

For both joints, the stiff configuration reached 50% of the load capacity in 30% of the ROM value. However, the flexible configuration reached this value up to 70% of the ROM. Moreover, the actuators exhibited a saturation state in all tests. Nevertheless, the stiff trials also evidenced an overload event (i.e., close to the stall torque), which led to the actuator's automatic switch-off. In contrast, the actuator for the flexible configuration remained moving despite the saturation state.

In structural terms, CASTOR did not evidence any damages in the 3D-printed pieces, elastic elements, bar mechanism, or actuators during the trials. Likewise, CASTOR kept the initial configuration (i.e., stress level) on the joints assessed despite the blocking condition conducted in this experiment.

Chapter 5

Qualitative Study: Effect of the Robot Appearance

One of the objectives of this work is to demonstrate the advantages and potential of the implementation of robotic agents in therapies for neuro-atypical populations. For this reason, a study with patients was designed to show the impact of the appearance of the robot in emotion recognition therapies. This chapter shows in detail the methodology and the process followed to develop this protocol in a clinical setting. However, this study is not only intended to determine the importance of the robotic agent's outfit, but also to draw further conclusions regarding the functional performance of the CASTOR robot in prolonged therapies. Thus, this study gives a glimpse of new phases of the project, always aiming at the development of long-term studies to maximize the expected results.

5.1 Methodology

This section describes the experimental protocol that was designed to address the proposed objectives. The validation study was also conducted at the clinic, where the social robot was deployed with three different appearances. For this, three groups were defined to evaluate each of the appearances separately: *Fantastic group*, *Robot Group* and *Human group* (Fig.5.1). The following sections describe the ethics statement, the participants that were allowed to participate in the study, the experimental design, and the experimental procedure.

Figure 5.1: Robot's appearances obtained from the participatory design process with the autism community at the Clinic.

5.1.1 Participants

A total of 21 children diagnosed with ASD were enrolled in this study, forming three different groups each one of seven participants: a fantastic group (F, one female, six males, 8.57 ± 3.01 years old); a robot group (R, two females, five males, 7.28 ± 2.81 years old); and a human group (H, two females, five males, 7.83 ± 1.95 years old). All children were randomly recruited at the clinic. The participants were selected according to the inclusion and exclusion criteria described below:

Inclusion Criteria: Children with ASD, between 5 to 10 years old. Children who obtained consent were informed by their legal representative.

Exclusion Criteria: Children that exhibited any visual, auditive, or cognitive impairment that impeded the correct understanding of the activity were excluded. Additionally, children who present with any co-morbidities such as Fragile X Syndrome or Down Syndrome were not able to participate in the study.

All participants were free to abandon the study whenever they decided to do it. The children did not know the other experimental conditions (i.e., the children of the fantastic group did not know the different appearances of the social robot and had no contact with them).

5.1.2 Experimental procedure

This study was based on emotion imitation and recognition tasks to assess the ability of the robot to facilitate emotion learning in children. A controlled phase (i.e., without the robot) and an intervention phase (i.e., with the robot) was performed for each robot's appearance to identify the effects of the robot and its appearance during the tasks. In both for control and intervention phases, the children only had three attempts to perform each activity (i.e., imitation and recognition). If the children succeeded in the task on the first attempt, they received three points. If the children required more than one attempt, one unit score decreased until all three attempts were completed. Otherwise, no points were summed up to their score. It is essential to highlight three aspects: (i) the children did not know about the scoring system; (ii) no child had seen the robot before; and (iii) the robot´s appearance did not change within the same group.

In the control phase, the sessions were conducted only with the therapist. First, the children were instructed to identify four basic emotions (i.e., happiness, sadness, anger, and fear) using four cards (See Figure 5.2). Then, the children were asked to imitate the emotions shown on the cards.

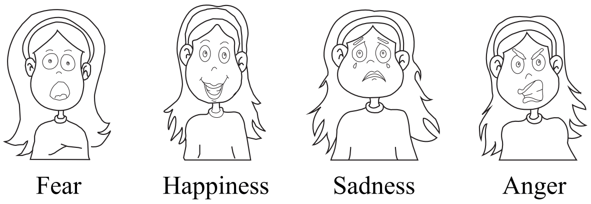


Figure 5.2: Basic emotion cards used in the first phase of the study. A therapist asked the participants to identify the emotions displayed in the cards.

The intervention phase was divided into two activities: familiarization and intervention. The familiarization phase was carried out considering that children with ASD might have difficulty accepting changes to their environment and their daily routine [119]. Therefore, this phase allowed us to introduce and socialize the robot with the children, and thus integration it into their environment. The children were able to freely explore the robot aiming to provide safety and confidence to the children. At this stage, the robot asked the children their names to establish a relationship between them.

Afterwards, the intervention was executed. In this phase, the social robot accompanied the therapist in the tasks. The cards were no longer required. The robot began to perform the four basic emotions previously mentioned See Fig. 5.3 and the therapist asked the children to identify them. Once the four emotions were completed, the robot started to perform one of the four emotions again. At this point, the therapist asked the children to imitate the emotion being carried out by the robot.

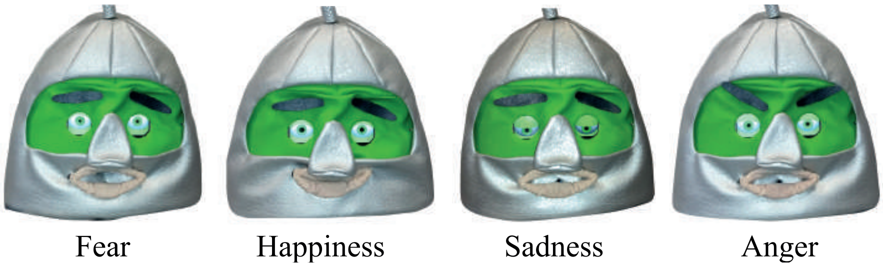


Figure 5.3: Robot's facial emotional expressions. The robot was introduced during the third phase, where a therapist asked the children to identify and imitate the robot's gestures/emotions.

5.1.3 Experimental setup

The study took place at the Clinic in an adapted room. The room had two divisions, an experimental area and a remote control area. The standard layout can be seen in Fig. 5.4. The cameras used to record the sessions had wide-angled lenses to ensure that the child was always in the field of view. During the experiments, the facial expressions, the eye gaze, and the children's movements were captured. In the hidden control room, the researchers controlled the robot's movements through a chatbot interface designed with the telegram bot API.

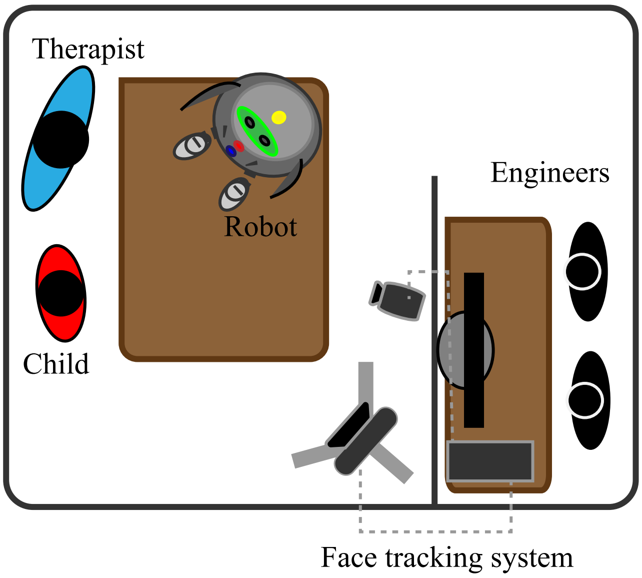


Figure 5.4: Experimental environment at the rehabilitation centre. A face-tracking system allowed the quantification of children's behaviours. A group of engineers remotely controlled the robot from a hidden area.

During control sessions, the robot was hidden, and the raw emotion cards were placed on the table. For the familiarization and intervention phases, the robot was placed on the table.

5.1.4 Variables

The experimental protocol contemplates the quantitative measurements related to the variables that can be recorded and stored with the information provided by the therapist and the system. This information indicates the performance of the child in the session.

Variables measured by the face-tracking system: Two metrics were obtained from this system. (1) *Visual contact* measures the time during which the patient makes eye contact with the therapist. (2) *Device Attention* measures the time during the session in which the patient looked at the robotic device. These measures will be presented as a percentage of attention $\%_{Att}$. That is, the percentage of eye contact is given as the ratio between the total time the child maintains eye contact with the therapist T_A, and the duration of the therapy T_T see equation (5.1). Likewise with the attention on the robot.

$$T_A/T_T * 100 = \%_{Att} \tag{5.1}$$

Variables recorded by the therapist: The therapist recorded the score obtained in the identification and imitation of emotions with the cards or the robot.

5.1.5 Statistical analysis

The software package SPSS (IBM-SPSS Inc., Armonk, NY, USA) was used for the statistical analysis. Considering the small sample size, non-parametric statistics (i.e., Kruskal Wallis test and Wilcoxon signed-rank test) were carried out to analyze the effects of the appearance in the performance and attention between control and intervention phases. In the same way, the Friedman test and the Conover Post-Hoc test were performed to determine the existence of significant differences among the emotions. The significance level was set to 0.05.

5.1.6 Ethics statement

The academic institution's ethics committee approved the protocol. The children's parents were informed about the scope and purpose of the experiment, and written consent was obtained from each of them before the study. The children's counsellor was consulted and informed about the activities to be performed and gave suggestions for the improvement of the protocol.

5.2 Results and discussion

This section describes the results obtained during the validation study with 21 children with ASD.

5.2.1 Emotions recognition and imitation

The performance score for both identification and imitation tasks in the control and intervention phases is presented in Table 5.1. These scores were estimated by computing the sum of the different scores obtained throughout the proposed activities for each assessed emotion.

The Kruskal Wallis test results showed that there were no statistically significant differences ($p > 0.05$) between groups (i.e., robot, fantastic and human). In this context, the three groups were considered homogeneous and it was concluded that the robot´s appearance did not influence the children's performance. One of the

Identification					
Groups		**Happiness**	**Sadness**	**Anger**	**Fear**
C	Fantastic	3.00 ± 0.00	2.50 ± 1.22	3.00 ± 0.00	2.20 ± 0.85
	Robot	2.57 ± 0.78	2.71 ± 0.75	3.00 ± 0.00	2.57 ± 0.78
	Human	2.71 ± 0.48	3.00 ± 0.00	2.28 ± 1.25	1.43 ± 1.27
I	Fantastic	3.00 ± 0.00	2.33 ± 1.21	2.00 ± 1.51	1.66 ± 1.51
	Robot	2.71 ± 0.75	2.71 ± 0.48	2.14 ± 1.21	2.14 ± 1.46
	Human	2.57 ± 1.13	2.57 ± 1.13	2.14 ± 1.46	1.85 ± 1.46
	Average	2.76 ± 0.53	2.59 ± 0.93	2.07 ± 1.27	2.11 ± 1.31

(a) Identification task in control and intervention phases for the three groups.

Imitation					
Groups		**Happiness**	**Sadness**	**Anger**	**Fear**
C	Fantastic	3.00 ± 0.00	2.33 ± 1.21	2.83 ± 0.41	3.00 ± 0.00
	Robot	2.71 ± 0.75	2.57 ± 1.13	2.71 ± 0.75	2.14 ± 1.35
	Human	2.71 ± 0.75	2.14 ± 1.46	2.71 ± 0.75	2.57 ± 1.13
I	Fantastic	2.14 ± 1.46	2.00 ± 1.54	2.00 ± 1.54	1.85 ± 1.60
	Robot	2.42 ± 0.75	2.42 ± 0.58	1.71 ± 1.60	2.57 ± 1.13
	Human	2.42 ± 1.13	2.14 ± 1.46	2.85 ± 0.38	1.28 ± 1.46
	Average	2.57 ± 0.94	2.23 ± 1.24	1.97 ± 1.42	2.54 ± 0.96

(b) Imitation task in control and intervention phases for the three groups.

Table 5.1: Performance scores (mean ± std) of children under emotion identification and imitation task. (C) Control, (I) Intervention.

reasons why a protocol was developed to validate the importance of the robot's appearance in therapy with children was the discrepancy of opinions between the healthcare staff and the children's tastes. Discrepancy questioned that a robot that did not have a human form would not correctly represent the emotions and the interaction with children would not be adequate. However, the results obtained disproved these isolated opinions and showed that appearance does not have a significant impact on children's perception of emotions.

Regarding the children's performance between the two activities, no statistically significant differences ($p > 0.05$) were found between the control and intervention phases. This means that the children's performance is not changed or improved by the robot. These results are consistent with the study by Yun et al. [13], which reported that facial emotion recognition was not significantly different between

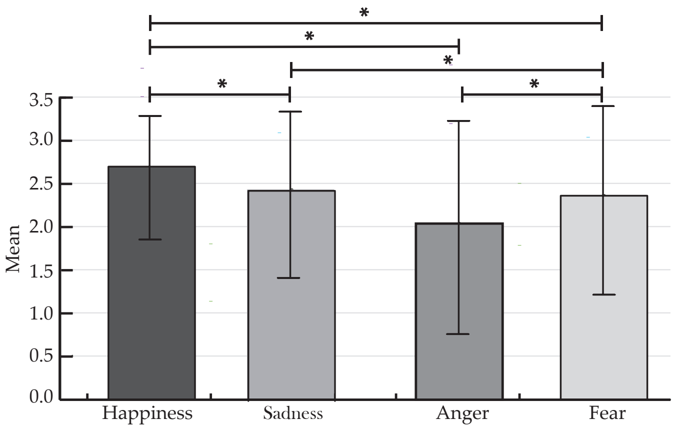


Figure 5.5: Comparison of participants' average score during imitation and identification of emotional gestures on the social robot. Asterisk (*) indicates significant differences between emotions ($p < 0.05$).

the robot group and the control group. On the other hand, the study by So et al. [120] reported that it is not clear whether the robot was better than humans (e.g., peers or therapeutics) at administering the assessments and training gestures with children with ASD. Moreover, although there are no significant differences in performance, the study by Zorcec et al. [121] reported that after eight sessions, parents stated that recognition and appropriate reaction to happy and sad emotions was used in everyday life. With the above, it is possible to state that the social robot can be a therapy aid and help as an assistive tool in traditional methods.

Participants displayed difficulty identifying and generalizing certain emotional expressions. Statistically significant differences were found between emotions, as illustrated in Fig. 5.5. In general, happiness and sadness were correctly labelled and matched most consistently. Although anger and fear were frequently labelled correctly, participants often confused anger expression with fear and sadness. Consequently, no statistically significant differences ($p > 0.05$) in the Post-Hoc test were found between sadness and anger. These findings are consistent with similar studies exploring the facial expressions of social robots [122–124]. These studies reported that complex emotions (e.g., fear and anger) were found more challenging to identify and discriminate.

These results indicate that the robot's anger expression needs to be improved. Regarding the robot's capability to portray facial emotions, there are only subtle differences between expressions of fear (e.g., pupil dilation, mouth widening) and sadness (e.g., pupil contraction). These discrepancies can be overlooked by children, generating confusion among the emotions, as evidenced in the Post-Hoc test results. However, therapists reported that these subtle facial details make the robot's expressions unique and can be used to highlight differences between emotions when teaching emotional recognition skills to children with ASD. Specifically, eye contact can be trained to improve the children's identification of the four raw emotions.

5.2.2 Child's attention assessment

The children's attention was estimated to determine the most attractive robot's appearance and the acceptability of the robot's presence during the therapy. Specifically, a face tracking system offline calculated the children's eye gaze. During control trials, the attention of the children to the therapist was extracted, and during intervention trials, both the attention to the robot and the therapist were estimated.

Fig. 5.6 illustrates the mean percentage of children's attention during the session over the three groups for both phases (i.e., control and intervention). Results showed that the robot-like outfit presented 72.56 % of the child's attention in the intervention phase corresponding to the maximum children's percentage of attention during all sessions and activities. The above suggests that the most attractive appearance of the social robot was robot-like. On the other side, the results indicated that the therapist's attention considerably decreased between control and intervention trials. The children's attention was more notable and constant in the intervention phase. Besides, the Kruskal Wallis test showed statistically significant

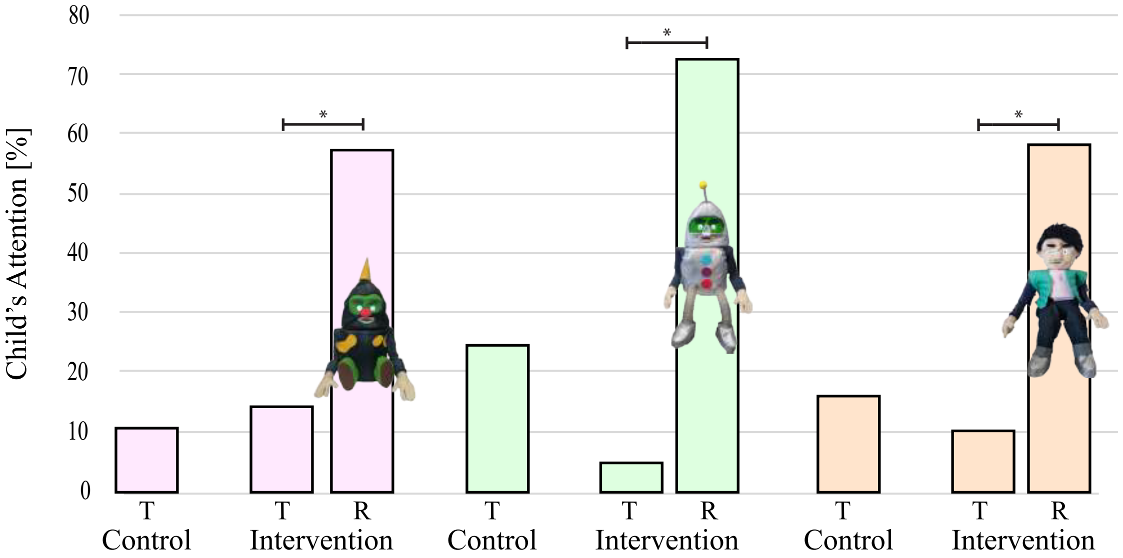


Figure 5.6: Mean values of children percentage of attention for the three robot appearances. T stands for the therapist's attention and R stands for the robot's attention. Asterisks indicate significant differences.

differences ($p < 0.05$) for each activity (imitation and recognition). This indicates that the robot's appearance impacts the children's attention, i.e., with the robot's presence, children devote more attention to the activity, and even depending on the robot's appearance, the attention was greater. These suggest that the child improved their attention, eye contact, and interest in the therapy with the robot's presence.

On the other hand, it was observed that for each of the robot's appearances, a minimum percentage of attention to the therapist was maintained. These results are consistent with Srinivasan et al. [125] and [10], who reported that the children devoted maximum attention to the robot rather than the therapist. Besides, they reported that throughout the treatment sessions, the children continued to devote the most attention to the robot, without losing interest in it. These findings should be taken into account when designing a long-term therapy with the social robot. Although the children may be more interested and comfortable in therapy, the visual fixation on the robot may affect the child's opportunities to engage with social patterns.

Finally, it is essential to note that at the end of the session, the therapists stated that the children felt safe, calm, comfortable, and interested in the company of the robot within the therapy. They even reported that some children with the presence of the social robot reduced their anxiety levels. This fact was observed and reiterated by the researchers, peers and caregivers through the recordings. With the above, it is possible to determine a positive acceptance of the child towards the social robot, regardless of its appearance. This shows the importance of participatory design, which allowed us to see rewarding results.

5.3 Conclusions

This chapter presented a study in a clinical setting using a novel social robot with three different appearances (i.e., human-like, fantasy-like, and robot-like) implemented and designed through an inclusive and participatory design (PD) process.

The main objective of this validation study was to determine the robot's functionality and acceptability in ASD therapies, as well as to identify the most attractive robot's appearance. Thus, this study presented the results from several emotion recognition tasks. These tasks were relevant for this study due to the importance of emotion recognition to establish relationships with others, as well as the fact that it plays a critical role in everyday communication. Specifically, a therapist asked the participants to identify four basic emotions (i.e., happiness, sadness, anger, and fear) using images or a social robot. Regarding the study results, the participating children were confused during the recognition of similar emotions (e.g., fear and anger). In contrast, with simple emotions (i.e., sadness and happiness), they made an outstanding performance. These emotions were correctly labelled and matched. Results also showed that the children spent more time looking at the social robot than the therapist. However, the children kept a portion of their attention on the therapist in both control and intervention trials, mainly due to adult-seeking and acceptance-searching behaviours. Moreover, the therapists played an essential role during sessions, as they helped to build the relationship and trust between the children and the robot. In other words, the active participation of therapists and the relationship between the children, the therapist, and the robot are essential characteristics to ensure the intervention's success.

In terms of appearances, the one that gained the most attention time was the robot-like outfit. Nevertheless, it is essential to point out that no matter what was the robot's appearance, the child felt safe, calm, and comfortable during the social robot presence. Also, some children reduced their anxiety levels.

On the other hand, the social robot design guarantees an assistive robot with simplified and realistic features that allow simple social interaction and more comfortable interaction with children with ASD. This robot is an aid for the teaching of emotion recognition and imitation, where children interact physically and cognitively with the robot on their terms. In this way, the robot serves as a social mediator, engaging children with autism in verbal and non-verbal communication scenarios with another person (e.g., parents, caregivers, or playmates). These results support the idea that robots are active agents of reinforcement in semi-structured behaviour for children with ASD.

Chapter 6

Conclusions and Future Works

This chapter shows the conclusions of this work, as well as a projection of future work in the short, medium and long term. Next, the conclusions will be presented as evidence of the fulfilment of each of the specific objectives set out at the beginning of the document.

6.1 Conclusions

The first objective frames the need to develop a platform that meets the needs stated at the beginning of the document (chapter 3). based on the great potential of new SAR technologies in therapies with children. In this context, this work managed to collect and interpret these needs through a participatory design strategy. Implementing PD is not just a methodology to improve and enhance a product's final design, but also an opportunity to understand and gain knowledge about the community's context and to build trust and confidence between researchers and the community. The current state-of-the-art also constrained the design criteria of the robot on social robots, to fragility and high acquisition costs. On the other hand, the social robot takes on additional significance regarding the development of robotic systems because, in Latin American countries, the community's awareness about the technology and robotics adoption in healthcare is lower than in countries like the USA and Japan.

This resulted in a design with adequate proportions (Robot with a height of approx. 50 cm). This allowed us to emphasize eye contact and thus attract the children's attention. On the other hand, it was possible to distribute the weight and space of the robot. The robot contains everything necessary for its operation within itself. This makes the robot transportable, and easy to handle and assemble. With this, it can be concluded that the robot meets the vast majority of design criteria in physical terms, see table 3.1. However, throughout the therapies, it could be evidenced that the robot after hours of operation begins to have attempts of overheating its motors. Therefore, it is interesting to focus on this limitation for future redesign stages.

Regarding the need for a robotic device based on elastic actuators. This device demonstrates, not only, that the robot works adequately to perform the therapies, but that it does so without problem in extended sessions. This makes it evident that the robot is functional for protocols designed for the long term. This is thanks to the development of elastic actuators that absorb the energy of physical interaction. This structure allows the user to interact longer with the robot joints, without affecting the correct functioning of the actuators, even in situations where the interaction is not adequate, as in the case of hitting or pushing. On the other hand, it was also necessary to ensure that the child's interaction with the robot was as friendly as possible when receiving or giving a hug. The design of deformable joints of the huggable module proved to be resistant to strong interaction, even in case of falls, because the robot was deformed, absorbing the energy of the impact and preserving the integrity of the device. In addition to being a completely safe system for users.

Thanks to the study conducted with children in a clinical setting, it was possible to validate and observe the robot's functional and technical characteristics in therapy. This provides information on the impacts of using the CASTOR robot in CwASD treatments. In this context, it was possible to conclude that the robot's appearance greatly influences the child's attention in therapy and that this influence reveals a great potential to perform emotion recognition activities, joint attention, and proprioception activities, among others. Thus increasing the child's interest in therapy. On the other hand, it could also be evidenced that the CASTOR robot meets all the design criteria, offering safety, easy manipulation, a friendly appearance and the ability to successfully emulate emotions, which made the study about emotion recognition possible. At the same time, the results show excellent performance in the identification of contrasting emotions such as happiness and sadness. It should be noted that there is a strong need to improve facial gesticulation to make emotions, such as surprise, anger and fear, more easily recognizable by users.

This study offers empirical support for continuing research on using SAR to promote social interaction with children with ASD. Further long-term research will help to identify the differences between high and low-functioning children. Moreover, future work will address the implementation of a physical interaction study to gather tactile information between children and the robot. Likewise, the social robot functionalities will benefit from more complex behaviours, such as body motion and proprioceptive awareness. Also, it would be interesting to test the relative improvements gained from a robot-assisted intervention compared to more traditional interventions that do not include robots, adding a control group to the procedure.

6.2 Future works

The conclusion of this master's work left, as a result, the development of a robotic platform for the accompaniment of therapies with CwASD. They provide a tool for medical personnel and research groups in social robotics centres interested in cognitive therapy, among others. However, this tool's most significant expected impact is primarily focused on improving treatments for populations with cognitive neurodiversity in developing countries. Although the CASTOR robot met the expectations of the stakeholders and the proposed design criteria, there are some limitations and features to be improved or possible lines of new research as a result of the results obtained. In this context, different works in the short term could give significant contributions to the platform already presented. An exciting work becomes evident of the need to work on a cooling system that prevents the motors from heating up, thus extending the time in which the robot works in optimal conditions. Another technical feature to be addressed would be the improvement of the design of facial expressions. Implementing new deformable materials that emulate the behaviour of synthetic skin to make the expressions look more natural and easy to recognize could improve the performance in therapy. Regarding user interfaces, there is a need to work on a graphical interface which provides an easy and intuitive way to program therapies, to facilitate the management of the platform with the medical staff.

On the other hand, thanks to the potential demonstrated by this platform, the need to implement this social robot in long-term studies is required. This is to generate more meaningful data on the therapies' performance. In addition, thanks to the replicability of the CASTOR robot, it becomes possible to conduct parallel studies in different parts of the world, expanding the range of action of the studies and thus obtaining more reliable and comparable information. On the other hand, although the CASTOR robot is functional and replicable, it still has a manufacturing and fabrication cost that could be strongly reduced by including the platform in an industrialization process—especially considering the manufacture of the robot's outfit. This would allow the platform to be even more replicable and easily accessible without ceasing to function as an open-source platform since the primary purpose is that CASTOR is and remains from the community for the community.

AVAL 09-2021
COMITÉ DE ETICA DE INVESTIGACIÓN

Asistentes	Cargo
Martha Pimienta Giraldo	Subdirectora de fomento y desarrollo a la investigación
Gladys Rocio González Leal	Profesora Centro de Estudios Ambientales
Ricardo Martinez Rozo	Médico

EL COMITÉ DE ÉTICA DE INVESTIGACIÓN de la Escuela Colombiana de Ingeniería Julio Garavito, certifica mediante la presente acta del 22 de octubre de 2021 que se revisó la propuesta "**Protocolo de apariencia de un robot social en reconocimiento de emociones para niños con TEA**" cuyo investigadores principales son los profesores Carlos Cifuentes Garcia, Marcela Múnera Ramírez (tutores) y los estudiantes Andrés Aguirre, Diego Casas, Paola Castro de la Escuela Colombiana de Ingeniería Julio Garavito

Se revisaron los siguientes documentos:

- Protocolo
- Consentimiento informado en donde se encuentra registrado: las estrategías para dar a conocer a los participantes la investigación, riesgos incluidos los de COVID-19, y beneficios, como se garantizará la privacidad y el anonimato de los mismos y confidencialidad de los datos de investigación, la cadena de custodia de la información obtenida y las restricciones para su uso por terceros
- Hoja de vida del investigador principal y coinvestigadores

Adicionalmente se revisaron los siguientes aspectos:

- Utilidad del protocolo para los participantes, la sociedad o el conocimiento
- Evaluación riesgos y beneficios
- Procedimientos, metodologías y procesos de investigación, el manejo divulgación y archivo de los datos obtenidos.

Adicionalmente se revisó que la investigación no vulnerará la dignidad de los sujetos, no constituye una amenaza bajo ninguna circunstancia, ni causa daño emocional ni moral a los investigados y se ajusta a estándares científicos y éticos propios

Concepto

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