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Optimized Child-Centered Textile Design for a Soft Robotic Glove in Pediatric Rehabilitation

Abstract: Cerebral palsy in children, a neurological condition that can affect the mobility and coordination of the upper limbs, presents challenges for the design of rehabilitation devices that are functional, comfortable, and emotionally acceptable to enhance therapeutic adherence. This study presents the development and optimization of a soft robotic glove specifically designed for the rehabilitation of children with cerebral palsy, integrating ergonomics, functionality, and aesthetics. The multilayer design of the glove prioritizes ergonomics through the use of three spandex materials: Dry Spandex, Fluity, and Lenatex, selected for their flexibility and anatomical fit. Mechanical tests conducted according to the American Society of Testing and Materials (ASTM) 4964-96 standards evaluated the behavior of the spandexes after three usage cycles. Dry Spandex, used in the inner layer, showed an average tension decay of 4%, standing out for its high elasticity and uniform tension decay at low elongations. Fluity, used in the outer layer, exhibited a higher tension decay of up to 7.7% but provided a balance between comfort and adequate initial support for electronic and pneumatic components. Lenatex, utilized in the wristband, was the most rigid spandex with the lowest variance (0.8), providing a uniform and predictable mechanical response. Additionally, a usability survey with children revealed positive perceptions of the glove's aesthetics, instructions, and overall experience, highlighting areas for improvement. The findings related to technical and emotional features support the design's potential to achieve a balance between comfort and usability, providing insight for future applications of soft robotics in child-centered designs.

Keywords: Cerebral Palsy; Ergonomic; Industrial design; Pediatric Rehabilitation; Robotic glove

1. Introduction

Soft robotic gloves have emerged as promising assistive devices for upper limb rehabilitation in individuals with motor impairments, particularly children with cerebral palsy (Polygerinos et al., 2015). These gloves, typically made from soft elastomers and actuated pneumatically or electronically, aim to support finger movement while preserving comfort and safety. However, user rejection due to the visible presence of electrical components or discomfort remains a significant barrier, particularly among pediatric users (de Jong et al., 2019). In parallel with these developments, various technologies have been developed to support motor rehabilitation in individuals with reduced mobility, particularly in the context of stroke recovery. For example, gamified rehabilitation systems that incorporate virtual reality have been studied for shoulder rehabilitation (Navea et al., 2025); mobile game-based applications have demonstrated utility in supporting hand rehabilitation

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(Octavia & Natasha, 2017); and tangible user interfaces have been developed to foster patient engagement during therapeutic interventions (Ockerman et al., 2024). Moreover, arm exoskeletons with electro-pneumatic mechanisms have been proposed for passive rehabilitation (Nacarino et al., 2024). These approaches highlight the growing interest in accessible and motivating technological solutions; however, a specific gap remains in the development of ergonomic soft robotic gloves for pediatric populations that also integrate user acceptance principles.

A user-centered design approach is essential to reduce emotional and functional resistance by integrating technical components discreetly and selecting breathable, lightweight, and washable materials (Norman, 2013; Proulx et al., 2021). Pediatric acceptance, in particular, depends heavily on emotional engagement and aesthetic appeal, as children require a positive connection with the device to adhere to treatment protocols (Jeong et al., 2015; Roberts et al., 2012). Friendly and modular designs not only improve hygiene and usability but also foster emotional connection, thereby enhancing therapeutic outcomes (Cappello et al., 2018; Stuart et al., 2022). However, current discussions of user acceptance of soft robotic gloves remain focused mainly on aesthetics and functionality, overlooking broader determinants that can be explored through usability surveys using the Likert scale. These models highlight key factors such as perceived usefulness, ease of learning, required effort, and social influence as essential to technology adoption (Venkatesh et al., 2003). Incorporating these dimensions can significantly improve the long-term acceptance and integration of assistive devices into daily life.

In terms of ergonomics, existing glove designs emphasize material selection, such as the use of silicone, polyurethane, and antimicrobial textiles (Yap et al., 2017; Biggar et al., 2017), but often neglect other critical ergonomic aspects. These include adaptability to various hand sizes and shapes, avoiding interference with joint movement, and ensuring thermal comfort during prolonged use. Devices such as the ExoGlove and Soft Robotic Glove demonstrate the potential of soft actuators and modular systems to enhance usability (Proulx et al., 2021; Proietti et al., 2024); however, challenges remain in reducing the size and weight of control units and fully integrating ergonomic needs for pediatric use. Similarly, commercial solutions, such as Carbonhand and ExoGlove, have demonstrated effectiveness in adult rehabilitation (Bioservo, 2024; Proulx et al., 2021), but they fall short in addressing the specific physical and emotional needs of pediatric users. These systems lack the necessary adaptability, comfort, and emotional appeal needed for children, especially those with severe spasticity or sensory sensitivity.

This study aims to bridge the identified gaps by proposing a pediatric-specific soft robotic glove that integrates technical functionality, ergonomic adaptability, and emotional engagement. The proposed design leverages soft materials, a modular architecture, and insights from user acceptance models to prioritize comfort, safety, and usability for children with cerebral palsy. In doing so, it seeks to reduce device rejection and enhance therapeutic adherence. The methodology combines a user-centered design approach with the development of a modular, textile-based glove that is pneumatically actuated and controlled via a compact, wearable system. Anthropometric data of children with cerebral palsy were used to inform the ergonomic design, and usability surveys were applied to assess user perceptions. The outcomes include a functional prototype, preliminary usability metrics, and design insights that emphasize comfort, safety, and emotional appeal. The novelty of this work lies in its comprehensive, multidisciplinary approach that systematically integrates textile ergonomics, affective design principles, and pediatric-centered usability; an intersection that has been little addressed in an integrated manner in the current literature. Unlike previous solutions that focus primarily on adult users or address isolated design factors, this glove was developed from the outset with the specific physical, emotional, and therapeutic needs of pediatric users in mind.

2. Methods

This study followed the systematic design methodology proposed by Leonard Bruce Archer (Table 1), which structures the development process into three sequential phases: analysis, design, and implementation. More recent authors, such as Wade et al. (2019) and Bila-Deroussy et al. (2017), have applied Archer's methodology while incorporating sustainability, interdisciplinary creativity, and a human-centered perspective, reinforcing its relevance for holistic design approaches. This structured approach ensures that complex design challenges in rehabilitation technology are addressed iteratively and rigorously, with a focus on both functional efficacy and emotional acceptance by pediatric users.

Table 1 Design process methodology of Leonard Bruce Archer

Analytical phase	Creative phase	Implementation phase
• Definition of the problem • Obtaining relevant information	• Data analysis and idea synthesis • Prototypes development	• Final design • Preparation and execution of experiments and studies to validate the design

2.1 Analytical Phase

This phase focuses on researching and understanding user needs to identify the problems to be solved, taking into consideration the limitations and design parameters. Based on the gathered information, functional requirements are identified, and initial materials are selected for the testing and iteration process. The analytical phase aimed to identify the main ergonomic and usability challenges faced by children with cerebral palsy (CP) when interacting with soft robotic gloves. This phase consisted of a literature review and direct user observations conducted at the Instituto para el Desarrollo Infantil – ARIE, in collaboration with a physician specializing in physical and rehabilitation medicine who has expertise and a commitment to pediatric rehabilitation. The goal was to gain a deeper understanding of the problem space. To support ergonomic and functional design decisions, a targeted anthropometric data collection process was conducted. The study involved direct measurements of hand dimensions, such as finger length, palm width, and wrist circumference, from a total sample of 14 children aged 8 to 12 years. The initial phase included an observational assessment of one child with a history of stroke, whereas subsequent design iterations were conducted with 13 children without a diagnosis of cerebral palsy. Participants were selected using purposive sampling to represent the intended user population. Inclusion criteria comprised children within the specified age range, with or without mild to moderate CP. Exclusion criteria included the presence of comorbidities affecting upper limb anatomy or motor coordination. Measurements were conducted using standard anthropometric tools, including calipers and measuring tapes, in accordance with established ergonomic protocols. Data collection was complemented with anthropometric databases relevant to Latin American pediatric populations.

Additionally, the motor development of children was characterized using the Gross Motor Function Classification System (GMFCS) to define relevant therapeutic objectives and to inform the device's functional requirements (Harvey, 2017). Interviews and observational assessments were conducted with users, caregivers, and rehabilitation professionals (e.g., physiotherapists and occupational therapists) to triangulate information on the functional needs and therapeutic expectations for soft robotic gloves in pediatric rehabilitation.

2.1.1 Definition of the problem

The issue is that soft robotic gloves intended for children's rehabilitation are not widely accepted or successful. It is known that these modern devices are technically advanced and feature pneumatic and electronic components, but pediatric users perceive them as invasive and face emotional or physical challenges. To achieve adherence to the device and treatment, it is essential to minimize discomfort and rejection of the design, as this can limit its therapeutic effectiveness. Additionally, the lack of aesthetic integration that fails to consider both functional and emotional aspects compromises the overall user experience, making it difficult to establish a positive connection with the device. Furthermore, there is a need to incorporate breathable, lightweight, and modular materials to facilitate maintenance, improve hygiene, and allow adaptation to users of various sizes and motor requirements. This problem underscores the need for a design that optimizes therapeutic functionality while considering ergonomic, aesthetic, and emotional aspects to foster a positive user experience.

2.1.2 Obtaining relevant information

a) Cerebral palsy in children

Cerebral palsy (CP) in children is a neurological disorder that impacts movement, posture, and balance, with manifestations depending on the severity and location of the brain lesion. The main types of CP are spastic, dyskinetic, ataxic, and mixed, each presenting distinct motor challenges. Spastic CP is characterized by muscle stiffness; dyskinetic CP by involuntary and uncoordinated movements; ataxic CP by balance issues; and mixed CP by a combination of these symptoms (Vitrikas et al., 2020). These motor impairments may affect the limbs or trunk, ranging from mild to severe limitations. Children with hand impairments often struggle with fine motor tasks, such as buttoning clothes or holding utensils, which hinders their autonomy in daily life. Reduced dexterity significantly limits participation in school, play, and home activities. These functional limitations demand targeted therapeutic interventions to enhance motor performance and promote independence (Carneiro et al., 2020). The analysis highlights the diversity of necessities and challenges that children face. On the one hand, they demonstrate the continuous development of their gross and fine motor skills (Table 2); on the other hand, children with CP face limitations (Table 3) as defined by the level of affection in the Gross Motor Function Classification System (Harvey, 2017; Merhy et al., 2025). These conditions affect their capacity to realize basic and advanced motor tasks.

Table 2 Analysis of users without cerebral palsy.

Age	Gross motor skills	Fine motor skills
6-8 years	At his age, children develop better coordination, balance, and control, which enables them to run, jump, climb, and participate in games that require coordination, such as jumping rope or catching a ball. They also show interest in demanding sports, such as cycling or skiing. Furthermore, they can participate in organized sports like soccer, basket, and swimming, which require coordination between strength and resistance (Wang et al., 2020; Schembri et al., 2019, Fallah et al., 2015).	At this stage, children demonstrate advanced manual dexterity, writing with increasing fluency, following lines while cutting with scissors, and precisely manipulating small objects, such as brushes or scissors. They can solve complex puzzles, build with small blocks, and participate in tasks that require eye-hand coordination, such as playing board games, demonstrating their ability to perform creative and precise tasks (Hafidz & Puspawati, 2022; Serrien & O'Regan, 2020).
10-12 years	At this age, children can participate in sports and activities that require advanced motor skills. They can run faster, jump higher, and throw with greater force and accuracy. They can also participate in sports with complex rules. Their movements are more fluid, and they can perform tasks with physical resistance (Giuriato et al., 2022).	As they approach adolescence, their fine motor control continues to improve. They can write quickly and clearly, perform detailed manual tasks, play musical instruments more precisely, and operate technological tools such as computers. They can also complete high-precision tasks, such as threading needles or constructing complex structures (Serrien & O'Regan, 2020).

Table 3 Analysis of users with cerebral palsy.

Age	Gross motor skills	Fine motor skills
6-8 years	At this stage, gross motor skills stabilize, reaching a limit that depends on the child's GMFCS level. For example, those with Level I can develop independent walking, while in Level III to V, mobility is more restricted and may require assistance. Balance control and coordination represent persistent challenges (Rosenbaum et al., 2003).	Children in this stage often face difficulties with their fine motor skills, which can impact their ability to participate in school activities such as writing and drawing. Their capacity to realise tasks that require manual coordination, such as buttoning clothes or using utensils, is also affected. Manual control and precision are restricted due to a lack of coordination and strength in the upper limbs (Johari et al., 2016; Beckung et al., 2007)
10-12 years	Some children at higher levels of the GMFCS experience a decline in their gross motor skills, such as postural control and mobility,	While fine abilities may stabilize, difficulties in manual tasks persist due to underlying problems in muscle control and coordination. These

	due to the progression of complications associated with their condition. At lower levels (I and II), individuals maintain functional abilities, such as running and jumping, albeit with limitations (Hanna et al., 2009; McCormick et al., 2007).	limitations are more evident in activities that require sequential and precise movements, such as writing or manipulating small objects (Kara et al., 2020; Ashraf & Nisar, 2019).

The glove design incorporates features that facilitate the user's active interaction in recreational, educational, and daily life activities. This involves incorporating technologies and ergonomic settings that optimize physical functionality, emphasizing usability, adaptability, and comfort. In addition, considering a user-centered design, the proposed solution can be ensured to improve the user's quality of life and social inclusion by positively impacting their functional capacities and interaction with the environment. The Gross Motor Function Classification System (GMFCS) categorizes mobility in individuals with CP into five levels. Level I includes walking without restrictions but with limitations in advanced activities; Level II involves walking without assistance but with difficulties on uneven terrains or long distances. In Level III, assistance devices and wheelchairs are required for long distances, while in Level IV, mobility depends on walkers or wheelchairs. Level V represents severely limited mobility, dependent on caregivers or technological devices (Harvey, 2017; Merhy et al., 2025).

b) Hand anthropometry

Hand anthropometry studies the dimensions of the human hand, encompassing its skeletal and muscular structures. The human hand is composed of a complex anatomy comprising more than 25 bones, 20 joints, and 30 muscles, which enable a wide range of movements. The bones of the hand are categorized into three main groups: phalanges (fingers), metacarpals (palm), and carpals (wrist). Each hand contains 14 phalanges divided into proximal, middle, and distal sections, except for the thumb, which lacks a middle section (Panchal-Kildare & Malone, 2013).

The joints of the hand allow specific movements in the fingers and wrist. The index, middle, ring, and little fingers have three joints: the distal interphalangeal, proximal interphalangeal, and metacarpophalangeal. The thumb has three unique joints that enable flexion, extension, abduction, and adduction. Similarly, the wrist performs flexion, extension, abduction, and adduction, contributing to the hand's high mobility for daily tasks and complex activities (Weiss, 2008).

To ensure an ergonomic adjustment of the robotic glove, direct measurements of children's hands were performed and complemented with anthropometric data reported by (Ávila-Chaurand et al., 2007). The anthropometric study measured finger length, palm width, and wrist circumference (Figure 1) to design textile patterns that provide a precise fit while preserving mobility for therapeutic use. The combination of direct measurements with the anthropometric data available enabled the design of a glove adaptable to various morphologies. Successive, dynamic anthropometry tests were made to evaluate the fit and flexibility of the design, verifying that critical zones, including the five proximal interphalangeal joint flexion points of the fingers and the radiocarpal joint of the wrist, allowed for a full range of motion during use.

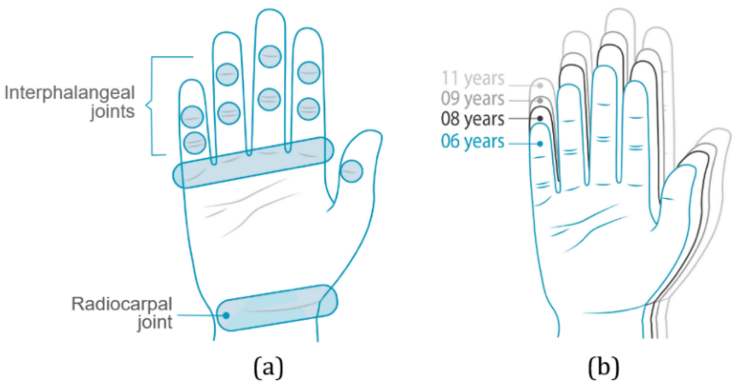


Figure 1 Anthropometric analysis of the hand: (a) joint flexion points of fingers and wrist; (b) ergonomic analysis from 6 to 11 years.

c) Integrated components

The pneumatic actuators used in the robotic glove, developed by Fabian et al. (2023) and Barrientos et al. (2024), are lightweight and flexible, allowing for the mimicking of natural hand movements through air-powered flexion and extension. When inflated, they bend the fingers or wrist; when deflated, they return to their original position, enabling actions such as grasping and releasing objects. Compared to electric or hydraulic systems, these actuators are lighter, which improves comfort and reduces the risk of joint or muscle injury. Their high power-to-weight ratio allows effective force generation without significantly increasing the glove's weight, making them ideal for therapeutic and assistive applications.

To obtain hand and wrist data, the BNO055 IMU sensor is used, which combines an accelerometer, gyroscope, and magnetometer to detect motion, orientation, and position in three-dimensional space. In the glove's design, pockets are integrated with the dimensions to store the IMU sensors (5.2 x 3.8 x 1.1 mm^3) and wiring. This ensures the stability and precise alignment of the X, Y, and Z axes, allowing for accurate measurements that reflect actual movements. The compact design, combined with automatic calibration and low power consumption, makes this sensor ideal for accurately tracking movement and orientation in robotics, augmented reality, wearable devices, and autonomous vehicles (Bosch Sensortec, 2015).

The electro-pneumatic system supplies compressed air to the actuators, utilizing a small, controllable air compressor and pneumatic valves to regulate airflow and adjust movements, such as flexion speed or fixed positions. Differential pressure sensors provide real-time data, allowing the system to ensure safe and accurate actuator responses. Compressed air is distributed through valves that enable independent control of each finger or hand section, allowing for coordinated or individualized motion based on therapeutic needs (Barrientos et al., 2024).

d) Type of fabrics

The fabrication of elastic polyamide/Lycra fabrics coated with conductive polymers, such as PEDOT, and integrated with polyurethane (PU) is notable for preserving high elasticity, reaching up to 650% elongation while maintaining stable electrical properties even after repeated cycles of mechanical stretching and washing. Dipping proved to be the most effective method for enhancing the uniformity and durability of conductivity, enabling functional fabrics to retain their properties after multiple cycles of stretching and washing without compromising their mechanical integrity. These findings highlight the potential of such fabrics for use in wearable devices and smart textiles (Tadesse et al., 2019). Another study highlights comfort properties related to moisture management in spandex fabrics, focusing on water vapor permeability, drying capability, and vertical absorption. The results indicate that incorporating spandex enhances fabric adaptability, facilitating improved ventilation and enhanced moisture management. Furthermore, the ability to remain washable and comfortable after several uses confirms its versatility for modern textile applications (Duru & Göcek, 2020).

Commercial textiles such as Fluity Spandex (82% nylon 6.6, 18% elastane) offer UV protection (SPF 50) and Dry Fit technology for moisture regulation and user comfort, aligning with research findings on Lycra's role in enhancing fabric breathability and comfort (Duru, 2020). Similarly, Lenatex Spandex (85% polyamide, 15% elastane) offers high elasticity, shape recovery, lightness, and resistance, making it ideal for activewear. Its Dry Fit technology also improves moisture management and anatomical fit during physical activity (Venoor et al., 2020).

Breathable Dry Spandex, composed of 92% spandex and 8% elastane, is an elastic fabric that combines the spandex's flexibility with perforation, enhancing ventilation, providing greater thermal comfort, and regulating body temperature. Combining mesh and perforated structures has improved airflow and reduced sweat accumulation, making it suitable for sportswear and functional clothes (Sun et al., 2015). Additionally, its high air permeability enables a constant airflow, optimizing ventilation and user comfort, especially during physical activities, by maintaining the necessary thermal balance under various environmental conditions (Ueda & Havenith, 2002).

2.2 Creative Phase

This section develops creative and feasible proposals for designs using the information gathered and analyzed in the previous phase. This process involves an analysis, where the possibilities and constraints of the data are identified; a synthesis, which entails combining ideas and approaches to generate solutions; and development, which involves materializing the solutions into preliminary prototypes. Iteration and feedback are essential in this stage, enabling the continuous improvement of the proposals until a solution is reached that fulfills the specifications and objectives of the glove.

During the creative phase, several conceptual and functional prototypes were developed through an iterative user-centered design approach. A range of textile materials was evaluated based on specific properties, including elasticity, breathability, tactile comfort, and drying capacity. The integration of pneumatic actuators and inertial measurement unit (IMU) sensors was considered in tandem with textile selection to preserve natural hand mobility and avoid interference with joint function. Internal compartments were strategically designed to house electronic and pneumatic components without compromising aesthetics or usability.

Low-fidelity prototypes were fabricated using material combinations, including Dry Spandex, Fluity-Unicolor, and Lenatex. These prototypes were reviewed for fit, modularity, and feasibility of component integration. Electrical insulation and sensor safety were addressed by embedding coated flex sensors in critical areas. Prototype reviews involved feedback from both technical experts and rehabilitation practitioners to ensure alignment with therapeutic goals.

2.2.1 *Data analysis and idea synthesis*

The analysis focused on integrating pneumatic and electronic components to ensure their functionality without compromising the natural mobility of the hand. The evaluation included: textile analysis of different percentages of elastane to ensure that the textile layers offer flexibility without interfering with the integration of the components; electrical isolation analysis to prevent current transmission from components such as flexible sensors, adding insulating layers, ensuring protection, comfort, and elasticity without contact with conductive parts; and a positioning analysis to determine a strategic location for the internal pockets to place actuators, maintaining a unified design and ensuring efficient functionality without affecting user comfort.

a) Materials

Different types and combinations of materials were evaluated. These included the Brazilian Dry Spandex (92% polyamide, 8 % elastane), a breathable fabric selected for its ventilation, ease of washing, and removability; Lenatex (85% polyamide, 15% elastane) with technology dry-fit; Fluity-Unicolor (82% nylon, 18% elastane) with biodegradable nylon and quick-drying properties; Light-Unicolor CO2 (90% nylon, 10% elastane) characterized by its quick drying and biodegradable nylon; Peruvian Full Lycra (95% cotton, 5% spandex) that offers high elasticity, breathability, a soft touch and resistance to wear. Additionally, it features Korean Lycra Spandex (80% nylon, 20% elastane) and USA Spandex Brightness (80% nylon, 20% elastane) for their elasticity, snug fit, and comfort, as well as durability, wear resistance, and quick-drying features.

The materials analysis focused on identifying combinations that improve the functionality and acceptance of soft robotics gloves for children with cerebral palsy. Fabrics were evaluated based on properties such as breathability, elasticity, quick drying, and ease of disassembly, prioritizing features that reduce sweating and facilitate efficient maintenance. Furthermore, an aesthetic and functional integration was considered to minimize the exposure of technical components, fostering emotional acceptance among young users.

b) Current flow through components

The analysis was conducted using flex sensors, also known as resistive sensors, which measure changes in electrical resistance based on the degree of applied bending. These sensors are widely used in wearable devices, biomedical interfaces, and robotic control systems due to their precision and ease of use. The sensors convert mechanical deformation into resistive variations, enabling applications such as smart gloves for sign language interpretation and prosthetic control (Saggio et al., 2015). To ensure proper functionality, sensors were installed with a coating that provides electrical insulation, minimizing the risk of discharges or short circuits, a requirement for devices like wearables that are in direct contact with the skin. Moreover, the coating protects against moisture and sweat, ensuring the sensor's accuracy and extending its lifespan under intensive use. They are also helpful in preventing mechanical damage, ensuring safe and efficient operations (Li et al., 2021).

c) Internal Pockets

There are various solutions for integrating inner pockets to organize and separate the actuators and IMU sensors, which are key components for controlling movement. Different locations, dimensions, and textiles for these compartments were evaluated to achieve an efficient and ergonomic integration. A key requirement was that the pockets facilitate the orderly routing of electronic wiring and pneumatic connections, ensuring stable fixation of the components during operation. Efforts were also made to maintain a user-friendly exterior design, avoiding the exposure of technical components that could cause discomfort or intimidation for young users. Preliminary findings showed that this arrangement allowed the actuators and sensors to control wrist flexion and extension without compromising functionality or comfort. Also, the ergonomic shape of the glove, tailored to the user's anatomy, was preserved. The proposed designs considered the placement of internal compartments to provide adequate protection, reducing the risk of external interference and sensor displacement, which helps prevent damage to the wiring and facilitates maintenance. The clear and accessible organization of the components reinforces their stability as well as the user experience, allowing for interaction with the device without distractions or discomfort.

2.2.2 Prototypes development

Following an iterative approach, the soft robotic glove underwent various designs in search of a balance between technology integration and comfort for pediatric users. Different prototypes were tested, applying techniques to integrate the components, structural arrangements, and material combinations. The main design iterations and design decisions are outlined in the ensuing subsections.

a) Low-fidelity prototype with different materials

To maintain an appearance similar to a conventional glove while balancing technological functionalities with the user's needs for usability and comfort, different combinations of materials were tested, as shown in Figure 2. The evaluation included the analysis of dimensions, breathable and flexible materials with elasticity and resistance properties, as well as the strategic distribution of components to assess their impact on the glove's functionality and ability to adapt to different hand sizes, ensuring the smooth execution of therapeutic movements. In each iteration, the textile patterns were adjusted to ensure mobility in critical areas, such as finger and wrist flexion points, improving the design's adaptability to different morphologies and levels of motor ability.

Figure 2 Glove and Wristband prototyping iteration: (a) Full Lycra; (b) Fluity-Unicolor; (c) Dry Spandex; (d) Lenatex.

Throughout the glove design process, it was found that movement restrictions depended on the incorporation of electronic and pneumatic components, as well as the textile properties, such as the elastane percentage used in each glove layer. Additionally, iterations highlighted that the glove's adaptability to diverse morphologies was a key factor in ensuring better usability. As a result of this iteration, Fluity-Unicolor and Dry Spandex were selected for the glove because they strike a balance between functionality, flexibility, and ergonomics.

The wristband design focused on providing better support to the actuators and IMUs, ensuring effective integration and usability. For this process, stability and flexibility tests were conducted using different materials to ensure the system's functionality and precision in the obtained measurements. After several iterations, the Lenatex material was selected because it strikes an ideal balance between elasticity and firmness, resulting in a stable and comfortable fit.

b) Low-fidelity prototype with electric isolation

A glove with electrical insulation featuring rubber layers was prototyped to incorporate a flex sensor, which prevents current transfer and ensures safe use for children. Even when the combination of elastane and rubber was intended to preserve elasticity and protect components, testing revealed that the rubber caused less accurate sensor readings and compromised ergonomics and aesthetics. As a result, it was excluded from the final design.

c) Low-fidelity prototype with inner pockets

Electronic and pneumatic components were integrated through internal pockets, achieving a uniform weight distribution that preserves the hand's mobility. This arrangement of components was designed and prototyped through different versions to ensure the efficient operation of the glove, as shown in Figure 3. By placing the pneumatic actuators and motion sensors in the internal pockets, the modularity and adaptability of the glove are enhanced, allowing for customization according to different hand sizes and users' motor needs. Thanks to interchangeable components, the glove can be quickly adjusted during therapy sessions, optimizing the therapist's and the user's experience with a tailored intervention.

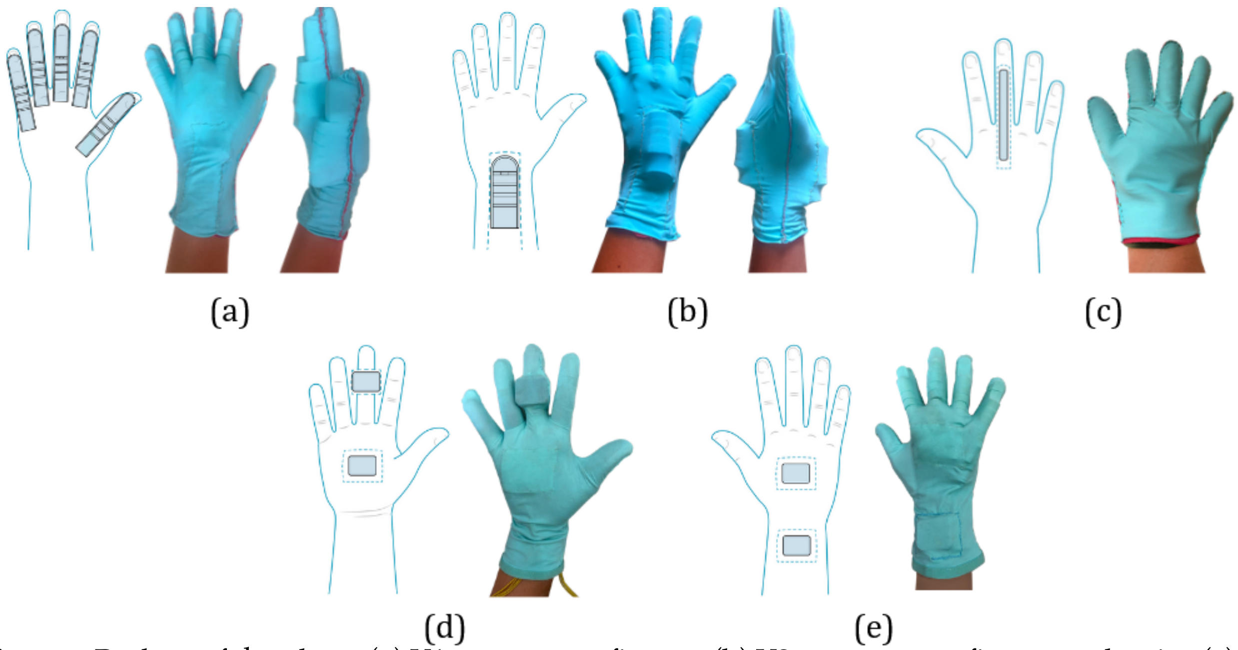


Figure 3 Pockets of the glove: (a) V1 actuator on fingers; (b) V2 actuators on fingers and wrist; (c) V3 Dorsiflexion sensor in hand; (d) V4 IMU sensor on the middle finger and palm; (e) V5 IMU sensors on the back of the hand and wrist.

Similarly, electronic and pneumatic components were integrated into the wristband through inner pockets, aiming to optimize performance while maintaining user comfort. During the fabrication process, the prototypes underwent multiple iterations due to challenges related to the attachment and positioning of actuators and IMU sensors on the wrist, as shown in Figure 4. Following several refinements to the design and internal pocket structure, a stable and functional configuration was achieved, enhancing performance and ensuring ergonomic adaptation. These design choices for the glove and the wristband seek to reduce discomfort perception, promote a positive user experience, and facilitate device acceptance.

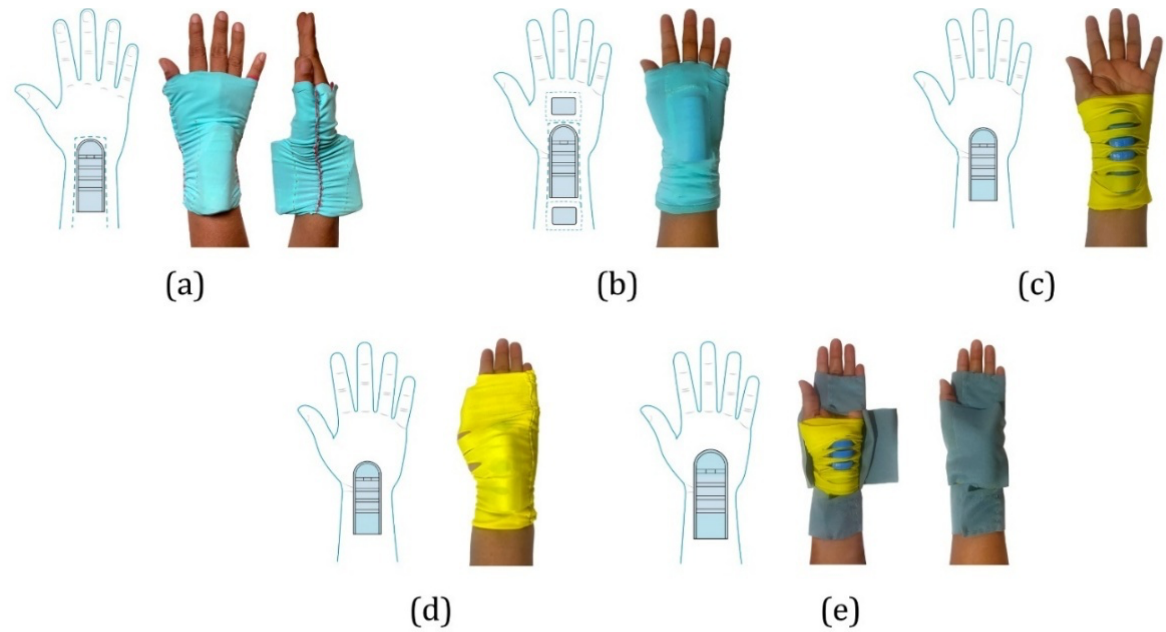


Figure 4 Pockets of the wristband: (a) V1 dorsal wrist actuator; (b) V2 palmar wrist actuator and IMU sensors; (c) V3 palmar wrist actuator; (d) V4 palmar wrist actuator; (e) V5 palmar wrist actuator and IMU sensors.

2.3 Implementation Phase

In this stage, the developed proposal is presented to evaluate its functionality and acceptance through direct feedback. This section describes and evaluates the final prototype, emphasizing its main features and overall performance. This evaluation considers technical documentation to ensure user understanding of the solution and customer feedback to adjust and optimize the design.

During the implementation phase, the final glove and wristband designs were developed in accordance with specifications established in the prior stages. The evaluation protocol included mechanical testing of the selected textile materials to assess durability, elasticity, and fatigue behavior under conditions simulating therapeutic use. Testing procedures were aligned with ASTM standards (specifically D4964-96) and involved cyclic elongation at different strain levels. To assess usability, a satisfaction assessment was prepared using a structured questionnaire adapted from validated instruments such as the System Usability Likert Scale, modified to accommodate the cognitive and developmental characteristics of children aged 8 to 12. This questionnaire was administered to a sample of 13 children during controlled simulation sessions with the glove under the supervision of trained facilitators.

2.3.1 <u>Final design</u>

The final design of the textile robotic system, as shown in Figure 5, incorporates both the glove and wristband, combining technology and comfort to maximize acceptance and efficiency during therapies. They are designed modularly to be adapted to different sizes, morphologies, and the needs of pediatric users. Light materials were selected, such as Fluity-Unicolor and Dry Spandex for the glove and Lenatex for the wristband, ensuring breathability, elasticity, and moisture control. Integrating pneumatic and electronic systems is organized within internal pockets, preserving natural mobility while ensuring a friendly and non-invasive appearance.

The final design of the soft robotic glove integrates an ergonomic textile structure with lightweight and breathable materials, such as Fluity and Dry Spandex, selected to ensure comfort and functionality during pediatric rehabilitation therapy. This glove provides elasticity, proper ventilation, and easy maintenance. The pneumatic actuators and IMU sensors are strategically distributed within internal pockets, as shown in Figure 5, to preserve the hand's natural mobility while maintaining a discreet and child-friendly appearance. The glove was designed to be modular, allowing for customization of its components according to the user's specific needs. The sensors are also protected by an insulating layer, ensuring electrical safety. At the same time, critical areas such as the finger points and wrist are designed to allow a full range of motion. The design aims to elicit emotional acceptance from the user through the use of attractive colors and soft textures, evoking a sense of familiarity and trust.

For the final design of the wristband, functional and ergonomic details were refined through a modular structure consisting of two main pieces made from Lenatex fabric, which improved moisture management and breathability during extended use sessions. The inner piece, as shown in Figure 5(d), secures the pneumatic actuators, keeping them in position to ensure proper functionality during wrist activity. The outer piece, as shown in Figure 5(c), features two pockets for the IMU sensors, providing proper calibration and protection from external interference. For an adaptive fit, Velcro fasteners were added to both the inner and outer sections, improving stability and customization and allowing the wristband to adapt to different user morphologies with specific needs of rehabilitation activities. The wristband was designed to adjust optimally to these variations as pediatric users undergo morphological changes based on age and the type of therapy they receive. The result integrates ergonomics, functionality, and ease of use, fostering an effective and safe experience.

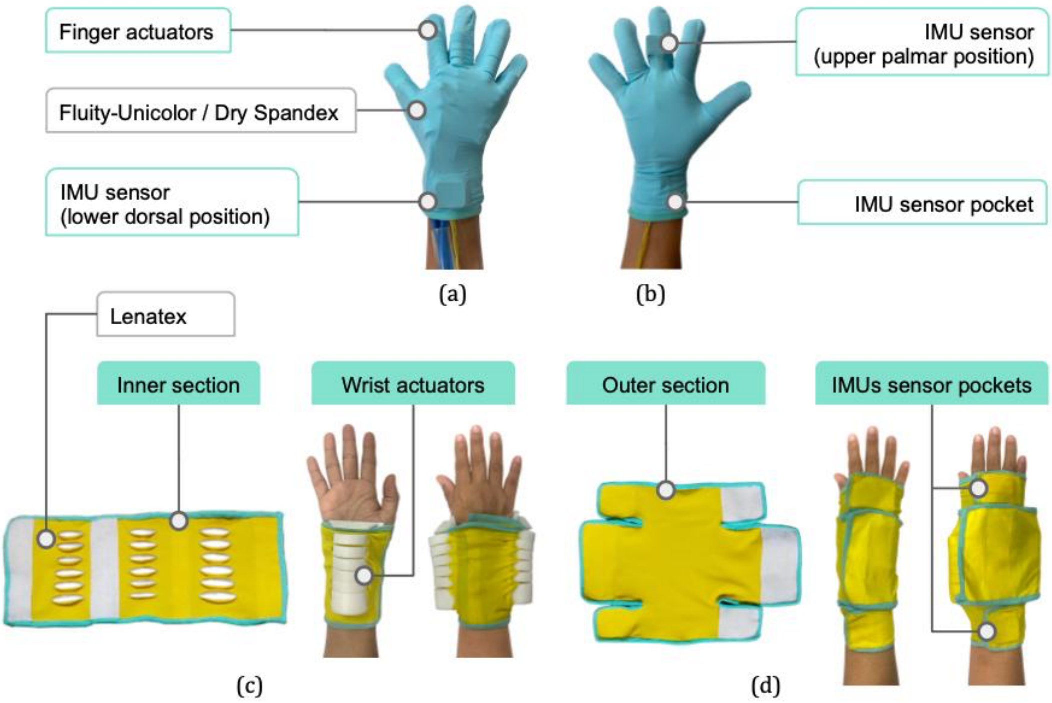


Figure 5 Final design of the glove and wristband: (a) dorsal position; (b) palmar position, (c) inner part for actuators; (d) outer part for IMU sensors.

2.3.2 <u>Preparation and execution of experiments and studies to validate the design</u>

In this stage, two experiments were defined to evaluate the proposed design. First, a mechanical experiment was conducted, including a fatigue test in cycles according to ASTM D4964–96 standards. Second, a survey was conducted among children who used the glove to ask about their satisfaction levels.

a) Mechanical essays to evaluate the material selection

Fatigue tests were conducted on elastic fabrics to evaluate the resistance of the glove and wristband materials. These tests are an approach to determine the structural integrity of the glove and any changes in its properties after multiple usage cycles, as expected in continuous movement therapy. Due to the glove's design, it was identified that during use, the wrist, fingers, palm, and dorsal areas are subjected to tensile stresses in tubular or loop configurations. For this reason, the ASTM D4964-96 standard was selected. This international standard relates loop tension and elongation in elastic fabrics using a constant rate of extension (CRE) testing machine (ASTM International, 2020). The inclusion of this international standard ensures that experiments are replicable, allowing for the comparison of results in different research contexts and commercial applications for elastic textiles. This approach is valuable because the extension-tension relationship in loops is a crucial criterion in determining whether the fabric meets the strength and elasticity requirements necessary for use in a rehabilitation glove (Yu et al., 2012).

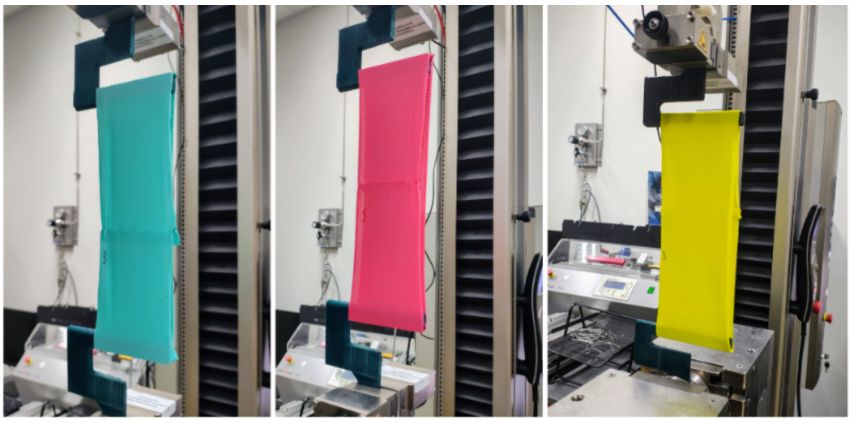
The experiment consisted of subjecting the fabric loops to elongations of 30%, 50%, and 70% during three cycles and recording the tension drop resulting from their elasticity. The applied force was kept below the breaking point, as the objective was only to analyze the load points. For each elongation level, five specimens were prepared for each of the three materials evaluated: Dry Spandex, Fluity-Unicolor, and Lenatex. The specimens were cut into pieces approximately 50 cm long and 10 cm wide and stitched to form a closed loop. The thickness of each fabric was measured as follows: Fluity (0.6 cm), Dry Spandex (0.74 cm), and Lenatex (1.01 cm). Before testing, the fabric samples were left to rest under no loop tension for 16 hours. On the test day, they were placed on 13 mm diameter hooks designed for tensile movement tests, initially positioned 25 cm apart in the same plane.

The Z050 testing machine by ZwickRoell was used, equipped with a 1 kN load cell, and operated with the TestXpert III software. Cycle tests of loading and unloading were performed at a speed of 300 mm/min, recording each data point corresponding to the loop tension curves during the three cycles. The procedure began with a preload of 0.5 N in the first cycle, followed by the tensile extension of the fabric up to the aimed elongation. Then, the fabric was relaxed to 10% elongation before continuing with the remaining cycles. This process was executed for all specimens of the three fabrics at 30%, 50%, and 70% elongation, as shown in Figure 6.

Due to the intended use of the glove and wristband in continuous movement therapy, an expected elongation of 40% is considered, particularly in areas such as the fingers, where the fabric stretches to accommodate both the finger and the soft actuator. In this context, the 30% and 50% elongation results correspond to expected usage conditions, while the 70% elongation represents an extreme case. The calculation of the tension (T) in the fabric is obtained by dividing the measured force (F) required to achieve the desired elongation level by the cross-sectional area of the fabric (A), as shown in Equation 1. The results of the tension decay are obtained by comparing the percentage of tension drop between the first cycle (T_0) and the third cycle (T_1), as shown in Equation 2.

$$Tension = \frac{F}{A} \tag{1}$$

$$Tension\ decay = \frac{T_0 - T_1}{T_0} x100\% \tag{2}$$



(a) (b) (c)

Figure 6 Executed Tensile Tests by Elongation Percentage at 30%, 50%, and 70%: (a) Fluity-Unicolor, (b) Dry Spandex, (c) Lenatex.

b) Satisfaction level survey for children

Ten surveys were conducted with children aged 8 to 12 without CP, focusing on comfort, appearance, and usability to evaluate the prototype's reception. The participants had anthropometric characteristics similar to those of the target population. Working with a small sample of healthy children during the design phases of pediatric rehabilitation devices is supported by previous studies (Siering et al., 2019). As in that study, it was intended that, although the children were not diagnosed with a specific condition, they were familiar with the concepts of medical treatment and physical therapy.

The children were accompanied by their parents, who were informed about the study and signed a consent form. Participants were asked to wear the rehabilitation glove and wristband during a continuous movement therapy session, and immediately afterward, they completed a five-point Likert scale survey. The seven main questions were: "Is the device comfortable to use?", "Do you like how the product looks?", "The device size did not bother me", "I am satisfied with my experience using the device", "The device is easy to use", "I quickly learned how to use the device", "The instructions provided were clear and easy to understand" and "Do you feel safe when using it?".

The questions in the Likert-based usability survey were selected following a discussion with medical professionals from the Institute for Child Development (ARIE), aiming to gather the most valuable initial feedback from a pediatric user's perspective. Although this instrument is not based on standardized scales, the goal was to ensure the relevance of the glove for children, focusing on core aspects of usability, emotional response, and perceived safety during first contact with the device. To evaluate the survey results, the Wilcoxon Signed-Rank Test was applied to determine the position of the children's opinions in comparison to a neutral opinion, allowing for a statistical assessment with a small population.

3. Results and discussion

This section analyses the results obtained from the mechanical essays and satisfaction surveys.

3.1 Results of the mechanical essays to evaluate the material selection

The 30% elongation corresponds to an extension of approximately 7.5 cm, 50% to 12.5 cm, and 70% to 17.5 cm per specimen. As shown in Figure 7(a), the Dry Spandex specimens exhibited the lowest tension drop at all elongation levels, indicating that they are the most stable fabric under repeated loading cycles, with a high recovery capacity that allows them to stretch easily without exceeding their limit. This information indicates that the material exhibits low energy loss during loading and unloading cycles, resulting in reduced heat dissipation between cycles. This is an essential characteristic because the material is in direct contact with the patient's hand.

Fluity specimens exhibited in Figure 7(b) show a significant tension loss at high elongations, indicating a lower recovery capacity and the presence of residual stress. Therefore, they require more force to reach the desired elongations, resulting in a higher tension loss; however, they provide better initial support due to their greater relative stiffness. Although this stiffness could become a disadvantage during repeated cycles and heat dissipation, its use is complemented by Dry Spandex, providing overall comfort.

The Lenatex specimens also showed a considerable tension drop near the levels of Fluity but required greater forces to reach these elongation levels. This indicates that Lenatex specimens have an even greater initial stiffness but offer better energy efficiency. While this stiffness may reduce comfort, the wristband's perforated design requires less initial elongation than the glove. Moreover, it is suitable for withstanding high forces without causing excessive fabric extension while maintaining good consistency, as shown in Figure 7(c), which aligns with its function of directing wrist movement where higher forces are exerted.

When analyzing the variance of the tension decay at different elongation levels, as shown in Figure 7(d), the Lenatex fabric demonstrated the lowest variability among specimens, reflecting good uniformity in composition and fabrication that maintains consistency even under high loads. This high consistency and low variance make it suitable for applications that require a uniform and predictable mechanical response, such as wristbands. On the other hand, Dry Spandex specimens show considerable uniformity at lower tension levels, making it suitable as an inner material without direct actuator action. Finally, the Fluity fabric exhibited higher inconsistency at high elongation levels, indicating lower uniformity under high mechanical demand. However, its moderate stiffness provides user comfort, making it suitable for controlled mechanical stress applications, such as finger movements during rehabilitation sessions.

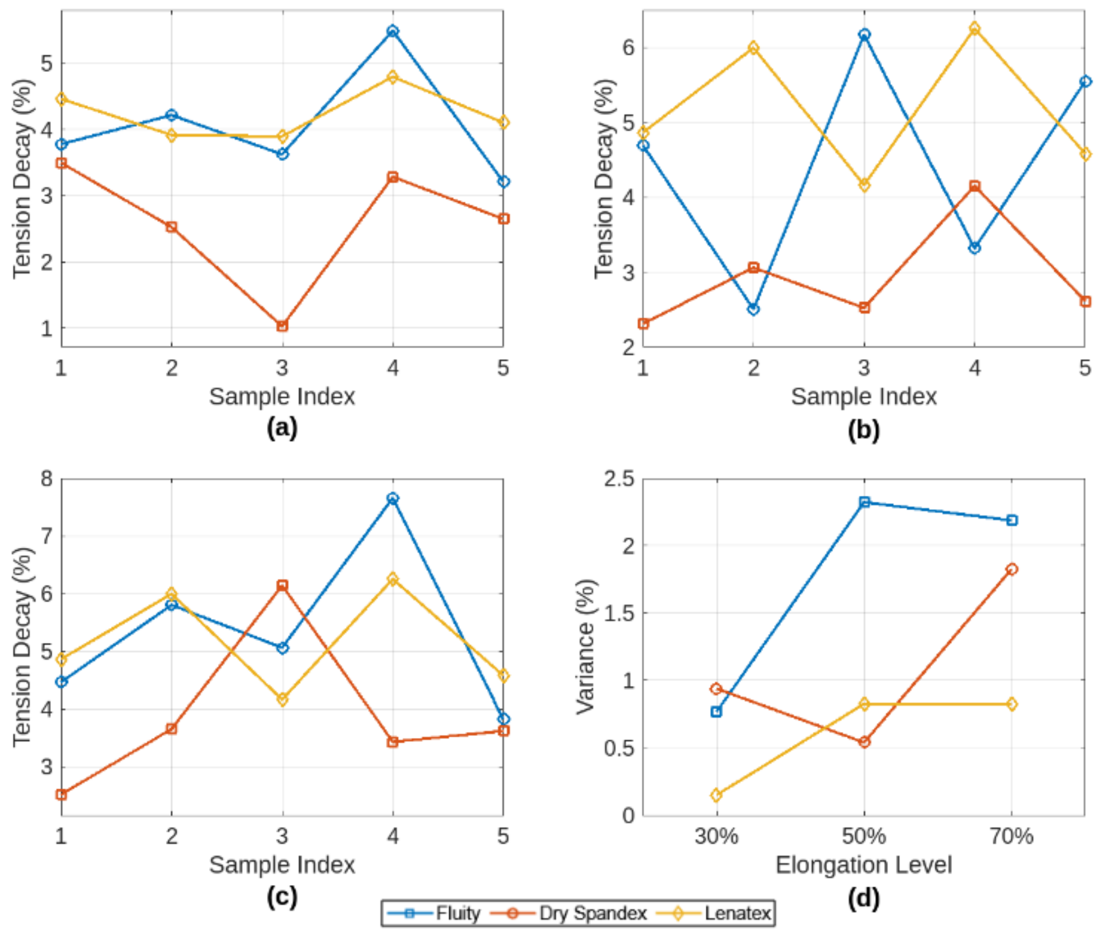


Figure 7 Tension drop for fabrics specimens of Fluity-Unicolor, Dry Spandex, and Lenatex at: (a) 30% elongation; (b) 50% elongation; (c) 70% elongation, (d) variance in tension decay of spandex fabrics at 30%, 50%, and 70% elongation.

3.2 Results of the user satisfaction survey

The survey results reflect the opinions of 10 children about the device's comfort, appearance, and size. Figure 8 presents an image of a child using and testing the device. In Table 4, the survey results are presented, and the statistics are shown in Table 5. Responses were converted to a 5-point numeric scale, where 1 = Strongly Disagree and 5 = Strongly Agree, to provide a more straightforward overview of the tendencies.

(a) (b)

Figure 8 A child using the device: (a) the glove; (b) wristband.

The comfort-related question obtained 50% agreement with a median of 3.5, suggesting that even if the children didn't express a refusal to the glove, there remains a challenge in integrating the pneumatics and electronics of the system while maintaining comfort. A total of 90% of participants reacted positively to the product's appearance, with 40% strongly agreeing. This reflects a favorable perception of the design, consistent with a median score of 4. Questions related to ease of use showed a favorable perception in most answers, as the device was rated with a median of 4 for ease of use, 3.5 for quick learning, and an outstanding 5 for clarity of instructions, with 70% of the children strongly agreeing. These results indicate that the children had no difficulty understanding the device's functioning with accessible guidance. The sense of safety, with 80% of the answers distributed between "agree" and "strongly agree", reinforced that, despite being a prototype with embedded technology, the glove was perceived as safe and friendly for children in this age group. Finally, only one participant gave a low score in the satisfaction question, indicating that most children didn't associate the use of the glove and wristband with a bad experience, which is relevant given its therapeutic purposes.

Other relevant statistics from the survey, presented in Table 5, include IQR values, which reflect the dispersion among the participants' opinions. This parameter indicates the variability of opinions in children and achieves a low value in aspects such as clarity of instructions, aesthetics, and satisfaction, suggesting high agreement in these areas. This high level of agreement in positive responses indicates that clarity, safety, and appearance of the device were well received and consistent across participants. To test whether these responses differed significantly from a neutral opinion (neutral = 3), a Wilcoxon Signed-Rank Test was conducted for each question. This non-parametric test compared the observed medians against the neutral opinion, yielding Z-scores and p-values. The strongest response was "I am satisfied with my experience using the device" ($Z = 1.96$, $p <= 0.05$), which was statistically significant, confirming that children's experience was reliably positive and enjoyable. Similarly, the question "Do you like how the product looks?" showed a low p-value and a positive Z-score, far from the neutral value, highlighting aesthetics as one of the strongest points of the design. However, other questions, such as the one referring to the size of the glove, yielded a higher p-value ($p > 0.05$), indicating a lack of statistically significant deviation from neutrality. The question "Is the device comfortable to use?" yielded an IQR of 2 and a Z-score of 0.7, with $p = 0.484$, indicating a varied response and no significant deviation from neutrality. Although certain aspects of the device were well received, the mixed responses from the children in areas like comfort and initial usability require further refinement.

Although the robotic glove achieved a good balance between resistance, comfort, and aesthetics, several limitations remain to be addressed. The selected fabrics should be tested for durability and hygiene challenges under prolonged use. While the materials were well received in terms of comfort by children and were able to support the weight of the electronic and pneumatic components, some tension decay was observed, as is typical of elastic fabrics. The decay was low, but it became necessary to implement an adaptive control to compensate for the changes in the forces due to the reduced resistance of the fabric over time. It is also essential to consider that the evaluation of user acceptance was limited to short-term exposure and was not tested in long-term scenarios, such as actual rehabilitation therapy. Finally, the design of the glove was based on anthropometric data and may require further adjustments to achieve a better, tailored fit that meets specific therapeutic needs.

Table 4 Distribution of participants' responses in percentages of the usability survey

Question	Strongly agree	Agree	Neutral	Disagree	Strongly Disagree
Is the device comfortable to use?	20%	30%	20%	20%	10%
The size of the device didn't bother me	20%	10%	30%	20%	20%
Do you like how the product looks?	40%	50%	0%	0%	10%
The device is easy to use.	20%	40%	20%	0%	20%
I quickly learned how to use the device.	30%	20%	30%	10%	10%
The instructions provided were clear and easy to understand.	70%	10%	10%	0%	10%
Do you feel safe when using it?	40%	40%	20%	0%	0%
I am satisfied with my experience using the device	60%	10%	20%	0%	10%

Table 5 Descriptive statistics of usability survey responses

Question	Median	IQR	Z-score	p-value
Is the device comfortable to use?	3.5	2.75	0.7	0.484
Do you like how the product looks?	4	1	2.52	0.012
The device is easy to use.	4	1	0.7	0.484
I quickly learned how to use the device.	3.5	1	1.26	0.207
The instructions provided were clear and easy to understand.	5	0.75	2.52	0.012
Do you feel safe when using it?	4	1.5	2.52	0.012
I am satisfied with my experience using the device	5	1.75	1.96	0.05

4. Conclusions

The present research aimed to design the textile component of a soft robotic glove for pediatric rehabilitation, carefully combining functionality, aesthetics, and ergonomics. A design of the glove was proposed to accommodate both pneumatic and electronic components while ensuring comfort and versatility through the incorporation of breathable and flexible materials, such as spandex and nylon. nylon. The choice of gentle textures, amiable colors, and a tidy exterior was made to establish a positive emotional connection with young users. After several prototypes, the system was implemented in a modular structure designed for a simple setup to encourage autonomous use. According to ASTM mechanical tests with the fabrics, Lenatex had the most consistency and rigidity, making it suitable for the wristband; Fluity provided moderate stiffness despite higher fatigue sensitivity, which is a good balance between commodity and stiffness for the outer layer; and Dry Spandex performed best at low elongations, making it a good option for the inner layer of the glove. Although additional fatigue tests of the system are recommended to be conducted under real conditions to evaluate the performance of the fabrics with patients, the obtained results confirmed that the selected materials are suitable for their intended purpose on the device. Furthermore, user surveys from children showed that the glove's size and appearance were well received. The findings of this survey suggest that even when comfort ratings were neutral, the modular design allows specific modifications to improve the user experience, agreeing with the integration of technical and emotional considerations during the development of pediatric devices. Future research should investigate the long-term effectiveness of the glove to assess its adherence and therapeutic impact, analyze tension decay in long-term tests such as clinical environments, and consider incorporating a version of the Technology Acceptance Model (TAM) to evaluate the ease of use and long-term intention to use the technology. Moreover, it is recommended to explore the use of the system in children with CP at different stages to evaluate at which severity level it can be most valuable.

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Author Contributions

Conflict of Interest

The authors declare no conflicts of interest.

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