

Defining the user needs for an assistive pediatric hand exoskeleton: An Italian explorative survey

Luca Emanuele Molteni, Denise Bentivoglio, Eleonora Diella, Emilia Biffi, Giuseppe Andreoni, Federica Bressi, Fabrizio Taffoni, Loredana Zollo & Fabio Alexander Storm

To cite this article: Luca Emanuele Molteni, Denise Bentivoglio, Eleonora Diella, Emilia Biffi, Giuseppe Andreoni, Federica Bressi, Fabrizio Taffoni, Loredana Zollo & Fabio Alexander Storm (14 Jan 2026): Defining the user needs for an assistive pediatric hand exoskeleton: An Italian explorative survey, *Assistive Technology*, DOI: [10.1080/10400435.2025.2596016](https://doi.org/10.1080/10400435.2025.2596016)

To link to this article: <https://doi.org/10.1080/10400435.2025.2596016>



© 2026 The Author(s). Published with license by Taylor & Francis Group, LLC.



[View supplementary material](#)



Published online: 14 Jan 2026.



[Submit your article to this journal](#)



Article views: 423












[View related articles](#)



[View Crossmark data](#)



Defining the user needs for an assistive pediatric hand exoskeleton: An Italian explorative survey

Luca Emanuele Molteni, MSc ^{a*}, Denise Bentivoglio, MSc ^{a,b*}, Eleonora Diella, PT ^a, Emilia Biffi, PhD ^a, Giuseppe Andreoni, PhD ^{a,b}, Federica Bressi, PhD ^c, Fabrizio Taffoni, PhD ^d, Loredana Zollo, PhD ^d, and Fabio Alexander Storm, PhD ^a

^aScientific Institute IRCCS, “E.Medea”, Bosisio Parini, Lecco, Italy; ^bDepartment of Design, Politecnico di Milano, Milano, Italy; ^cPhysical Medicine and Rehabilitation Unit, Campus Bio-Medico University of Rome, Rome, Italy; ^dCREO Lab, Università Campus Bio-Medico, Roma, Italy

ABSTRACT

Children with neuromotor disorders often experience hand impairments that limit independence in daily tasks as well as the acquisition of new skills. Robotic aids like hand exoskeletons can improve function, but many designs fail to meet user needs, reducing adoption. This study collected parental feedback to guide the development of user-centered hand exoskeletons. An anonymous online survey was distributed to the parents of children with neurological disorders and previously treated at IRCCS E. Medea – Associazione “La Nostra Famiglia” in Bosisio Parini, Italy. Only parents of children with upper limb impairments were invited to answer. The survey explored their perceptions of hand exoskeletons, focusing on functional needs, user-friendliness, and training expectations. A total of forty-six surveys were completed, of which three were incomplete and therefore excluded. Of the forty-three considered, 76.3% expressed interest in a hand exoskeleton for their child, identifying dressing, hygiene, and eating as key activities to address. Key issues in the development of an exoskeleton for the parents were weight, comfort, associated aesthetics and trust. User feedback emphasizes the need for comfortable, lightweight designs with aesthetic appeal to reduce stigma. Parents prioritized functional benefits for daily activities over recreational use.

ARTICLE HISTORY

Accepted 21 November 2025

KEYWORDS

Exoskeleton; hand; pediatric; survey; user needs

Introduction

Mobility and exploration are crucial components of physiological development in children and influence the progression of essential skills, including motor, cognitive, language, and social abilities (Lobo & Galloway, 2008; Thelen, 2012). Neuromotor disorders impair movement quality and increase risks of developmental delays (Lobo et al., 2015).



The human hand is vital for environmental interaction, and impaired function significantly affects daily living activities (ADLs) and quality of life (Boser et al., 2021; Pentland & Twomey, 1994). Research has shown that children with physical disabilities who utilize assistive devices to enhance their mobility experience improvements in environmental participation, independent activities, and self-awareness (Moir, 2010; Ryan et al., 2009).

The most common conditions associated with neuromotor disorders affecting hand function in children are congenital and acquired brain injuries, characterized by functional impairments that vary based on the location and extent of the lesion (Bleyenheuft & Gordon, 2014; Jackman et al., 2014; Mimouni-Bloch et al., 2023). Cerebral Palsy (CP) is among the most impactful conditions, affecting

hand function in nearly 50% of cases, causing muscle weakness, uncoordinated movements, spasticity, and reduced tactile sensitivity (Eck et al., 2010). In high-income countries, the prevalence of CP is 1.6 per 1000 live births. However, prevalence is higher in low- and middle-income countries. Advances in early detection make it possible to identify CP as early as 3 months of age, allowing for timely and intensive early intervention that improves outcomes for children and parents (Novak et al., 2025). Despite this, deficits persist which seriously hinder children’s ability to carry out activities of daily living, limiting their independence and general development (Falzarano et al., 2019; Fasoli et al., 2008; Novak et al., 2025).


While many assistive devices have been developed for lower limb mobility impairments, a significant lack of upper limb solutions specifically tailored for children needs to be reported (Crowe et al., 2019; Latif et al., 2024; Li et al., 2024). Given that hand function limitations significantly impact the ability to perform ADLs, effective assistive and rehabilitative technologies are crucial (Russo et al., 2009).

Research indicates that the needs of potential users of upper limb assistive technologies vary widely depending on the type

CONTACT Luca Emanuele Molteni  luca.molteni@lanostrafamiglia.it  Scientific Institute IRCCS, “E.Medea”, Bosisio Parini, Via Don Luigi Monza, 1, Lecco 23842, Italy.

*These authors contributed equally.

This article has been corrected with minor changes. These changes do not impact the academic content of the article.

 Supplemental data for this article can be accessed online at <https://doi.org/10.1080/10400435.2025.2596016>

© 2026 The Author(s). Published with license by Taylor & Francis Group, LLC.

This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives License (<http://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited, and is not altered, transformed, or built upon in any way. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

of device and the specific ADLs they aim to support. Tasks such as food manipulation, dressing, and handling nearby objects are particularly prioritized across different robotic solutions (Nam et al., 2019). To address these challenges, various assistive technologies have been developed, including adaptive orthoses for muscle support, robotic arms, functional electrical stimulation (FES) and wearable technologies such as soft robotic suits (Van der Heide et al., 2014). Among these technologies, hand orthoses are widely used to stabilize joints or facilitate controlled hand movements, aiding children in improving their functional abilities (Michalec et al., 2024). Among active devices, exoskeletons play an important role: wearable motorized systems that can act simultaneously on multiple joints (Maciejasz et al., 2014).

Active hand exoskeletons focus on restoring hand function by assisting finger flexion and extension (Du Plessis et al., 2021). These devices apply targeted forces to enable grasping tasks, guiding fingers into functional movements that may otherwise be unachievable or ineffective independently (Maciejasz et al., 2014; Peters et al., 2017). Numerous hand exoskeleton designs (Chiri et al., 2009; Cui et al., 2015; Lamercy et al., 2013; Randazzo et al., 2018; Schabowsky et al., 2010; Wang et al., 2018) emphasize features like adjustability to hand sizes, lightweight structures, and portability. However, as reported by Li et al. (2024), and Fosch-Villaronga et al. (2020), few studies focus on the pediatric population, revealing a significant gap in accessibility. A noteworthy example includes designs such as PEXO (Butzer et al., 2019), proposed by Lieber et al. (2022), which address challenges like accommodating children's growth and ensuring intuitive operation. Designing assistive devices for children presents unique challenges, including variations in motor abilities, physical growth, cognitive development, and limited communication of feedback (Botelho, 2021). Pediatric hand exoskeletons must address functional requirements and user needs to ensure long-term usability and therapeutic adherence. The functional requirements and user needs of the pediatric population differ from those of adults. This population is characterized by specific features related to performed activities, cognitive abilities, and aspects of acceptability. Moreover, children present distinct physical traits, including the need to accommodate growth. Understanding the preferences of children, caregivers, and healthcare professionals is key to achieving therapeutic outcomes. A poor match between device design and user needs can lead to abandonment and limited effectiveness (Phillips & Zhao, 1993). These devices must be comfortable, adaptable, and easy to use. Recent research emphasizes that pediatric exoskeletons should enhance function while being lightweight, comfortable, and aesthetically acceptable to encourage consistent use (Li et al., 2024). While recent studies provide critical insight for pediatric hand exoskeleton design, expanding the sample size and clinical diversity could yield more universally applicable design guidelines. Within the 3Daid++ project framework, we propose integrating end-user perspectives through a structured survey to systematically identify unmet needs and preferences, ensuring alignment between device functionality and real-world usability requirements.

This paper addresses this gap by focusing on end-user needs to inform design requirements for pediatric hand exoskeletons. Through an anonymous questionnaire distributed online, the research seeks to explore the functional assistance requirements of potential end users, focusing on mobility, reaching, and handling for daily activities at home and in the broader community. The information collected in this exploratory survey may provide preliminary guidance for prototype specifications, by reflecting parental perspectives on user needs and priorities regarding assistive exoskeletons.

Materials and methods

Study design and inclusion criteria

Over four months from April 2024 to July 2024, an anonymous survey was distributed via e-mail to the parents of children with neurological disorders who had previously received treatment at the Scientific Institute IRCCS E. Medea – Associazione “La Nostra Famiglia” in Bosisio Parini, Italy. During this period, a reminder was sent to all subscribers to the mailing list. Only parents of children with an upper limb impairment were invited to answer. All parents had previously given their consent to be recontacted via e-mail, and a link to our data processing policy according to GDPR was provided within the e-mail. Patient identification, personal data, or contact data were not collected. Health data, such as diagnosis, were collected only as far as they were necessary for the objective of the survey. These data were processed in compliance with EU Regulation 2016/679, (GDPR) and Legislative Decree 10 August 2018, n. 101. Informed consent was obtained by the decision to proceed with the online survey, in accordance with the Declaration of Helsinki and Public Health (Williams, 2008). After interacting with our Clinical Trials Unit, this study was not considered as requiring ethical approval because of its nature of anonymous survey study.

Survey development

A structured questionnaire was designed and deployed using the REDCap electronic data capture tools hosted at IRCCS E. Medea (Harris et al., 2009, 2019). The questionnaire comprises three core sections, each addressing different areas of interest. Multiple-choice and Likert scale questions were used to ensure a standardized response format, minimizing response bias and simplifying completion (Fink, 2025). In order to gather only quantitative data to facilitate statistical analysis, and to avoid the collection of personal information, no open-ended questions were included.

The investigation was developed on the basis of previous research in the literature, on the evaluation of orthoses and exoskeletons in the pediatric population, with a focus on device usability and the identification of patient needs. Three main sections were structured to address distinct objectives, as described below.

The first section focused on collecting demographic data such as age, gender, and clinical characteristics of the participants, including information about their specific neurological conditions affecting upper limb mobility. This section also

presented questions related to the functional abilities of the children, with particular attention to their current level of hand mobility and daily activities that might be impacted by these impairments (Yang et al., 2015).

The second section of the survey assessed the participants past experiences with hand orthoses. For those with previous exposure, questions explored the frequency of hand orthosis usage and perceptions of its effectiveness in improving their child's hand function (Bula-Oyola et al., 2022). This section provided context on prior interactions with assistive technologies and how such experiences influenced expectations for advanced solutions like hand exoskeletons.

The third section of the questionnaire explored the needs and expectations of the participants regarding the potential use of a pediatric hand exoskeleton. This section investigated their interest in exoskeleton technology, the functionalities they believed would be most beneficial, and any concerns they had regarding its implementation (Boser et al., 2021; O'Sullivan et al., 2015). Additionally, the survey specifically assessed four critical factors likely to influence the acceptance and adoption of such devices: perceived usefulness (Venkatesh & Davis, 2000), trust (Heerink et al., 2010), aesthetics (Razmdoost et al., 2015) and stigma (King et al., 2007).

Additionally, participants provided their opinions on exoskeleton technology, including expectations about functionality, training requirements, and suggestions for future improvements.

The complete questionnaire was administered in Italian to all participants, who were native Italian speakers. Items adapted from the literature were translated into Italian by bilingual members of the research team with expertise in rehabilitation and assistive technologies, and subsequently reviewed by the multidisciplinary group (clinicians, engineers, therapists) to ensure clarity and appropriateness for Italian parents. An English translation of the questionnaire is provided in the Appendix.

Data analysis

Questionnaires with at least 80% of items completed were considered valid, whereas those with fewer responses were discarded. The collected responses were analyzed using descriptive statistics, both for the overall dataset and, where noteworthy, within subgroups categorized by age. For rank-order questions, mean and standard deviation values were calculated to summarize central tendencies, while summary counts and percentages were used to describe categorical multiple-choice responses. Figure 1 illustrates the method used for distributing and collecting survey responses.

Results

The survey was completed by the parents of 46 individuals. However, due to incomplete responses, only 43 were

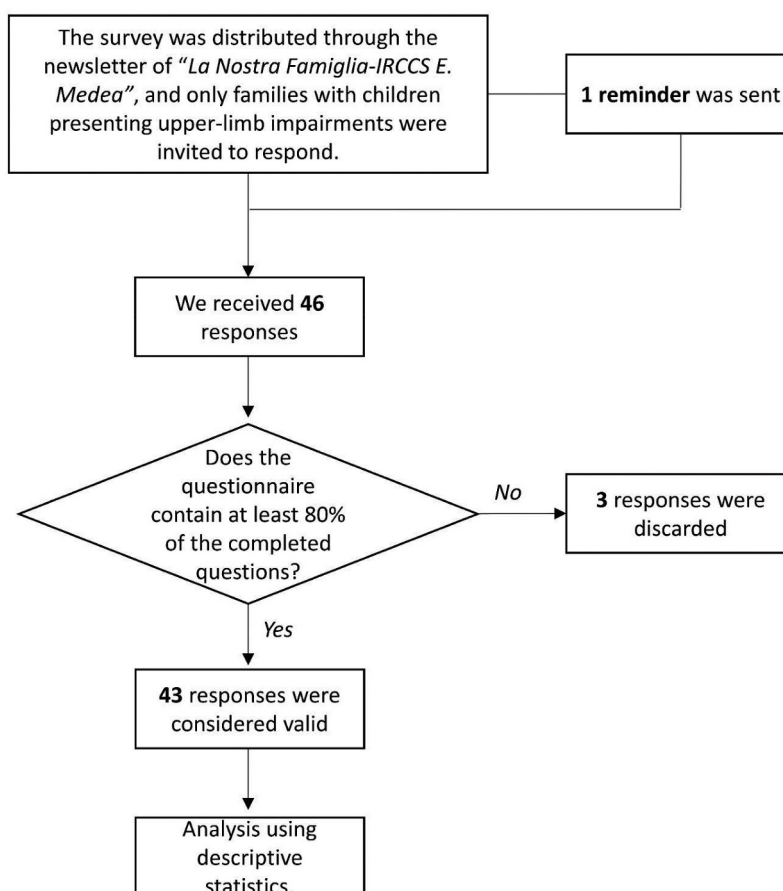


Figure 1. Method of distributing and collecting survey responses. The flowchart illustrates the procedure adopted for survey distribution and response collection.

Table 1. First section data.

	% (n = 43)
Gender	
Boys	58.0
Girls	40.0
Not declared	2.0
Age group, years	
<3	7.0
3–5	20.9
6–10	32.6
11–14	18.6
>14	20.9
Pathologies	
Cerebral Palsy	30.2
Acquired Brain Injury (ABI)	2.3
Neuropathy	4.7
Muscular Dystrophy	2.3
Others	60.5

Demographic characteristics of the pediatric population as reported by parents in the anonymous survey. The overall distribution of Gender, Age Group, and Pathology are reported as percentages of total respondents.

included in the analysis. Overall, there was a majority of males (58.0%), as shown in Table 1. The age distribution of the subjects covered all groups from 0 to 18 years, and the most represented is the 6–10 years old (32.6%), while the less represented is the < 3 years old (7.0%). All age groups were included to provide a comprehensive overview of parental perspective across developmental stages. Although the technical feasibility of exoskeleton use in children under 3 years is limited, their inclusion reflects parental expectation for future independence. The data show that *Cerebral Palsy* was the most represented condition among those reported (30.2%).

First section of the survey

In the first section of the survey, parents identified eating as the most important ADL for most age groups, followed by dressing and self-care. In contrast, recreation and technology use were perceived as less important (Figure 2).

Table 2 presents the perceived complexity of daily life activities, ranked from most complex (at the top) to least

complex (at the bottom). Most activities were considered moderately to highly complex, with the lowest minimum score (2.7) recorded for “turn on a bedside lamp.” Additionally, parents rated the importance of specific movements (Table 3), all of which received similar scores (spans from 3.6 to 4.3), with cylindrical grip, hook grip, thumb movement and pinch grip receiving the highest score (4.3).

Second section of the survey

Among the surveyed population, only 25.6% had prior experience using a hand orthosis. The primary reasons for nonuse included a lack of medical recommendation (56.3%), perceived lack of necessity (31.3%), and, in a small number of cases, unspecified personal reasons (12.5%) (Table 4). For those who had used hand orthoses, the majority (73.0%) required assistance to wear them, and most used the device for less than 8 hrs per day (Table 4).

The most used orthoses were postural thermoplastic orthoses (Model B – 54.5%) and functional gloves designed to support and facilitate grip and manipulation (Model E –

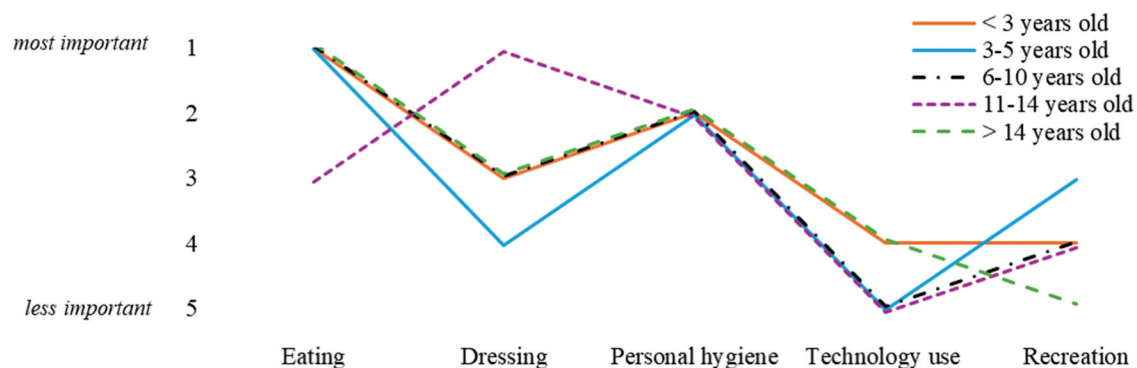


Figure 2. Ranking of daily life activities by importance (n = 43). The lines represent the age groups as indicated in the legend located in the upper right corner. Each line represents the importance the respondent placed on the ADL activity, with 1 being the most important and 5 being the least important. Data are reported as median (IQR interquartile range) for age group. < 3 years old: Eating 1.0 (1.0–1.0), Dressing 3.0 (3.0–4.0), Personal hygiene 2.0 (2.0–2.0), Technology use 5.0 (3.5–5.0), Recreation 4.0 (4.0–4.0); 3–5 years old: Eating 1.0 (1.0–3.0), Dressing 3.0 (2.5–4.0), Personal hygiene 2.0 (2.0–3.0), Technology use 5.0 (3.0–5.0), Recreation 3.0 (2.0–4.0); 6–10 years old: Eating 1.0 (1.0–2.3), Dressing 3.0 (2.0–4.0), Personal hygiene 2.0 (1.3–2.0), Technology use 5.0 (4.0–5.0), Recreation 3.0 (3.0–4.0); 11–14 years old: Eating 2.0 (1.0–3.0), Dressing 2.0 (2.0–2.0), Personal hygiene 2.0 (1.0–3.0), Technology use 5.0 (4.0–5.0), Recreation 3.5 (1.8–4.0); > 14 years old: Eating 2.0 (1.0–3.0), Dressing 3.0 (2.0–3.0), Personal hygiene 2.0 (2.0–3.0), Technology use 4.0 (2.0–5.0), Recreation 4.0 (3.8–5.0).

Table 2. Activity complexity ($n = 43$, SD = Standard deviation).

Complexity of the Movement	mean	±	SD
(1-very easy to 5-very difficult)			
Buttoning a shirt	4.3	±	0.8
Opening a jar of jam	4.3	±	1.0
Buttoning up your pants	4.2	±	1.0
Zip up a jacket	4.1	±	1.0
Roll up a sweater sleeve	4.0	±	0.9
Opening a package of bread	3.7	±	1.2
Raise the zipper on your pants	3.7	±	1.2
Fasten the snaps on a jacket	3.7	±	1.2
Sharpening a pencil	3.7	±	1.2
Unscrew a bottle cap	3.6	±	1.2
Opening a bag of chips	3.6	±	1.1
Put toothpaste on the toothbrush	3.5	±	1.2
Wash the upper body	3.4	±	1.3
Take off a shirt	3.3	±	1.3
Fill a glass with water	3.3	±	1.3
Open the toothpaste cap	3.3	±	1.4
Wearing a school backpack	3.3	±	1.4
Unwrap a chocolate bar	3.2	±	1.2
Take a coin from your pocket	3.1	±	1.3
Wear a hat	2.7	±	1.5
Turn on a bedside lamp	2.7	±	1.4

Complexity rating of various daily tasks (Boser et al., 2021), ranked from most to least difficult. Participants rated the difficulty of each task on a scale from 1 (very easy) to 5 (very difficult). Overview of participants' prior experience with hand orthoses or exoskeletons along with the associated reasons for their use or nonuse. Additionally, the frequency of utilization of assistive or rehabilitative devices is presented.

45.5%) (Figure 3). Parents were also asked to evaluate their child's experience with orthoses in terms of importance and satisfaction using a Likert scale (from 1-not important to 5-very important). The summary of responses is provided in Table 5.

Third section of the survey

The preferred design of the hand exoskeleton was explored, with the survey showing models of exoskeletons currently on the market or in development. Figure 4 shows the models and respondents' preferences. Parents when asked about weight capacity, responses varied, but higher capacities (> 1 kg) were generally preferred, as shown in Figure 5.

Parents also identified the benefits they expected from an exoskeleton (Table 6 – *Importance of Activities for Hand Exoskeleton Assistance*), as well as the specific movements it should support (Table 6 – *Agreement with the Potential Benefits of Using the Hand Exoskeleton*). The results suggest that parents believe an exoskeleton would be beneficial across all ADL tasks, with particular emphasis on small object manipulation. They also reported several key factors regarding the design of a hand exoskeleton, including concerns about weight, overall comfort, potential pain during use, and social perception (Table 6 – *Potential Problematics with Hand Exoskeleton Use*).

Many respondents thought that the exoskeleton would most likely enhance their child's ability to perform tasks related to dressing, personal hygiene, and eating (Figure 6). On the other hand, the potential use of the exoskeleton for recreational activities and technology interaction was considered less important.

When asked about the objects an exoskeleton should assist with (Figure 7), parents prioritized clothing, eating utensils, and drinking glasses. In contrast, technology-related objects such as smartphones, keyboards, and joysticks received less interest.












Additionally, parents evaluated various aspects that are crucial for the acceptance of the exoskeleton, including its perceived usefulness, trustworthiness, aesthetic appeal, and potential stigma. These factors were assessed using a Likert scale (1–strongly disagree to 5–totally agree), where parents rated their agreement with each statement. The results, broken down across different domains of evaluation, are illustrated in Figure 8. In this assessment, parents gave more attention to trust (4.0) and aesthetics (rated between 4.0 and 4.3), but less to stigma (rated between 2.8 and 3.1).

The expected daily usage of the exoskeleton was also analyzed, with most parents indicating a preference for moderate usage durations (Figure 9).

The expected frequency of use was explored with respect to different activities, parents identified school as the most relevant setting for the application of the exoskeleton, whereas sports activities were considered less applicable (Table 7 – *Frequency of Exoskeleton Use for Activities*).

While most parents (78.4%) believe their child would be interested in using a hand exoskeleton (Table 7 – *Perceived Child Interest in Using a Hand Exoskeleton*), fewer were willing to buy one. Cost was identified as a major barrier (Figure 10), with nearly half (48.6%) expressing they would only consider using the device if it was prescribed through the national health system.

Table 3. Movement importance ($n = 43$, SD = Standard deviation).

Importance of the movement (1-not important to 5-very important)		mean	\pm	SD
E. Cylindrical grip		4.3	\pm	0.9
G. Hook grip		4.3	\pm	0.9
M. Thumb movements		4.3	\pm	1.0
H. Pinch grip		4.3	\pm	0.9
F. Spherical grip		4.2	\pm	0.9
I. Three-finger grip		4.2	\pm	0.9
L. Lumbrical grip		4.1	\pm	1.0
B. Extension		3.9	\pm	1.1
C. Ulnar deviation		3.7	\pm	1.0
A. Flexion		3.7	\pm	1.1
D. Radial deviation		3.6	\pm	1.1

Importance rating of different hand movements (Yang et al., 2015), ranked from most to least important. Participants evaluated the significance of each movement on a scale from 1 (not important) to 5 (very important).

Table 4. Previous experience with orthoses ($n = 43$).

Previous experience with hand orthoses or exoskeleton		
No		74.4%
	Motivation	
	Never proposed by the doctor	56.3%
	Not available on prescription	0.0%
	Too complex to use	0.0%
	Use not tolerated	0.0%
	Not useful	31.3%
	Other reason	12.5%
Yes		25.6%
	Wear it autonomously	27.0%
	Need help to wear it	73.0%
	Frequency of Use	
	<2 hrs/day	45.5%
	2–8 hrs/day	45.5%
	8–12 hrs/day	9.1%
	>12 hrs/day	0.0%

Overview of participants' prior experience with hand orthoses or exoskeletons along with the associated reasons for their use or nonuse. Additionally, the frequency of utilization of assistive or rehabilitative devices is presented.

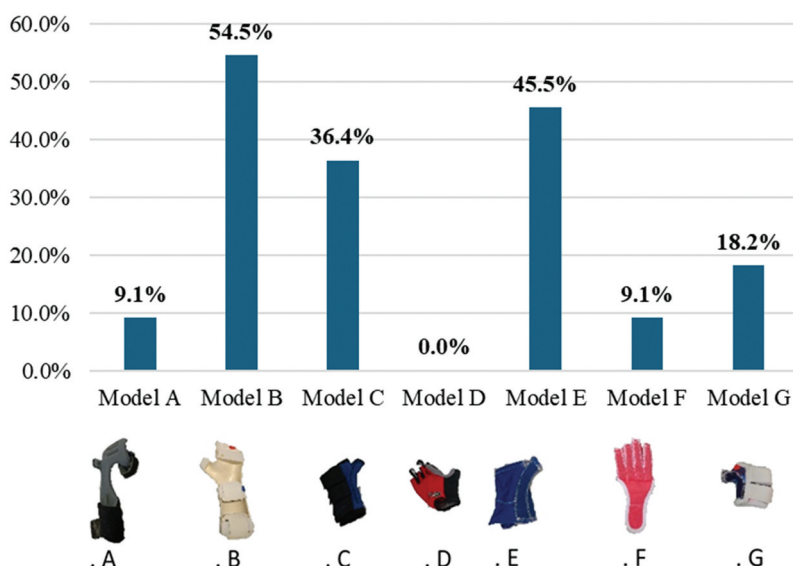


Figure 3. Distribution of orthoses models used by patient respondents ($n = 11$). Distribution of different orthosis models used by the patient respondents. The bar chart presents the percentage of participants that used each model in prior experience. Below the chart, images of the corresponding orthoses models provide a visual reference.

Table 5. Perceived importance and satisfaction with orthoses features ($n = 11$, $sd =$ Standard deviation).

	Importance				Satisfaction		
	mean	\pm	SD		mean	\pm	SD
Weight	4.8	\pm	0.4	Resistance	3.7	\pm	0.4
Comfort	4.8	\pm	0.4	Washability	3.5	\pm	1.1
Function	4.8	\pm	0.4	Dimensions	3.5	\pm	0.8
Dimensions	4.4	\pm	0.6	Weight	3.4	\pm	1.0
Wearability	4.4	\pm	0.6	Wearability	3.4	\pm	1.1
Resistance	4.0	\pm	0.4	Function	3.4	\pm	0.9
Washability	3.9	\pm	0.9	Aesthetic appearance	3.3	\pm	0.6
Aesthetic appearance	3.6	\pm	0.9	Comfort	3.1	\pm	0.8

Comparison between the perceived importance and satisfaction levels associated with various orthosis features based on prior user experiences. The features are ranked from most to least important according to participants' responses. Ratings were assessed on a scale from 1 (not important/not satisfying) to 5 (very important/very satisfying).

However, training time was not perceived as a significant obstacle, as 43.2% of parents were willing to participate in a three-hour training program, and 40.5% would commit to a 5–7-hour program (Table 7 – *Parental Commitment to Hand Exoskeleton Training*).

Discussion

This study highlights the user needs for pediatric manual exoskeletons as reported by parents of children with upper-limb neuromotor disorders who had previously been hospitalized at our facility. The results provide valuable insights into both functional priorities and potential barriers to adoption.

The first section of the survey confirmed that almost all ADL present challenges for children with neuromotor disorders. In our sample, parents most frequently identified eating and self-care as important tasks, reflecting their view that these activities are fundamental to fostering independence and improving quality of life. These findings align with previous research (Li et al., 2024; Nam et al., 2019), reinforcing that solutions must prioritize daily self-care activities over recreational use. Additionally, in the

various age groups we can highlight some interesting differences: dressing seems very important for the 11–14 age group and – on the contrary – unimportant for the 3–5 age group. To quantitatively analyze these differences, a larger sample and more targeted questions would be required, offering valuable insights for future research.

Interestingly, the ranking of task complexity (Table 2) adds a functional dimension to design requirements. Parents reported that buttoning clothes, opening jars, and zipping jackets were among the most complex tasks, reflecting multi-step actions that combine fine motor control, strength, and bilateral coordination. These responses suggest that parents envision a pediatric exoskeleton that could facilitate not only monolateral task but also more complex, bimanual activities. Conversely, tasks rated as less complex (e.g., turning on a lamp, putting on a hat) may require simpler forms of assistance.

Our findings on grasp types (Table 3) are consistent with prior work in adult populations, where cylindrical and pinch grips were found to be fundamental for daily living (Lambercy et al., 2013; Randazzo et al., 2018; Schabowsky et al., 2010). In this way, the importance of this type of grips is reinforced by this finding,

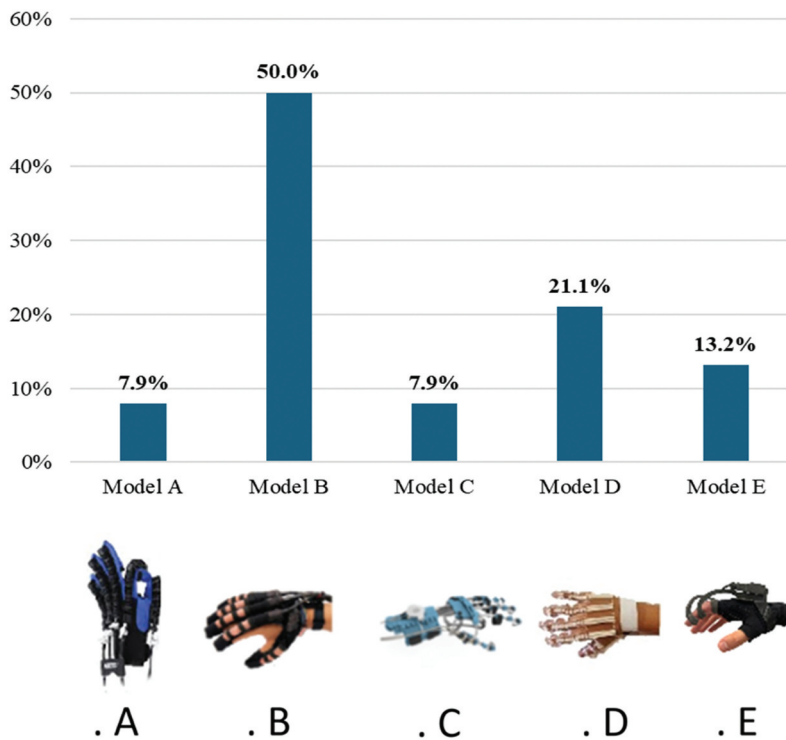


Figure 4. Preferred exoskeleton design ($n=38$): distribution of participant preferences for various exoskeleton designs. The bar chart shows the percentage of respondents who selected each design as their preferred choice. Below the chart, images of the corresponding exoskeleton models provide a visual reference in the survey. (image source: a) Hand Therapy Rehabilitation Glove for Stroke, <https://www.saebo.com/products/saeboglove>, accessed on March 2024; B) Polygerinos et al. (2015) C) PEXO <https://relab.Ethz.ch/>, accessed on March 2024; d) Araujo et al. (2021); e) CNR archives).

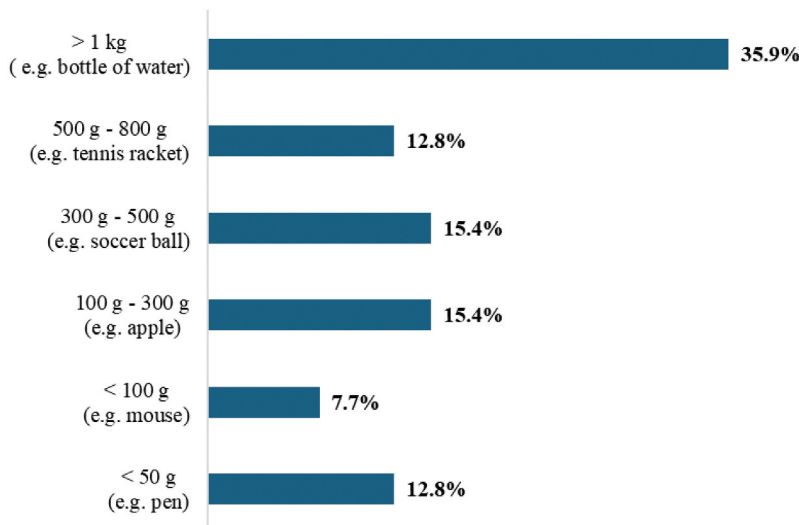


Figure 5. Preferred weight capacity for exoskeleton hand ($n=39$): distribution of weight capacity rated in the survey. The horizontal bar chart illustrates the percentage of respondents who selected a weight capacity range.

which also applies to the pediatric population. These grips are directly linked to eating, hygiene, and dressing, which are tasks repeatedly prioritized by parents. This pediatric focus distinguishes our work from earlier adult-oriented research, underlining parents' perception that grasp-support strategies should be tailored to children's developmental and functional contexts.

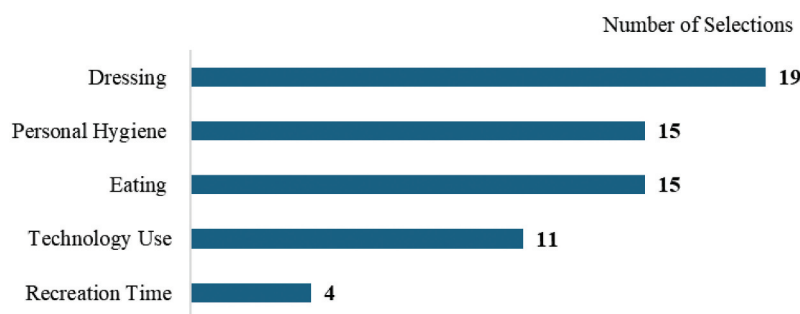
The second section revealed that nearly 25% of respondents had prior experience with orthoses, suggesting that some families are already familiar with assistive technologies.

However, despite prior exposure, existing orthotic solutions did not fully meet user expectations in terms of weight, comfort, and functionality. This finding is consistent with Li et al. (2024), who reported that many pediatric users abandon assistive devices due to discomfort or difficulties in daily use reinforcing parents' view of the necessity of user-centered design approaches to improve functionality and long-term adherence. The responses indicate a clear need for improvements in these aspects to ensure higher satisfaction and sustained use (Bula-

Table 6. Parental preferences, perceived benefits, and potential challenges regarding hand exoskeleton use in Italy ($n = 43$, SD = Standard deviation).

Importance of Activities for Hand Exoskeleton Assistance (1-not important to 5-very important)			
	mean	±	SD
Small Object Manipulation	4.4	±	0.7
One-arm object rotation	4.2	±	1.0
Two-arm Grasp	4.2	±	0.8
Large object Grasp	4.2	±	0.9
One-arm Throw	4.1	±	0.9
One-arm Front hold	4.0	±	0.9
Two-arm Front hold	4.0	±	0.9
One-arm Side hold	3.4	±	1.0
Agreement with the Potential Benefits of Using the Hand Exoskeleton (1-strongly disagree to 5-strongly agree)			
Quality of Life	4.1	±	0.8
Better activity Performance	4.1	±	0.8
Independence Improvement	4.1	±	1.0
Daily usefulness	4.1	±	0.7
Activity improvement	4.1	±	0.7
Potential Problematics with Hand Exoskeleton Use (1-not problematic to 5-very problematic)			
Weight	3.8	±	1.0
Skin irritation	3.7	±	1.0
Pain	3.7	±	1.1
Discomfort	3.7	±	1.0
Sweating	3.4	±	1.1
Difficulty wearing	3.2	±	1.2
Embarrassment	3.2	±	1.2
Aesthetics	3.1	±	1.2
Battery life	3.1	±	1.0
Maintenance	3.0	±	1.0

The table presents the mean scores of participant responses ranked from the most important to the least one regarding (1) Importance of Activities for Hand Exoskeleton Assistance, rated from 1 to 5, where 1 is “not important” and 5 is “very important” for various hand functions; (2) Agreement with the Potential Benefits of Using the Hand Exoskeleton, showing the mean agreement scores (on a scale of 1 to 5, where 1 is “strongly disagree” and 5 is “strongly agree”) regarding the perceived benefits of hand exoskeleton use; and (3) Potential Problematics with Hand Exoskeleton Use, presenting the mean ratings (on a scale of 1 to 5, where 1 is “not problematic” and 5 is “very problematic”) for potential challenges associated with hand exoskeleton use.

**Figure 6.** Preferred activities for hand exoskeleton support ($n=43$): distribution of parental preferences for ADLs where a hand exoskeleton would be most beneficial for their child. The horizontal bar chart displays the number of times each activity was selected by parents when asked to identify the two most important ones they believed an exoskeleton would help their child perform. The activities are ranked from the most frequently selected to the least frequently selected.

Oyola et al., 2022; Ryan et al., 2009). The frequency of orthoses usage observed in this study mirrors findings from Russo et al. (2009), with more than half of the users (54.6%) wearing the device for more than four hours per day.

Initially, the third section aims to identify parents' expectations regarding the device design. As shown in Figure 4, they selected a design that is very hand-fitting and has partially visible activation mechanisms. This finding may suggest the use of a cable-based activation mechanism instead of a joint during

the design phase. Furthermore, parental feedback on design preferences underscores the importance of weight, comfort, and wearability as key success factors for a pediatric hand exoskeleton, highlighting that findings previously reported in the adult population are also confirmed in the pediatric population. While stigma was rated relatively low, parents consistently indicated that visual appearance should not be a secondary concern. A child-friendly, discreet design that minimizes stigma while remaining appealing could enhance acceptance and daily

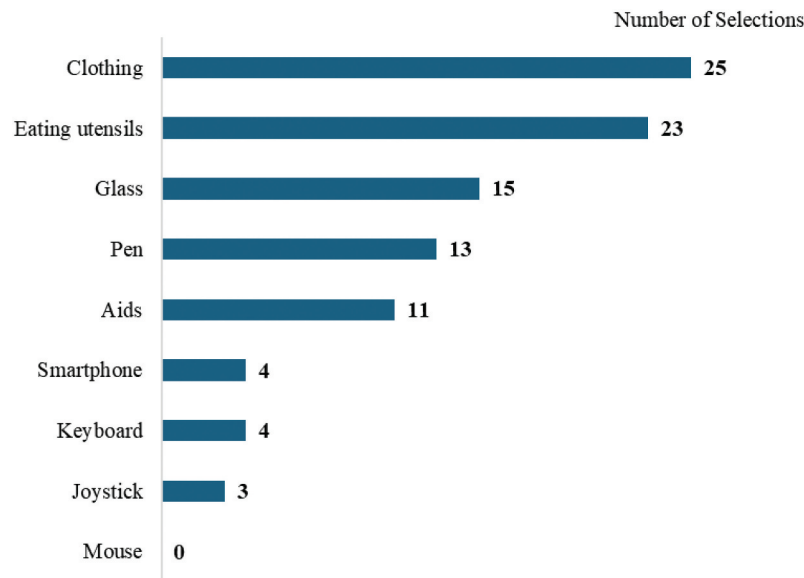


Figure 7. Objects facilitating use with a hand exoskeleton ($n=43$): distribution of types of objects that respondents believe would be most easily used with a hand exoskeleton. The horizontal bar graph displays the number of times each object category was selected when asked to indicate the three most important objects. Objects are ranked from the most selected to the least selected.

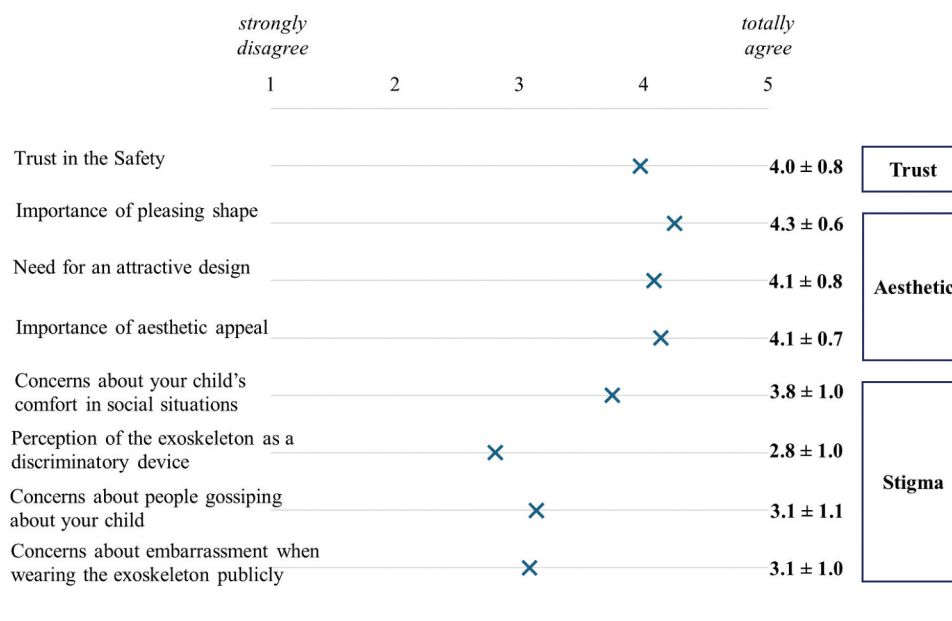


Figure 8. Parental attitudes towards hand exoskeletons in Italy ($n=43$): this figure presents the distribution of parental responses regarding their attitudes towards hand exoskeletons for their children in Italy, based on a Likert scale from 1 (strongly disagree) to 5 (totally agree). The figure illustrates parental agreement with statements related to trust in safety, aesthetics, and potential stigma associated with exoskeleton use. Mean scores are shown for each statement, grouped into the categories of trust, aesthetics, and stigma.

use (Butzer et al., 2019). At the same time, in the survey, parents showed a high level of trust in exoskeletons, implying that once issues of comfort and aesthetics are resolved, the likelihood of adoption would be much higher.

Another key finding relates to expected daily use. Most parents envisioned their child wearing the device for 2–8 hours per day (Figure 8), consistent with earlier reports that children tolerate extended wear when comfort is prioritized (Russo et al., 2009). This parental expectation reinforces the perceived

need for lightweight materials and ergonomic designs to prevent fatigue during prolonged usage.

Cost and reimbursement emerged as critical barriers. Almost half of parents (48.6%) stated they would only consider the device if provided through the national healthcare system (Figure 9). Similar results have been reported in other studies (Li et al., 2024; Lieber et al., 2022), underscoring that accessibility will depend not only on technical development but also on healthcare policy

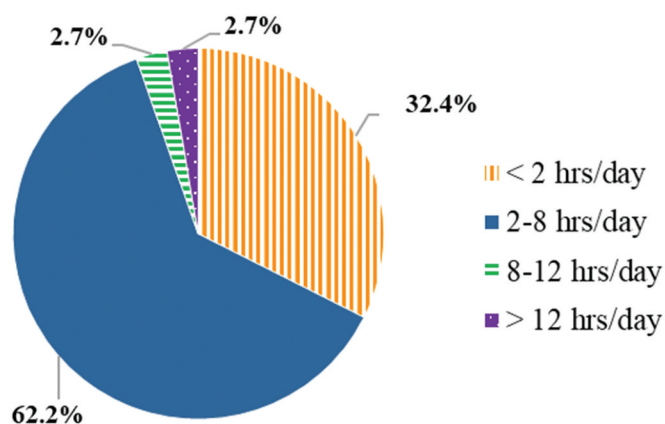


Figure 9. Estimated daily usage of hand exoskeleton ($n=43$): the pie chart displays the percentage distribution of time ranges for expected daily use, with categories including less than 2 hours per day, 2–8 hours per day, 8–12 hours per day, and more than 12 hours per day.

and funding mechanisms. These parental responses highlight that reimbursement considerations will be crucial for future design and dissemination processes. This finding is particularly relevant in the Italian healthcare context, where medical devices are typically prescribed through public healthcare services. Different contexts and national health systems may provide different results. At the same time, we believe that the design should take into account the need for the device to adapt to the growth of pediatric patients, in order to minimize production costs.

Finally, parents expressed strong willingness to commit to training, with over 80% ready to participate in multi-session programs. This attitude confirms the feasibility of implementing structured learning protocols (Santos et al., 2017), which may further improve adherence and usability.

Overall, the high level of parental interest in pediatric hand exoskeletons, with 76.3% indicating potential benefits for their child, reflects promising expectations for future development. To meet these expectations and ensure successful implementation, future designs should prioritize comfort, ease of use, and aesthetics, while also addressing financial accessibility.

Strengths & limitation

This study provides an exploratory description of parental perspectives on the needs for an assistive pediatric manual exoskeleton, based on feedback from 43 parents of children with neurological disorders. To our knowledge, very few studies have investigated user requirements specifically for pediatric upper-limb exoskeletons, and this work contributes to filling that gap. By directly capturing the voices of caregivers, the study offers preliminary but valuable insights to guide user-centered design and healthcare integration of such technologies.

This study also has several limitations. First, it was conceived as an exploratory descriptive survey with a relatively small and heterogeneous convenience sample recruited from a single Italian clinical network, which limits generalizability and does not allow for robust inferential subgroup analyses (e.g., by age group or prior orthosis experience). All reported patterns should therefore be interpreted as descriptive trends only. Additionally, the survey was adapted from existing instruments but was not subjected to a formal psychometric evaluation (e.g., internal consistency, test – retest reliability, construct validity), nor did we perform back-translation or cultural adaptation procedures. These steps were beyond the scope of our exploratory aim but should be addressed in future confirmatory research. Finally, perspectives were collected only from parents or caregivers; future studies should also attempt, where feasible, to incorporate the views of children themselves, particularly those old enough to express their own experiences.

Table 7. Parental perceptions of exoskeleton usage, training Commitment, and child interest ($n = 43$, $sd=$ Standard deviation).

Frequency of Exoskeleton Use for Activities			
<i>(1-never to 5-always)</i>			
	mean	±	SD
School Time	4.0	±	1.0
Meal Time	3.7	±	1.0
Personal Hygiene	3.6	±	1.0
Game Time	3.6	±	0.9
Sport activities	3.3	±	1.3
Parental Commitment to Hand Exoskeleton Training			
	%		
1 session of 1 h	16.2%		
3 sessions of 1 h	43.2%		
5–7 sessions of 1 h	40.5%		
Perceived Child Interest in Using a Hand Exoskeleton			
	%		
Yes	78.4%		
No	21.6%		

The table is divided into three sections: (1) Frequency of Exoskeleton Use for Activities, shows the mean ratings (on a scale of 1 to 5, where 1 is “never” and 5 is “always”) for how often parents envision their child using the exoskeleton for various activities. (2) Parental Commitment to Hand Exoskeleton Training, displays the percentage of parents willing to dedicate different durations of training time. (3) Perceived Child Interest in Using a Hand Exoskeleton, presents the percentage of parents who believe their child would be interested (“Yes”) or not interested (“No”) in using the device.

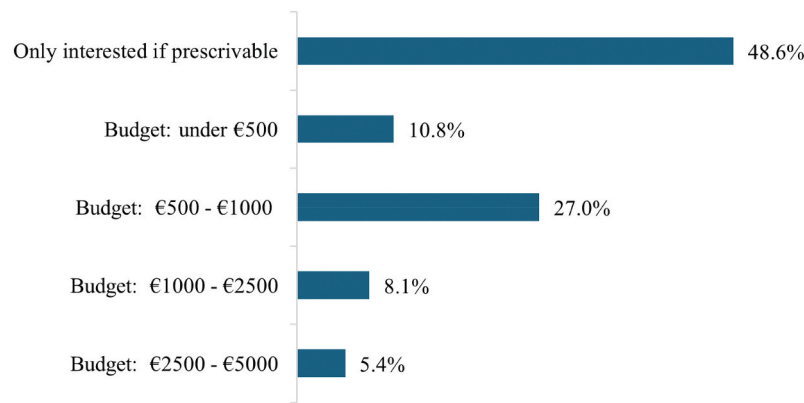


Figure 10. Willingness to pay for an active hand exoskeleton in Italy ($n=43$): distribution of parental responses regarding their willingness to pay for an active hand exoskeleton in Italy. The horizontal bar chart illustrates the percentage of respondents who selected each budget range, including those who indicated they were not interested in purchasing the device. Budget ranges are presented in euros (€).

Future research should therefore focus on validating and refining the survey instrument, expanding recruitment to larger and more diverse international samples, and integrating both caregiver and child perspectives. Such studies will be essential to confirm subgroup differences and to strengthen the evidence base for designing pediatric exoskeletons that are both effective and acceptable in real-world contexts.

Conclusion

This study provides a comprehensive overview of the potential user needs for pediatric hand exoskeletons, focusing on functional, design, and aesthetic factors that may influence adoption. The primary findings reveal that parents are most concerned with improving their children's ability to perform ADLs and less focused on recreational activities or use of technology. Furthermore, the survey highlighted critical design features such as weight, comfort, and wearability, which were deemed highly important. For hand exoskeleton developers, these insights suggest that future prototypes must prioritize lightweight materials, comfort-enhancing designs, and a focus on practical functions to meet the high expectations of potential users. Moreover, efforts to minimize stigma through thoughtful design choices will be crucial in encouraging adoption among children and their families.

Author contributions

CRedit: **Luca Emanuele Molteni MSc:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing; **Denise Bentivoglio MSc:** Conceptualization, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing; **Eleonora Diella PT:** Conceptualization, Methodology, Writing – review & editing; **Emilia Biffi PhD:** Conceptualization, Formal analysis, Methodology, Project administration, Supervision, Writing – review & editing; **Giuseppe Andreoni PhD:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing; **Federica Bressi PhD:** Writing – review & editing; **Fabrizio Taffoni PhD:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing; **Loredana Zollo PhD:** Writing – review & editing; **Fabio Alexander Storm PhD:** Conceptualization,

Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Writing – review & editing.










Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the Centro Protesi INAIL (Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro) within the project PR23-PAS-P3 “3Daid++” - Protesi di mano e ausili robotici esoscheletrici a basso costo per bambini e adulti, under Grant CUP: E57G23000220005; and by the Italian Ministry of Health (Ricerca Corrente 2024–2025 awarded to Dr. E. Biffi).

ORCID

Luca Emanuele Molteni MSc  <http://orcid.org/0009-0009-5193-2899>
 Denise Bentivoglio MSc  <http://orcid.org/0009-0001-4349-0017>
 Eleonora Diella PT  <http://orcid.org/0000-0003-2756-9355>
 Emilia Biffi PhD  <http://orcid.org/0000-0002-2568-9735>
 Giuseppe Andreoni PhD  <http://orcid.org/0000-0002-5537-4128>
 Federica Bressi PhD  <http://orcid.org/0000-0001-5462-2743>
 Fabrizio Taffoni PhD  <http://orcid.org/0000-0003-3215-1375>
 Loredana Zollo PhD  <http://orcid.org/0000-0002-8015-010X>
 Fabio Alexander Storm PhD  <http://orcid.org/0000-0002-5977-8090>

Data availability statement

The anonymized dataset generated and analyzed during the current study has been deposited in the Zenodo repository and is publicly available at: [10.5281/zenodo.0.17079227](https://doi.org/10.5281/zenodo.0.17079227).

References

- Araujo, R. S., Silva, C. R., Netto, S. P. N., Morya, E., & Brasil, F. L. (2021). Development of a low-cost EEG-controlled hand exoskeleton 3D printed on textiles. *Frontiers in Neuroscience, 15*. <https://doi.org/10.3389/fnins.2021.661569>
- Bleyenheuft, Y., & Gordon, A. M. (2014). Precision grip in congenital and acquired hemiparesis: Similarities in impairments and implications for neurorehabilitation. *Frontiers in Human Neuroscience, 8*. <https://doi.org/10.3389/fnhum.2014.00459>
- Boser, Q. A., Dawson, M. R., Schofield, J. S., Dziwenko, G. Y., & Hebert, J. S. (2021). Defining the design requirements for an assistive

- powered hand exoskeleton: A pilot explorative interview study and case series. *Prosthetics and Orthotics International*, 45(2), 161–169. <https://doi.org/10.1177/0309364620963943>
- Botelho, F. H. F. (2021). Childhood and assistive technology: Growing with opportunity, developing with technology. *Assistive Technology*, 33 (sup1), 87–93. <https://doi.org/10.1080/10400435.2021.1971330>
- Bula-Oyola, E., Belda-Lois, J. M., Porcar-Seder, R., & Page, A. (2022). Aspects determining adherence to wrist-hand orthoses in patients with peripheral neuropathies. *Technology and Disability*, 34(4), 247–260. <https://doi.org/10.3233/TAD-210365>
- Butzer, T., Dittli, J., Lieber, J., Hedel, H. J. A., Meyer-Heim, A., Lamercy, O., & Gassert, R. (2019). Pexo - A pediatric whole hand exoskeleton for grasping assistance in task-oriented training. *IEEE International Conference on Rehabilitation Robotics*, 108–114. <https://doi.org/10.1109/ICORR.2019.8779489>
- Chiri, A., Giovacchini, F., Vitiello, N., Cattin, E., Roccella, S., Vecchi, F., & Carrozza, M. C. (2009). Handexos: Towards an exoskeleton device for the rehabilitation of the hand. *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 1106–1111. <https://doi.org/10.1109/IROS.2009.5354376>
- Crowe, C. S., Impastato, K. A., Donaghy, A. C., Earl, C., Friedly, J. L., & Keys, K. A. (2019). Prosthetic and orthotic options for lower extremity amputation and reconstruction. *Plastic and Aesthetic Research*, 2019. <https://doi.org/10.20517/2347-9264.2018.70>
- Cui, L., Phan, A., & Allison, G. (2015). Design and fabrication of a three dimensional printable non-assembly articulated hand exoskeleton for rehabilitation. In *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, (pp. 4627–4630). <https://doi.org/10.1109/EMBC.2015.7319425>
- Du Plessis, T., Djouani, K., & Oosthuizen, C. (2021). A review of active hand exoskeletons for rehabilitation and assistance. *Robotics*, 10(1), 40. <https://doi.org/10.3390/robotics10010040>
- Eck, M., Dallmeijer, A. J., Lith, U. S., Voorman, J. M., & Becher, J. G. (2010). Manual ability and its relationship with daily activities in adolescents with cerebral palsy. *Journal of Rehabilitation Medicine*, 42 (5), 493–498. <https://doi.org/10.2340/16501977-0543>
- Falzarano, V., Marini, F., Morasso, P., & Zenzeri, J. (2019). Devices and protocols for upper limb robot-assisted rehabilitation of children with neuromotor disorders. *Applied Sciences (Switzerland)*, 9(UE 13), 9 (13), 2689. <https://doi.org/10.3390/app9132689>
- Fasoli, S. E., Fragala-Pinkham, M., Hughes, R., Hogan, N., Krebs, H. I., & Stein, J. (2008). Upper limb robotic therapy for children with hemiplegia. *American Journal of Physical Medicine and Rehabilitation*, 87(11), 929–936. <https://doi.org/10.1097/PHM.0b013e31818a6aa4>
- Fink, A. (2025). *How to conduct surveys: A step-by-step guide* (7th ed.). SAGE Publications Incorporated.
- Fosch-Villaronga, E., Čartolovni, A., & Pierce, R. L. (2020). Promoting inclusiveness in exoskeleton robotics: Addressing challenges for pediatric access. *Paladyn, Journal of Behavioral Robotics*, 11(1), 327–339. <https://doi.org/10.1515/pjbr-2020-0021>
- Hand Therapy Rehabilitation Glove for Stroke | Saeboglove*. (n.d.). Saeboglove. Retrieved March 8, 2024, from <https://www.saeboglove.com/products/saeboglove>
- Harris, P. A., Taylor, R., Minor, B. L., Elliott, V., Fernandez, M., O'Neal, L., McLeod, L., Delacqua, G., Delacqua, F., Kirby, J., & Duda, S. N. (2019). The REDCap consortium: Building an international community of software platform partners. *Journal of Biomedical Informatics*, 95, 103208. <https://doi.org/10.1016/j.jbi.2019.103208>
- Harris, P. A., Taylor, R., Thielke, R., Payne, J., Gonzalez, N., & Conde, J. G. (2009). Research electronic data capture (REDCap)—a metadata-driven methodology and workflow process for providing translational research informatics support. *Journal of Biomedical Informatics*, 42(2), 377–381. <https://doi.org/10.1016/j.jbi.2008.08.010>
- Heerink, M., Kröse, B., Evers, V., & Wielinga, B. (2010). Assessing acceptance of assistive social agent technology by older adults: The Almere model. *International Journal of Social Robotics*, 2(4), 361–375. <https://doi.org/10.1007/s12369-010-0068-5>
- Jackman, M., Novak, I., & Lannin, N. (2014). Effectiveness of functional hand splinting and the cognitive orientation to occupational performance (CO-OP) approach in children with cerebral palsy and brain injury: Two randomised controlled trial protocols. *BMC Neurology*, 14(1). <https://doi.org/10.1186/1471-2377-14-144>
- King, M., Dinos, S., Shaw, J., Watson, R., Stevens, S., Passetti, F., Weich, S., & Serfaty, M. (2007). The stigma scale: Development of a standardised measure of the stigma of mental illness. *British Journal of Psychiatry*, 190(MAR.), 248–254. <https://doi.org/10.1192/bjp.bp.106.024638>
- Lamercy, O., Schröder, D., Zwicker, S., & Gassert, R. (2013). Design of a thumb exoskeleton for hand rehabilitation. *Proceedings of the 7th International Convention on Rehabilitation Engineering and Assistive Technology*, 1–4. <https://doi.org/10.5555/2567429.2567477>
- Latif, A., Al Janabi, H. F., Joshi, M., Fusari, G., Shepherd, L., Darzi, A., & Leff, D. R. (2024). Use of commercially available wearable devices for physical rehabilitation in healthcare: A systematic review. *BMJ Open*, 14(11), 084086. <https://doi.org/10.1136/bmjopen-2024-084086>
- Li, B., Arcemont, S., & Lobo, M. A. (2024). Identification of users' needs for pediatric upper extremity exoskeletons. *Pediatric Physical Therapy*, 36(3), 329–336. <https://doi.org/10.1097/PEP.0000000000001109>
- Lieber, J., Dittli, J., Lamercy, O., Gassert, R., Meyer-Heim, A., & Hedel, H. J. A. (2022). Clinical utility of a pediatric hand exoskeleton: Identifying users, practicability, and acceptance, and recommendations for design improvement. *Journal of Neuroengineering and Rehabilitation*, 19(1), 1–15. <https://doi.org/10.1186/s12984-022-00994-9>
- Lobo, M. A., & Galloway, J. C. (2008). Postural and object-oriented experiences advance early reaching, object exploration, and means-end behavior. *Child Development*, 79(6), 1869–1890. <https://doi.org/10.1111/j.1467-8624.2008.01231.x>
- Lobo, M. A., Kokkoni, E., Cunha, A. B., & Galloway, J. C. (2015). Infants born preterm demonstrate impaired object exploration behaviors throughout infancy and toddlerhood. *Physical Therapy*, 95(1), 51–64. <https://doi.org/10.2522/ptj.20130584>
- Maciejasz, P., Eschweiler, J., Gerlach-Hahn, K., Jansen-Toy, A., & Leonhardt, S. (2014). A survey on robotic devices for upper limb rehabilitation. *Journal of Neuroengineering and Rehabilitation*, 11(1), 3. <https://doi.org/10.1186/1743-0003-11-3>
- Michalec, P., Schusser, M., Weidner, R., & Brandstötter, M. (2024). Designing hand orthoses: Advances and challenges in material extrusion. *Applied Sciences*, 14(20). <https://doi.org/10.3390/app14209543>
- Mimouni-Bloch, A., Shaklai, S., Levin, M., Ingber, M., Karolitsky, T., Grunbaum, S., & Friedman, J. (2023). Developmental and acquired brain injury have opposite effects on finger coordination in children. *Frontiers in Human Neuroscience*, 17. <https://doi.org/10.3389/fnhum.2023.1083304>
- Moir, L. (2010). Evaluating the effectiveness of different environments on the learning of switching skills in children with severe and profound multiple disabilities. *British Journal of Occupational Therapy*, 73(10), 446–456. <https://doi.org/10.4276/030802210X12865330218186>
- Nam, H. S., Seo, H. G., Leigh, J.-H., Kim, Y. J., Kim, S., & Bang, M. S. (2019). External robotic arm vs. upper limb exoskeleton: What do potential users need? *Applied Sciences*, 9(12). <https://doi.org/10.3390/app9122471>
- Novak, I., Jackman, M., Finch-Edmondson, M., & Fahey, M. (2025). Cerebral palsy. *Lancet (London, England)*, 406(10499), 174–188. [https://doi.org/10.1016/S0140-6736\(25\)00686-5](https://doi.org/10.1016/S0140-6736(25)00686-5)
- O'Sullivan, L., Power, V., Virk, G., Masud, N., Haider, U., Christensen, S., Bai, S., Cuypers, L., D'Havé, M., & Vonck, K. (2015). End user needs elicitation for a full-body exoskeleton to assist the elderly. *Procedia Manufacturing*, 3(Ahfe), 1403–1409. <https://doi.org/10.1016/j.promfg.2015.07.302>
- Pentland, W. E., & Twomey, L. T. (1994). Upper limb function in persons with long term paraplegia and implications for independence: Part I. *Paraplegia*, 32(4), 211–218. <https://doi.org/10.1038/sc.1994.40>
- Peters, H. T., Page, S. J., & Persch, A. (2017). Giving them a hand: Wearing a myoelectric elbow-wrist-hand orthosis reduces upper extremity impairment in chronic stroke. *Archives of Physical Medicine and Rehabilitation*, 98(9), 1821–1827. <https://doi.org/10.1016/j.apmr.2016.12.016>

- Phillips, B., & Zhao, H. (1993). Predictors of assistive technology abandonment. *Assistive Technology*, 5(1), 36–45. <https://doi.org/10.1080/10400435.1993.10132205>
- Polygerinos, P., Wang, Z., Galloway, K. C., Wood, R. J., & Walsh, C. J. (2015). Soft robotic glove for combined assistance and at-home rehabilitation. *Robotics and Autonomous Systems*, 73, 135–143. <https://doi.org/10.1016/j.robot.2014.08.014>
- Randazzo, L., Iturrate, I., Perdakis, S., & Millán, J. D. R. (2018). Mano: A wearable hand exoskeleton for activities of daily living and neurorehabilitation. *IEEE Robotics and Automation Letters*, 3(1), 500–507. <https://doi.org/10.1109/LRA.2017.2771329>
- Razmdoost, K., Dimitriu, R., & Macdonald, E. K. (2015). The effect of overconfidence and underconfidence on consumer value. *Psychology and Marketing*, 32(4), 392–407. <https://doi.org/10.1002/mar.20787>
- Russo, R. N., Atkins, R., Haan, E., & Crotty, M. (2009). Upper limb orthoses and assistive technology utilization in children with hemiplegic cerebral palsy recruited from a population register. *Developmental Neurorehabilitation*, 12, 92–99. <https://doi.org/10.1080/17518420902783223>
- Ryan, S. E., Campbell, K. A., Rigby, P. J., Fishbein-Germon, B., Hubley, D., & Chan, B. (2009). The impact of adaptive seating devices on the lives of young children with cerebral palsy and their families. *Archives of Physical Medicine and Rehabilitation*, 90(1), 27–33. <https://doi.org/10.1016/j.apmr.2008.07.011>
- Santos, S., Soares, B., Leite, M., & Jacinto, J. (2017). Design and development of a customised knee positioning orthosis using low cost 3D printers. *Virtual and Physical Prototyping*, 12(4), 322–332. <https://doi.org/10.1080/17452759.2017.1350552>
- Schabowsky, C. N., Godfrey, S. B., Holley, R. J., & Lum, P. S. (2010). Development and pilot testing of HEXORR: Hand exoskeleton rehabilitation robot. *Journal of Neuroengineering and Rehabilitation*, 7(1), 36. <https://doi.org/10.1186/1743-0003-7-36>
- Thelen, E. (2012). Grounded in the world: Developmental origins of the embodied mind. *Developmental Perspectives on Embodiment and Consciousness*, 1(1), 99–130. <https://doi.org/10.4324/9780203809778>
- Van der Heide, L. A., van Nijhuijs, B., Bergsma, A., Gelderblom, G. J., van der Pijl, D. J., & de Witte, L. P. (2014). An overview and categorization of dynamic arm supports for people with decreased arm function. *Prosthetics and Orthotics International*, 38(4), 287–302. <https://doi.org/10.1177/0309364613498538>
- Venkatesh, V., & Davis, F. (2000). A theoretical extension of the technology acceptance model: Four longitudinal field studies University of Maryland at College Park. *Management Science*, 46(2), 186–204. <http://www.jstor.org/stable/2634758>
- Wang, D., Meng, Q., Meng, Q., Li, X., & Yu, H. (2018). Design and development of a portable exoskeleton for hand rehabilitation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 26(12), 2376–2386. <https://doi.org/10.1109/TNSRE.2018.2878778>
- Williams, J. (2008). The declaration of Helsinki and public health. *Bull World Health Organization*, 86(8), 650–2. <https://doi.org/10.2471/blt.08.050955>
- Yang, Y., Fermüller, C., Li, Y., & Aloimonos, Y. (2015). Grasp type revisited: A modern perspective on a classical feature for vision. In *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition* (pp. 400–408). <https://doi.org/10.1109/CVPR.2015.7298637>