Assisted Child-centered Interactive Therapy Space Design

Integrating Multidisciplinary Perspectives to Design a Therapeutic Child-centered Play Space for Autistic children with Hybrid Material Systems

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1 Configuration of the final prototype was tested by children to ensure usability

ABSTRACT

Computational design and fabrication have expanded the possibilities for creative exploration and the development of diverse sensory experiences. For autistic children with sensory processing difficulties, a suitable sensory environment can reduce stress and emotional dysregulation, enhance learning focus, and improve social interactions. Inspired by Temple Grandin's "Hug Machine," this study aims to construct a therapeutic play space prototype that incorporates an alternative play therapy approach. The prototype includes diverse movement pathways and a responsive mechanism delivering varying levels of pressure through a hybrid material system. In this context, the sensation of embrace is provided by the play space designed with CNC-knitted textiles, rather than a machine. The tunnel spaces, some equipped with an interactive pneumatic system, allow users to intuitively switch between different modes based on their play experience, resulting in a range of deep pressure sensations. The project empowers users to engage in mixed sensory experiences, providing crucial feedback for children who are over- or under-responsive to sensory inputs during play. This design focuses on utilizing established technological frameworks such as digital knitting, pneumatic systems, and user-centered design methodologies to support children with autism in navigating sensory processing and social interaction challenges. Collaboration among architecture, computational design, human-computer interaction, and practitioners in ASD therapies is essential for the project.

INTRODUCTION

According to an analysis from the CDC (Centers for Disease Control and Prevention) published in the Morbidity and Mortality Weekly Report (MMWR) in May 2023, one in 36 (2.8%) 8-year-old children has been identified with autism spectrum disorder (ASD), an increase from the previous estimate of one in 44 (2.3%) in 2018. Autism spectrum disorder is a lifelong neurodevelopmental condition characterized by early impairments in socio-communicative skills, along with a set of restricted interests and/or repetitive stereotypical behaviors. Most children with ASD experience impaired sensory processing, which affects their perception of sounds, touch, body movement/position, sight, taste, and smell. This sensory input can lead to behavioral responses known as sensory processing difficulties.

Sensory processing difficulties are common in children with ASD and can variably affect abilities in self-regulation, movement, learning, and interaction with others (Allen et al., 2011). Research efforts have focused on identifying precursors to ASD, resulting in a significant decrease in the age of diagnosis, which facilitates earlier intervention. However, due to the wide range and intensity of characteristics that can vary greatly from child to child, developing learning tools and therapies tailored for children with ASD is quite challenging, as these tools need to be specific and unique for each individual.

Play therapy is a versatile therapeutic approach that addresses the diverse needs of children, particularly those on the autism spectrum. In most children under 11 years of age, the capacity for abstract thinking—a prerequisite for expressing meaningful language and understanding complex issues, motivations, and emotions—is not fully developed (Piaget, 2013). Thus, in play therapy, play is utilized as a vehicle for communication between the child and therapist. It is based on the premise that children will use play materials to express their feelings, thoughts, and experiences either directly or symbolically (Schaefer, 2011). This adaptability enables therapists to customize play activities according to each child's individual preferences and sensory sensitivities, creating a safe environment for exploration and interaction.

Another effective therapeutic technique is deep pressure therapy (DPT), which involves applying sustained pressure to the body. DPT was first reported in occupational therapy as producing a calming effect through the modulation of central nervous system (CNS) sensory information processing (Ayres, 1972). In the 1990s, Temple Grandin developed a squeeze machine, originally created as a stress-relieving device to help her calm down. The principle behind this device is to provide "hug" stimulation, where the deep pressure effect calms the user. This tool was developed based on her own experiences as a patient with ASD, who frequently experienced heightened states of anxiety and hyperactivity (Grandin, 1992).

This research closely examines two evidence-based therapeutic approaches through the use of digital knitting and child-machine interaction technologies, aiming to create a dynamic play space that offers individualized therapeutic support for children with autism. In this project, the play space is defined as a hybrid system composed of two parts: a digital knitting textile, which serves as both a spatial and tactile surface, and a responsive system consisting of a pneumatic setup with silicone tubing and bladders integrated into the textile. The term "material system" refers to the interplay between materiality, form, structure, and space, alongside the multitude of performative effects that arise from their interaction with environmental influences and forces (Menges, 2013). Heino Engel (2007) defines the concept of hybridity in material systems as the intermixing of structural actions. In this paper, the prototype is characterized as a hybrid material system that combines Computer Numerical Control (CNC) knitted textiles with silicone bladders activated by a pneumatic system.

The motivation behind this work is to propose a hybrid material system that integrates two evidence-based therapeutic approaches to create a personalized play space for assisted therapy. Interdisciplinary design validation is a crucial process to ensure that user characteristics and requirements are adequately reflected in the design. To this end, we conducted a nine-week field study involving 18 children with autism to investigate, observe, and analyze their interactions with the prototypes.

LITERATURE REVIEW

Therapy approaches for autistic children

Child-Centered Play Therapy (CCPT) is a therapeutic approach that allows children to express their experiences and feelings through play, their natural mode of communication. This method is grounded in the belief that play is crucial for children's cognitive, emotional, and social development. The non-directive nature of this therapy provides a safe and supportive environment where children can explore their emotions and thoughts without fear of judgment or failure. This freedom can be particularly beneficial for children with Autism Spectrum Disorder (ASD), who often face challenges in traditional communication and social settings. Research has demonstrated the effectiveness of CCPT in improving emotional, social, and behavioral outcomes in children with ASD (Lin et al.,, 2015). A study by Ray, Stulmaker, and Lee (2013) showed that CCPT led to notable improvements in social interaction and communication skills among children with ASD. These findings support the theory that a safe and accepting environment enhances the motivation and capacity of children with ASD to interact freely and naturally with their external environment, thereby improving their self-healing power. Overall, CCPT is a promising intervention for increasing emotional and social behaviors in children with ASD.

Deep pressure is defined as the “sensation produced when an individual is hugged, squeezed, stroked, or held” (Krauss, 1987). The use of deep pressure for individuals with autism spectrum disorders has gained attention since Temple Grandin described her self-designed "hug machine," which provided her with the pressure sensations she craved (Grandin, 1986). Other forms of deep pressure therapy include weighted garments, swaddling, holding, stroking, hugging, squeezing, and therapeutic brushing (Chen et al., 2013). For example, Blairs et al. (2007) implemented a program of non-contingent deep pressure using bed linen (swaddling) for an adult with autism, severe anxiety, and intellectual disability. They proposed that he might benefit based on his previous positive experiences with being hugged by his mother during distress and his preference for wearing a tightly fitting coat in anxiety-provoking situations. As an adult, he was observed to be more relaxed when tightly tucked into bed or physically restrained. Following the introduction of non-contingent deep pressure, episodes of restraint and as-needed medication were used less frequently to manage his behavior. Additionally, physiological indicators of stress, such as blood pressure, heart rate, and respiration rate, reduced after implementing this form of deep pressure.

Hybrid material system

Previous studies have explored various pneumatic responsive systems and hybrid textile material systems. Projects such as PneuSystems utilized a control system that varied pressure within each pillow to drive the transformation of the overall assembly (Velikov et al., 2014). Earlier knit-constrained pneumatic systems concentrated on differentiation in knit structure to achieve specific geometric results while utilizing standard elastomeric bladders (Ahlquist, 2016; Baranovskaya et al., 2016). The development of seamless pneumatically actuated systems, whose motion is controlled by a combination of differentially knitted textiles and standardized thin-walled silicone tubing, has also been investigated (Ahlquist et al., 2017). Furthermore, Sean Ahlquist has explored the potential of machine knitting as an information-mediating interface for responsive environments specifically designed for children with ASD (Ahlquist, 2016). Additionally, 3D digitally knitted fabric canopy structures composed of responsive tubular and cellular components utilize recycled textiles, along with photo-luminescent and solar-active yarns that absorb and store UV energy, change color, and emit light (Sabin et al., 2018).

Current state-of-the-art research has focused on material systems (including surface-responsive, high-tech, and high-performance composite fabrics in knitting technology and silicone bladders), hybrid structures, and responsive environments. While Sean Ahlquist's work has demonstrated the use of machine knitting in the context of autism therapy, there are still numerous opportunities to integrate machine knitting and responsive systems with a variety of therapeutic approaches. This paper presents the design and fabrication of a prototype that combines two therapeutic methods for children with autism, alongside the interdisciplinary design and validation of the prototype with practitioners in the field of autism treatment.

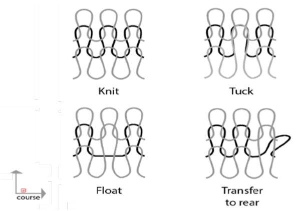
METHOD

The main components of the research included the fabrication of hybrid material systems through CNC knitting workflows, as well as the development of a pneumatic responsive system, complemented by an interdisciplinary collaborative design workflow.

Textile hybrid material system

CNC knitting technology facilitates the creation of highly customizable, flexible, and tactile interfaces, making it ideal for therapeutic environments. In this research, an industrial dual-bed weft knitting machine was employed to manufacture highly differentiated textiles, which serve as the tensile component of a hybrid material system. Before the design process, a series of textile material experiments were conducted to understand the fundamental aspects of applying digital knitting technology. Weft knitting forms a textile by looping yarn fibers in the horizontal (weft) direction, with each loop defining a wale and each row of wales defining a course. Critical variables such as stitch length, stitch pattern, and yarn material greatly influence the amount of yarn allocated to each stitch (Figure 2). Generally, with CNC knitting, the stretch properties of textiles can be controlled by adjusting the length, material, and type of each stitch. The material experiments aimed to identify the relevant parameters of the textiles to meet the design requirements (Figure 3).

Another critical aspect of CNC textile technology is knitting techniques, which control the geometry of the textile. This paper explores textile techniques for fabricating four



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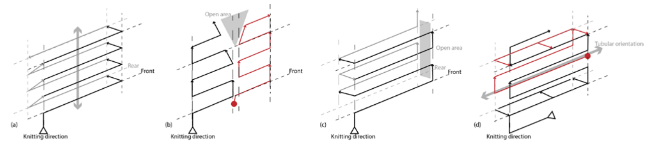

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2 Stitch types

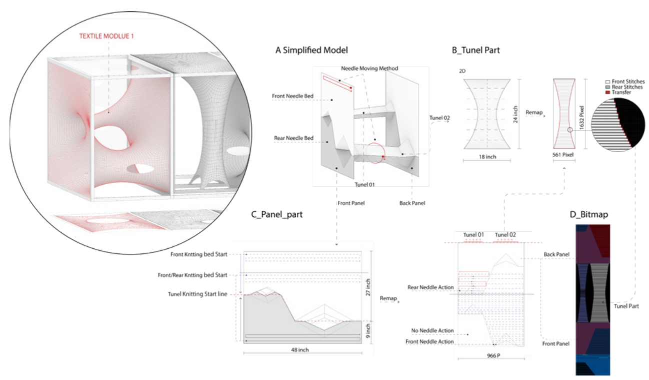
3 CNC Knitting material experiment from bitmap to textile

4 Four fundamental knitting techniques

specific geometries, which are applied in the development of the final prototype (Figure 4).

- Non-uniform tubular structure: There are various methods for fabricating this structure. The method employed in this paper utilizes yarn and the front and rear needle beds of the knitting machine, with the yarn moving in a circular motion between the front and rear. The advantage of this method is that a panel structure can be attached to the front and back needle beds before entering the tubular structure. This panel structure makes it easy to adjust the number of stitches in each course, allowing for the realization of an asymmetric tube geometry. Also, the knitting direction aligns with the orientation of the tube, theoretically enabling an unlimited tube length.
- Panel structure with holes: The knitting of holes on a panel requires the use of two yarns on one needle bed. These two yarns are knitted independently on each side of the desired opening to create a natural hole.
- Panel structure with pockets: The mechanism is similar to that of a tubular structure. Yarn is switched between the needle beds only on the side that does not require an opening, resulting in holes at specific locations in the two layers of the knitted textile.
- Muti-tubular structure: This method allows for separate control of the number of stitches knitted in the front and rear, as well as the length of each yarn. The asymmetrical distribution of material in the front and back of the textile enables control over the bending direction and shape of the silicone tubing to a certain extent when it is inserted into the textile tube and inflated.

Based on research into knitting technology, the development of an efficient and reproducible digital fabrication workflow supports rapid design iteration. The CNC knitting machine used in this project utilizes Mplus software as an interface for editing design files. While editing stitch attributes is straightforward in this software, it lacks the capability to translate digital models into knitting files, necessitating manual editing for non-planar geometries. To minimize manual work, Bitmap files were selected as information carriers to link Mplus with other design software involved in this research. In Rhino, a class was created to include the various properties of a stitch while inheriting the attributes of the point class. This design enables digital simulation by allowing interaction with other geometric types within the digital model. Subsequently, the stitch class is converted into a 2D graphic, and this information is transformed into a bitmap using Python's Pillow library. In the bitmap, each pixel represents a stitch, with pixels of different colors indicating different types of stitches. In Mplus, specific colors are assigned to particular stitch types, ensuring that only these colors need to be used in the bitmap generation process to successfully transfer stitch information for knitting (see Figure 5).



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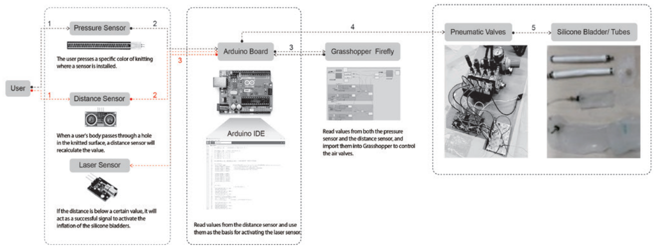
5 Digital fabrication workflow

Interactive Pneumatic Control System

Pneumatic systems are constructed to actuate silicone components integrated with textiles, providing depth pressure. Pneumatic valves can be categorized into two primary types: on/off valves and proportional valves. Proportional valves offer the highest degree of control by translating an electrical input signal and input air pressure into a controlled output pressure within the rated flow limit. However, the main drawback of proportional technology is its high cost. As an alternative, this paper integrates air pressure regulators into on/off valves to achieve some functions of proportional valves at a lower cost. The specific workflow of the pneumatic system is as follows



6 Pneumatic control system workflow

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(Figure 6): A sensor integrated into the textile connects to the input port of the Arduino circuit board. When the sensor is triggered (e.g., a pressure sensor detects pressure), the signal is processed by the Grasshopper component FIRFLY and output through the Arduino port, converted by a voltage converter to the required voltage to activate the solenoid valves. These solenoid valves control the output of air pressure from the pneumatic tank, managed by the air pressure regulator, by changing their open or closed state. In this process, the air pressure regulator is manually set to a fixed value—one that has been pre-tested to match the connected silicone product. Continuous air pressure variations can be simulated by adjusting the switching duration.

On the input side, different sensors can serve as sources of input signals (in this study, both pressure and proximity sensors were tested). The output signals can be more flexibly converted in FIRFLY, allowing for greater variations in the depth pressure provided by the silicone assembly. For instance, at a specific input value, the silicone tube can be programmed to inflate for one second, hold for one second, and then release the air.

Integrating multidisciplinary design process

Creating an effective, safe, and practical therapeutic play space for children with ASD using CNC knitting and a pneumatic system involves several key principles:

- Understand the limitations and advantages of CNC knitting. CNC knitting technology enables the creation of highly customizable, flexible, and tactile structures. These knitted structures can integrate silicone tubes that, when inflated, provide deep pressure therapy, which is essential for sensory regulation in children with ASD.
- Integrate knowledge from ASD therapy professionals Collaborating with occupational therapists and specialists ensures that the play space aligns with therapeutic goals. Gathering feedback from children with ASD through testing is vital for refining the design to promote sensory integration, emotional regulation, and social interaction.
- Prioritize privacy and security. The design must guarantee that the play space is safe and secure, minimizing any potential physical risks to children. Furthermore, data collected for research and therapeutic purposes should be adequately protected to ensure confidentiality.
- Design for adaptability. The play space should facilitate user-driven modifications to accommodate changing needs. This flexibility allows for reconfiguration or adjustments based on the ongoing feedback from children and therapists, thereby enhancing the long-term utility and effectiveness of the design.
- Ensure ease of transport and installation. The design scale should be suitable for diverse settings, including homes, schools, and therapy centers, facilitating easy transport, installation, and de-installation.

7 Prototype iteration and On-Site research at the therapy center

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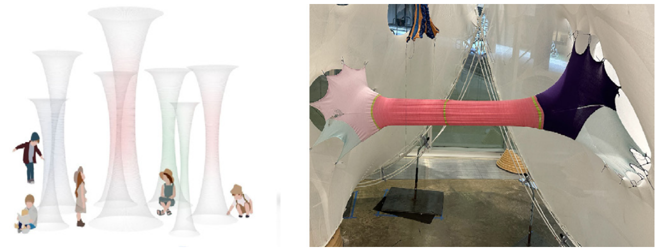
Three iterations of test prototypes were developed prior to the final version (Figure 7). Each prototype was reviewed by professionals in the fields of autism therapy and computational design and was also tested by children with ASD to inform the development process. Below, the design intentions and details of these three test prototypes are presented:

- The prototype of a responsive textile was developed through research into materials, fabrication processes, and digital knitting technology, as well as the expansion properties of silicone materials. This prototype demonstrated the practicality of the workflow from digital modeling to physical fabrication for the primary interactive interface of the play space and showcased the feasibility of using silicone materials to provide deep pressure. Two therapists specializing in autism therapy and a materials professional reviewed the prototype, discussing its potential applications in assisted therapy for children with autism (Figure 8).
- Each member of the design team participated in at least two one-hour occupational therapy sessions for children with autism. Following these sessions, we summarized and exchanged potential design directions based on our observations. This collaborative process allowed us to establish a design concept informed by both our observations and a literature review on therapy approaches, ultimately leading to



8 Design concept and prototype 01

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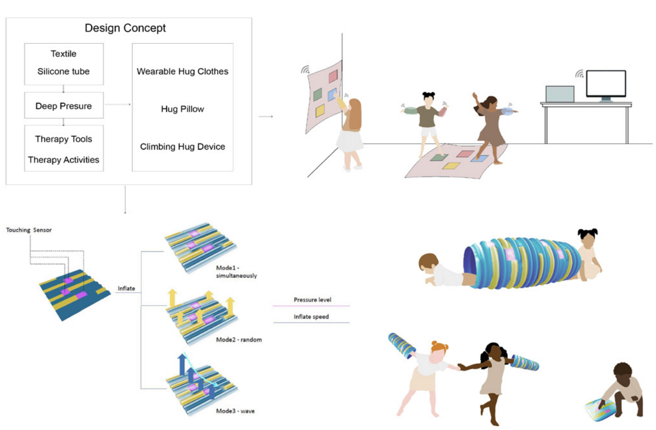
the completion of the second prototype for testing. This prototype was designed to provide deep pressure through a pneumatic system, which inflates and deflates a silicone tube embedded within the textile material, offering varied pressure experiences to the user. By pressing a textile "pillow" integrated with pressure sensors at different force levels, users can activate the pneumatic system to produce various modes of air pressure output to the silicone tube (Figure 9). Technically, the prototype demonstrated the pneumatic system's capability to control pressure output based on sensor input (Figure 10). Fifteen local adolescents aged 12-15 with autism, along with two therapists, tested the prototype in our lab. During the testing, we observed the users' interest in the dynamic textiles, as they engaged in behaviors such as pinching the expanding parts of the textile with their hands, attempting to understand how to trigger the textile's expansion or contraction, and wrapping the textile around their bodies to feel the pressure provided. These observed behaviors validated our design assumptions regarding the deep pressure therapy approach and provided positive feedback for further design improvements.

- Based on the feedback collected from the previous versions of the prototype, along with the technical insights gained from the first two prototypes, we fabricated a third prototype in the lab and transported it to



9 Design concept of prototype 02

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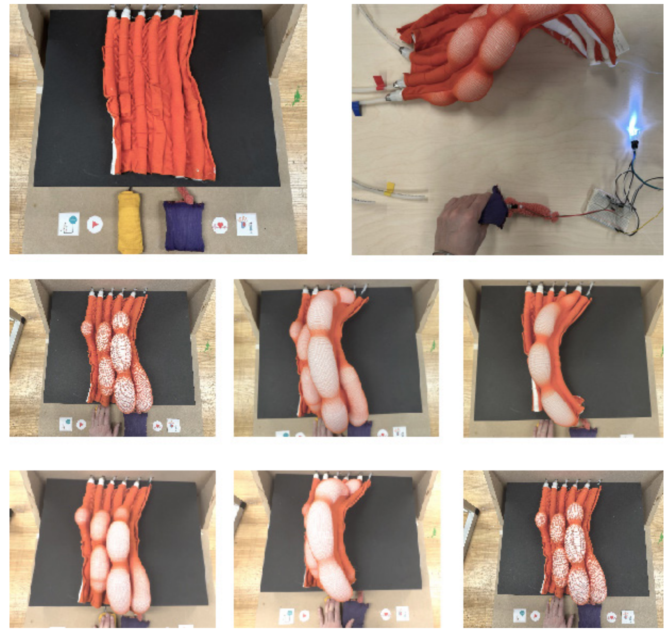

10 Prototype 02 and test process

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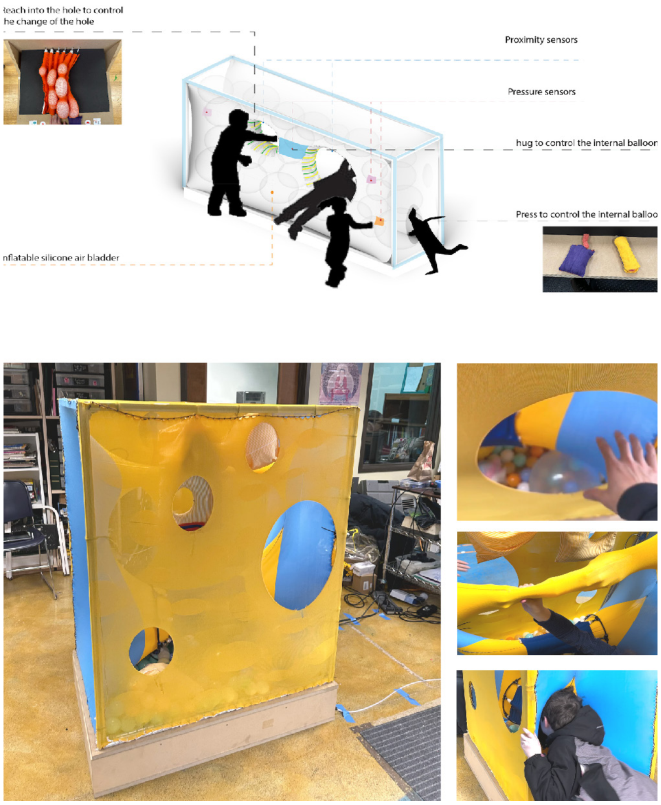
an autism therapy facility for testing with 15 children with autism and two five-year-olds (Figure 11). This prototype served as a preliminary version of the final design, fully realizing the intended technical flow and undergoing assessment during the lab assembly, disassembly, transportation, and reassembly processes. During the reinstallation process at the autism therapy facility, several design defects were identified, including failures in sensor hardware connections caused by transport, an increase in reassembly time (which escalated from the expected 2 hours to 5 hours), and the unreasonable positioning of the pneumatic control system (located at the bottom of the design, which made it difficult to repair in the event of a breakdown). These findings provided critical guidance for improving the design and ensured that the testing process for the final prototype would be successful. During testing, we observed a variety of activities unfolding around the tubes and the holes in the textiles. Users attempted to insert their hands into the thinner tube or control the pneumatic system of the thicker tube by pressing special points on the textile (which contained pressure sensors), while also leaning their heads into the tubes to experience the deep pressure. Notably, one behavior that exceeded our design expectations occurred when a little girl expressed a desire to enter the interior of the textile. With the help of a therapist, she crawled through the holes into the inside, where she felt comfortable. (This possibility had not been considered in our design process but inspired us to think about how to integrate the internal space of the design) Feedback from this testing helped us determine the overall dimensions of



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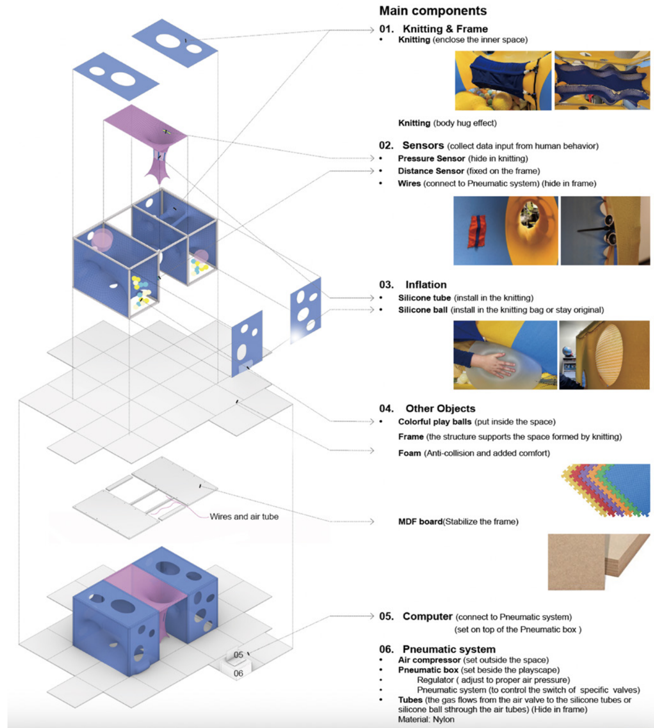
11 Design concept and prototype 03/Activities observation



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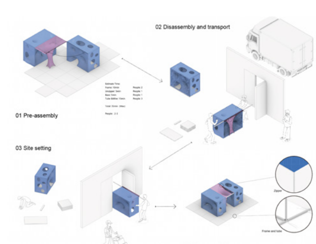
12 Main components diagram of the final prototype

the final prototype, refine the specific flow of interaction, optimize sensor placement, and identify potential activities that could occur around and within the play space.

RESULTS AND DISCUSSION

The final prototype was evaluated over four days at a local autism therapy organization, involving 18 autistic children aged 3 to 6 and 5 practitioners specializing in autism therapy to validate its feasibility. The main body of the design consists of a portable, detachable metal frame that serves as the primary support structure, along with five seamless textiles configured as a tensile structure. This tensioned textile forms four horizontally oriented tubular structures and one vertically oriented tubular structure. Two of these tubular structures incorporate textiles with built-in silicone tubes that can be inflated and expanded when a child's body or arm enters the tubular structure or presses on the sensors embedded within, thereby providing deep pressure (Figure 12). The panels on both sides feature holes designed to engage the child by allowing them to look through or enter the textile-enclosed interior space. Two of these holes are equipped with distance sensors, lights, and a pocket for the silicone bladder. When a child crosses through these holes, the sensors are activated, the lights turn on, and the silicone bladder rapidly inflates and expands inward, delivering deep pressure to those inside the space. Small balls were strategically placed around the design to enhance interaction. Additionally, some holes have zippers sewn around the edges, enabling quick opening and closing. The prototypes are designed to be adaptable to various usage scenarios and allow for quick assembly. Two small frames were pre-assembled and transported, allowing for rapid setup at the test site using zippers along the textile edges. (Figure 13). Extra tubular knitted textiles with zippers at both ends are provided to connect adjacent holes, allowing for space reconfiguration. The zippers also facilitate easy assembly (Figure 14). Furthermore, a user manual was created to assist therapists in effectively utilizing the design (Figure 15).



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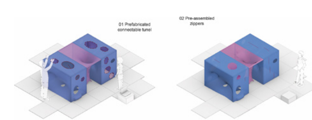

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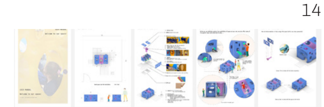

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13 Diagram of Prototype disassembly for transportation and Assembly Process

14 Redesign System through zippers integrated in textiles

15 User manual for Companions assisting children during Use

16 Final Prototype in the treatment Room of the Center. The ventilation tubes and control components of the pneumatic system are concealed by foam floor mats to prevent any potential accidents during children's exploration."

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Testing and Observation

With the therapy center's consent, we conducted on-site observations, collected transcripts, and made video recordings of the children's interactions with the design for subsequent analysis (Figure 16). To protect privacy, all publicly viewed photos and videos were carefully edited to obscure the facial features of the participants. Our observations during testing were summarized as follows: activities anticipated by the design were confirmed, unexpected activities beyond the design occurred, and some activities expected by the design did not manifest (Figure 17).

Several straightforward activities were frequently observed, including crawling through the passageway, standing inside the central tube to feel the pressure, interacting with the tube using a ball, and engaging in ball play with the therapists. Additionally, our design stimulated the children's interest in independent exploration. They discovered ways to make themselves comfortable that were not initially intended, such as lying on and climbing on the fabric, using it as a cradle, and exploring the design in other creative ways. The prototype also encouraged the child's desire to communicate; for instance, children actively expressed a wish to interact with the therapists by passing the toy ball or asking for help during the climbing process (Figure 18). However, no interactions with the pneumatic system—triggered by pressing or moving through specific areas—were observed. This deviation from our design expectations might be attributed to two primary reasons: the interactions may not have been intuitive enough for the children to comprehend, and the testing period may have been too brief for the children to fully explore the more indirect interactions intended by the design.

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13 Observation Summary and activities analysis

Future work

Based on the results of field tests with autistic children and evaluations from several professionals in the fields of autism and child education, future work should focus on simplifying interaction mechanisms and increasing design variety.

- First, this includes enhancing trigger mechanisms by providing more obvious cues, such as using distinct colors in the trigger areas of the textiles. Additionally, incorporating feedback mechanisms like real-time audio feedback could help autistic children better understand how their actions trigger specific system responses. Furthermore, developing more sensitive and reliable

18 Interaction Activities during final prototype testing.

sensing systems—such as replacing physical sensors with computer vision—could offer improved insights into how the textiles are pressed, moved, and responded to by the children.

- Secondly, it is essential to further diversify the design. This can encompass expanding the overall space and varying the dimensions of the passageways to increase the possibilities for children's activities. Diversifying textile materials can provide children with different tactile sensations and pressures. Lastly, research on how textile colors stimulate sensory experiences in children should be introduced to enhance engagement and interaction.

CONCLUSION

The prototype of the play space and interaction design responds to the sensory processing and social interaction challenges faced by children with autism. The user-centered exploration of the prototype reveals various possibilities for interaction—many of which extend beyond the original design intent—supporting sensory and emotional regulation as well as the development of social skills. Although the findings presented in this paper are still a long way from establishing an evidence-based therapeutic tool for autism, there is no doubt that our research represents a promising direction (utilizing computational design to integrate the advantages of different therapy approaches) for the future of early therapeutic practices for children with autism.

Additionally, the results of the prototype testing have opened up new topics for further research into the sensory experiences of children with autism, particularly regarding the colors, textures, material properties, and interactions of CNC textiles. This paper also provides a technology application template for expanding knowledge in the fields of computational design and digital fabrication, aimed at benefiting the ASD community. The documented design workflow could serve as a reference for interdisciplinary collaboration applicable to real-world needs.

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IMAGE CREDITS

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