

Research Article

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Promoting inclusiveness in exoskeleton robotics: Addressing challenges for pediatric access

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Abstract: Pediatric access to exoskeletons lags far behind that of adults. In this article, we promote inclusiveness in exoskeleton robotics by identifying and addressing challenges and barriers to pediatric access to this potentially life-changing technology. We first present available exoskeleton solutions for upper and lower limbs and note the variability in the absence of these. Next, we query the possible reasons for this variability in access, explicitly focusing on children, who constitute a categorically vulnerable population, and also stand to benefit significantly from the use of this technology at this critical point in their physical and emotional growth. We propose the use of a life-based design approach as a way to address some of the design challenges and offer insights toward a resolution regarding market viability and implementation challenges. We conclude that the development of pediatric exoskeletons that allow for and ensure access to health-enhancing technology is a crucial aspect of the responsible provision of health care to all members of society. For children, the stakes are particularly high, given that this technology, when used at a critical phase of a child's development, not only holds out the possibility of improving the quality of life but also can improve the long-term health prospects.

Keywords: pediatric exoskeletons, wearable robotics, life-based design, children, health-care system, access, personalized medicine, trust

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1 Introduction

Robotics have increased productivity and resource efficiency in the industrial and retail sectors, and now there is an emerging interest in realizing a comparable transformation in other areas, including health care [1]. However, the introduction of robots for health-care and therapeutic purposes that interact directly with patients, older adults, and children is not straightforward. It is widely recognized that these robots can entail risks for users and could infringe on rights and further may have a significant impact on care-recipient values, including those of workers' and end-users' values [2–9].

A relatively new technology that is changing the lives of impaired users is physical assistant robots. Physical assistant robots, also named exoskeletons, help users perform a task by augmenting or supplementing their capabilities (ISO 13482:2014). Exoskeletons derive their name from the fact that they work as an external skeleton that supports the user. First developed in the military, these robotic devices were designed to help soldiers carry heavier weights for longer distances. Nowadays, these robots are already deployed in the industry, aiming to improve the conditions of workers as well as in the health-care sector to help wheelchair users stand up and walk or assist in the rehabilitation of persons with neurologic or musculoskeletal problems with their ambulatory needs [10]. One of the common characteristics of the available exoskeleton solutions is that they have focused mainly on adult populations. A recent review of exoskeletons shows that companies build exoskeletons for persons from 150 cm tall onward: the Japanese Cyberdyne starts at 150 cm, followed by EksoBionics at 152 cm and Indego at 155 cm [8]. By contrast, the average height of a 5-year-old in Europe is between 108 and 113 cm [9]. These height parameters prevent shorter populations from accessing the benefits of this technology.

A particularly salient gap in access is found in children. Although advanced wearable exoskeletons are currently available, their benefits and challenges in addressing childhood movement disorders remain underexplored [11]. Damage to the central nervous system during early development can lead to neuromotor disorders such as cerebral palsy

that negatively affect the quality of life of users, including children. However, gait rehabilitation robotic devices have primarily focused on restoring lost function after stroke or spinal cord injury in adult populations [12–14]. Nevertheless, despite the clear need and multifaceted potential benefit, smaller orthoses suitable for children are not available in the market in any substantial variety or amount. Even the most recent literature reviews of exoskeletons include little reference to pediatric active orthoses [15–17], suggesting either relative absence of product or an understudied use of the technology in this population.

Part of the problem may lie in the current design approach. It is often the case that robotic engineers develop robotic devices primarily on the premise that the product should fit as many end-users as possible. This procrustean design choice seems legitimate from a return on investment point of view, but it may not ultimately serve marginalized groups of people who physically deviate from the majority of users [8]. Failing to address the needs of a broader spectrum of users may eventually impede the fair and effective access to the benefits of such technologies for a population that most needs it [18].

Avoiding the “one size fits all approach” and devising a commercially viable design strategy that accommodates more personalized needs of the end user may be more beneficial for the society in the long run. To the extent that specific populations, like children, are deprived of access to such technologies, given the short- and long-term benefits that they can yield, the health-care system has failed them, even though the fault is broadly distributed throughout the design, production, compensation, and policy pipeline. Furthermore, at a broader level, developing solutions for groups that may not present as an attractive market opportunity is necessary in order to support the fair and equitable nature of health care and health-care systems. With the widespread national embrace of personalized medicine in many countries around the world [19], it is surprising and puzzling that a clear need for interventions designed to make health care more accessible to young people is not approached with greater commitment. Pediatric exoskeletons provide a compelling example of the rationale of personalized medicine in that a “one size fits all approach” underserves significant segments of society. The use of medicines that are known to work in only 40% of the population, for example, results in a situation in which 60% of that patient population derives no benefit and may suffer toxic side effects, nonetheless [20]. Similarly, the absence of pediatric exoskeletons leaves children to use ill-suited adult devices with limited positive effect, at best, or to forego this type of therapeutic intervention altogether. Even more indefensible are the long-term effects of not

having this type of rehabilitative intervention for children at a time when it could improve the course of their lives in terms of physical health, well-being, and quality of life. This is particularly disturbing when one considers the technical availability and feasibility of the technology, in contrast to the commercial feasibility, that development of this product line does not appear to offer a highly profitable market. In the following sections, we explore ways in which both the need for commercial viability and the needs of this largely overlooked population could be met.

In this article, we aim to promote inclusiveness in exoskeleton robotics by addressing the challenges and barriers to pediatric access. Our contribution lies in the interplay between age, wearable robot technology, and access. We explore available pediatric exoskeleton solutions in the market and identify challenges and opportunities for children. Concretely, we focus on differential access to health technology and pediatric design challenges. In this sense, our contribution suggests applying a life-based design (LBD) which is an approach sustained by the pursuit of children’s good life and flourishing and has its roots in the philosophy of Wittgenstein [21], specifically Wittgenstein’s notion of *form of life* can be applied in this instance because it suggests the steering of the engineering process toward a more personalized and person-centered approach addressing the needs of children in the design approach. We conclude that the myriad ways in which the pediatric patient group can benefit from the use of exoskeletons, particularly at critical times in their physical and psychological development, justifies and even demands a more nuanced and committed approach to the design of pediatric exoskeletons. Addressing the barriers to pediatric access can lead to a more inclusive health-care system.

2 Exoskeletons: a question of access

Exoskeletons are robotic-assistive devices that originated in the military to enable soldiers to carry heavy loads longer and more comfortably [22]. This function convinced several industries to adopt the technology to support those workers who regularly handle heavy things¹ [23,24] and were subsequently included in as an example of “physical-assistant robots” within ISO 13482:2014 Safety Requirements for Personal Care Robots, which defines them as a “personal care robot that physically assists a user in

¹ See <http://www.robo-mate.eu/>.

performing required tasks by providing supplementation or augmentation of personal capabilities.”

Seeing the increasing development in the field of exoskeleton innovation, some sectors saw in this technology a promising approach to rehabilitation and health-care sectors, especially for patients with physical impairments in either the upper or the lower limb. Several research groups have made significant progress in increasing mobility for patients who suffered a stroke or spinal cord injury [12–14]. The primary role of a therapeutic exoskeleton is to substitute or provide the missing function resulting in health benefits such as improvements in gait function, body composition, aerobic capacity, bone density, spasticity, bowel function, and quality of life [25,26]. Enhancing users’ ability to move and walk helps them to fulfill a primary human function that stabilizes blood pressure, improves pulmonary ventilation, prevents the degeneration of muscle and bone tissue, and increases joint mobility [27].

Other research shows promising advances in hand orthoses, for therapy or daily assistance, which are increasingly simplified and less cumbersome [28]. These advancements enhance hand function and reduce fatigue while grasping and are particularly relevant for individuals with muscular dystrophy [29]. Such health-care advances can prolong the life expectancy of several populations with impairments, in that complete or partial restoration of physical abilities contributes to a persons’ ability to engage in daily life activities and to their self-esteem, both of which can be of vital importance to the psychological and physical well-being of a person and hence to his or her ability to flourish. Furthermore, exoskeletons afford much more independence than wheelchairs in everyday environments such as in shopping malls, local parks, or movie theaters [30].

Although exoskeletons are a powerful tool to help restore motor functions and provide effective assistance for those that cannot afford human caregivers, access to these technologies is largely limited to or through hospitals or rehabilitation centers where these expensive devices are financed through institutional means, such as insurance or subsidized health care. It is not yet common to see exoskeletons in private homes, as they are usually cumbersome and prohibitively expensive or still under development [31,32]. Exoskeleton technologies in the open market are only available either through purchase using one’s resources or in the select cases where individual health insurance covers robotic rehabilitation. This limitation could raise social justice concerns, including regarding equal access to health care [32]. The potential use of exoskeletons outside of these limited settings and

circumstances points to the need to enhance access in systematic ways.

At the crossroads between realizing an innovative idea and the return on investment lie a very dynamic balance in which the interests of potential users are subordinated to commercial viability. Even inadvertent failure to provide access to health technologies in the service of the health-care needs of a segment of society ultimately contributes to an unresolved ethical and social issue of health-care inequality. As a matter of health policy, this differential access warrants serious consideration. Just as measures are taken to incentivize and encourage the development of health-enhancing pharmaceuticals for all persons who may need them, e.g., pregnant women, children, or persons with rare diseases, the need to operationalize this imperative for pediatric exoskeletons in the service of children is compelling. Moreover, the standard that regulates personal care robots (including physical-assistant robots and exoskeletons, ISO 13482:2014) already acknowledges that these populations deserve special consideration. Nevertheless, no major steps have been taken to realize such an imperative [4].

3 Pediatric exoskeletons

The expanding and ongoing research demonstrates the potential for a patient’s improvement from medical, technological, and social viewpoints. However, it is not entirely clear how market players will efficiently implement this technology for younger populations that need to train a different walking pattern rather than to restore the lost walking capability [11]. When we refer to children, we refrain from alluding to a specific age range, because age is not a common parameter companies take into account. Several types of exoskeletons exist globally, differing in intended use, complexity, device weight, and device size, i.e., to fit different femur lengths (height related or hip width). We conducted a review of the robots, exoskeletons for children using the databases Google scholar, PubMed, and IEEE Explorer, using the key words “pediatric AND exoskeleton”, “exoskeleton AND for AND children,” and “rehabilitation AND robots AND for AND children.” We excluded social robots that served no physical therapeutic purpose. Since the first pediatric exoskeleton dates from 2011 [33], our review covered the period of 2010 to 2019. We noted that many of these robots were never brought to market. A non-systematic review of commercially available exoskeletons revealed that main manufacturers, significant players in the exoskeleton market such as Rewalk,² EksoBionics,³ Indego,⁴ and Cyberdyne⁵ do not

currently offer any product for short femurs or small hips, which would typically fit pediatric or short populations.

The only company on rehabilitation technology offering pediatric solutions seems to be Hocoma. The LokomatPro from Hocoma is one of the very few treadmills that offer orthoses for adults or children. Treadmill-based body weight support locomotor training has shown positive results in children and adults with cerebral palsy. The pediatric orthoses are designed to accommodate small children by offering a unique set of harnesses and cuffs that provide a precise fit for patients with femurs between 21 and 35 cm.⁶ However, Lerner, Damiano, & Bulea [11] highlight that improvements in controlled trials were not more significant to therapies of equal intensity, pointing out that these treatments should not replace overground training. However, this single example illustrates the type of lost opportunity for improved health and well-being for children at formative stages that the narrow offering of adult-oriented exoskeletons creates.

Existing solutions are in some measure limited by height, e.g., Japanese Cyberdyne starts at 150 cm, followed by EksoBionics at 152.40 cm and Indego at 155 cm. Most of these exoskeleton solutions follow the average human height beginning at 62.2 inches, i.e., 157.98 cm in Indonesia presented by World Population Review (2019). However, some populations have an average below this, such as Filipino females with an average height of 150 cm, which is 3 cm higher than Indonesian females, but 3 cm shorter than females from Southeast Asia [34]. Dividing the sum of the values by their number provides an average height population of below 150 cm. However, this approach not only goes against the existing ethnic and cultural differences but also underestimates the current diversity in a society, i.e., persons with dwarfism, youth, or children would not benefit from these exoskeleton solutions for adults of average height [8].

The following table includes a non-systematic review of some of the available pediatric wearable exoskeletons (see Table 1). There are not many commercially available models. Atlas 2020 and 2030 from MarsiBionics have been developed, but the company is still in a crowdfunding status, not

yet mass-producing these technologies.⁷ Tréxō Robotics is a Canadian company that has developed TrexoPlus pediatric exoskeletons attached to a walker for home use at a cost of nearly \$30,000.⁸ Agilik technologies, also a Canadian company, has developed ExoStep,⁹ and a tried-and-tested exoskeleton technology developed by Bionic Power, a military company focusing on exoskeletons,¹⁰ which is not available for sale but rather can be licensed.

Other research centers are developing solutions to assist children with their lower or upper limbs. One such solution is the exoskeleton developed by Lerner, Damiano, & Bulea that featured in Science in 2017 that focused on the development of a lower extremity exoskeleton that improves knee extension in children with crouch gait from cerebral palsy [11,35]. MIT's Pediatric AnkleBot is a lower extremity robotic therapy module that aids the recovery of ankle function in children with cerebral palsy [33,36]. In Italy, some researchers also developed a solution for children with cerebral palsy: the "Wearable Ankle Knee Exoskeleton" or *WAKE-up*, which was a powered knee-ankle-foot orthosis to assist children with their volitional movements [37]. Researchers are also working on upper limb exoskeleton solutions. Some researchers developed ChARMin, an actuated upper limb exoskeleton, to provide intensive rehabilitative training for children with affected arm motor function [38]. At ETH Zurich, other researchers developed a pediatric hand exoskeleton for grasping assistance in task-oriented training called PEXO [39].

4 Facilitating access: Revisiting the approach to exoskeleton design

The preceding overview of current and developing exoskeletons could suggest two underlying barriers to pediatric access, first that children as a group appear to show limited interest in a market-driven industry and, second, that the design of pediatric exoskeleton is more challenging compared to adult ones. From this overview, we also understand that pediatric robotics entails a vast trust ecosystem comprising children, parents, caregivers, and technology

² See <https://rewalk.com/rewalk-personal-3/>.

³ See <https://eksobionics.com/>.

⁴ See <http://www.indego.com/indego/en/home>, in particular <http://www.indego.com/Indego/ImageDownload?staticfile=/Indego/Indego%20Therapy%20Datasheet.pdf>, last accessed October 15, 2019.

⁵ See <https://www.cyberdyne.jp/english/>.

⁶ See <https://www.hocoma.com/solutions/lokomat/modules/#Pediatric-Orthoses>.

⁷ See <https://www.marsibionics.com/portfolio/atlas-2020/?lang=en>.

⁸ See <https://trexorobotics.com/>.

⁹ ExoStep is not yet available for sale to consumers, although they are selling units in limited numbers for research purposes. See <https://agilik.com/product/>.

¹⁰ See <https://www.bionic-power.com/>.

Table 1: Examples of available pediatric lower limb exoskeletons

Pediatric lower limb exoskeletons		Parameters					Price
	Intended user	User age	Intended use	Exoskeleton size	Device weight	Accessories	
pediAnklebot	For children with lower extremity neurological disorders.	6–10 years of age	Recovery of ankle function.				
PEXO	For children with hand motor impairment due to cerebral palsy, traumatic brain injury, or pediatric stroke.	From 6 to 12 years of age	PEXO provides assistance in various grasp types needed for the execution of functional tasks.	kidPEXO for 6–9 years of age and juvenilePEXO for 10–12 years of age.	0.5–0.6 kg	Spill water and dust proof	
Atlas 2020/2030	For children with severe neuromuscular diseases, cerebral palsy, spina bifida, and others. It provides self-control gait balance without the need of external aids like crutches or walkers	From 3 to 14 years old		It adapts in dimension to the child's growth	14 kg		
Trexo Home	For children with cerebral palsy, muscular dystrophy, and acquired spinal cord or brain injury	From 2 to 10 years old	Correcting the gait pattern, providing regular bearing through walking	Trexo device can be adjusted with child's growth			\$29,900
RoboExoskeleton Lerner, Damiano, & Bulea (2017) model	Designed to alleviate crouch gait from children with cerebral palsy.	Individuals between the ages of 5 and 19 were recruited	In addition to a diagnosis of crouch gait from CP, inclusion criteria were gross motor function classification system (GMFCS) levels I and II, thigh-foot angle from 10° internal tibial rotation to 25° external rotation, and less than 5° and 10° knee flexion and plantar flexion contractures, respectively.		Varied by individual ranging from 2.6 to 4.5 kg for both legs combined.		
WAKE-up	For the rehabilitation of locomotion children with neurological diseases such as cerebral palsy.	From 5 to 8 years of age	Knee and ankle rehabilitation		2.5 kg		
ExoStep	Gait rehabilitation device for children	Adjustable	Moves with the wearer, providing dynamic, knee assistance and resistance, when needed during a patient's gait.	Adjustable			While ExoStep is not yet available for sale to consumers, we are selling units in limited numbers for research purposes.

developers, from which other barriers at the implementation stage may arise.

4.1 Children may seem to present limited opportunity in a market-driven industry

We speculate that purely from a market perspective, the design and manufacture of pediatric exoskeletons may seem less profitable than the steady and growing market of adults. However, leaving the design, manufacture, and production of pediatric exoskeletons completely to market forces results in a highly significant and consequential unmet need in that children could avoid long-term impacts on the health and well-being by the use of various types of exoskeletons. This is an unmet health need that society knowingly allows persisting despite the technical feasibility of addressing it. A purely market-driven approach would suggest that the industry should be free to choose its target market, particularly in developing a particular product line that seems expensive and time-consuming [27].

Some of the current design approaches, such as in EksoGT or EksoNR from EksoBionics,¹¹ appear to be based on an “ableist perspective,” which assumes and grounds the design approach based on average or common adult abilities. Such a presumption leads to the design of pediatric exoskeletons carrying over virtually all of the characteristics of the adult exoskeleton only in a much smaller version. Generally speaking, the current design methodologies tend to be less person-centered and more technology-centered, essentially miniaturized versions of adult exoskeletons that demand that the child user adapt to technology. Therefore, the design of pediatric exoskeletons shifts from a mere engineering or commercial challenge and becomes a moral requirement to provide children with musculoskeletal disorders with equal opportunity for a good life and an ability to flourish.

In the domain of assistive robotics, traditional industrial approaches oriented primarily toward profit maximization should not be detrimental in ensuring safety, adaptivity, long-term autonomy of operation, user-friendliness, and low cost [40]. The introduction of a robot in a person’s life is not a simple, monodimensional event. On the contrary, it is a long process that, in principle, should align with that person’s values, wishes, and sensibilities, such as personal intimacy [41]. These values might complement other universal values already recognized in the design of social robots such as autonomy, privacy, safety, enablement, independence, and

social connectedness [41]. Current literature does not address what values could or should be translated or integrated into pediatric exoskeletons directly, beyond standard considerations of safety, user-friendliness, and autonomy enhancing. Current regulations seem not to reflect this either [4]. The only available framework concerning physical-assistant robots is the ISO 13482:2014 which stresses the importance of such aspects and disclaims that “future editions of this International Standard might include more specific requirements on particular types of personal care robots, as well as more numeric data for different categories of people (e.g., children, elderly persons, pregnant women).”¹² Although the industry recognizes the unique safety demands for specific populations, including children, not having developed standards and guidelines covering these particular needs puts a twofold barrier: to the safe design of these devices and their subsequent market entrance.

4.2 Design challenges of pediatric exoskeletons

Among the first and perhaps most formidable challenges confronting the design of pediatric orthoses is the fact that children, by definition, are in a growth phase during which their bodies are changing in size and proportion. This has a profound effect on the capacity of an exoskeleton to serve a child’s rehabilitative needs effectively. While the likelihood of outgrowing an exoskeleton device might be very minimal in adult populations, as they do not tend to grow significantly after a certain age, a child of 4 years is likely to outgrow the exoskeleton by the age of 6 [42]. Adaptable modules to different femur sizes might be ideal, along with whatever other physiological changes to what the exoskeleton should accommodate. Moreover, the child’s preferences may also grow or change over time. This particular design challenge is also likely to have implications for commercial viability discussed earlier.

Another challenge relating closely to the development and evolution of children is the fact that children, with the assistance of an orthosis, may learn to walk for the first time. Before this, they might not have a strong, fixed notion, or experiential conception of what it means to move in this way. Other children who may have had the experience of walking and moving freely in a natural environment, but subsequently may have suffered an injury, may have difficulties in accepting the limited

¹¹ See <https://eksobionics.com/>.

¹² See <https://www.iso.org/standard/53820.html>.

movements that current exoskeletons provide. Therefore, in both cases, one of the biggest challenges will be the users' acceptance and accessibility. Different factors might influence users' acceptance. Concerning the characteristics of the robot, size, adaptability, functionality, perceived ease of use, and usefulness might be necessary [43,44]. Age, stage of physical, cognitive, and social development, specific needs, attitudes, and personal circumstances should play an important role also with robot-based characteristics. Functionality and perceived ease of use are essential to the development of exoskeletons in respect to age, where their design needs to take into consideration not only the physical body structure but also the cognitive abilities of the person, which affect a person's ability to understand how the technology works as well as the ability to learn how to use it.

Similarly, age and stage of development affect both the capacity for technological dexterity and non-tangible but valued considerations such as social comfort. In a child-based context, active emotional support from parents and caregivers in the understanding of the technology is of particular importance. Age also represents a challenge for the research community, designers, and engineers who are designing a product that can be effective and easier to use [45] because of the variability in the development of cognitive capacities and maturity. In the case of exoskeletons for children, the challenge is even more significant because, as noted, the design needs to be adaptable to the physical development of children. This requirement directly opposes the more "average-user design" preferred by industry.

Playing is the most desired activities among children. The ability to move freely and play with other children are generally regarded as critical to their well-being. However, significant differences in capabilities can make this difficult or even impossible. One critical role of the pediatric exoskeletons is to provide children with the ability to play with their peers and empower their sense of "being one of them." However, current exoskeletons are not always lightweight, and they do not provide natural movement. Some users have reported feeling like a "Christmas tree" due to the multitude of sensors that adorn the user [10]. These features may hinder a child's sense of "blending in," but at the same time, make the desired interaction possible. Although exoskeletons may have some autonomous functions, users can usually overpower the device. This way, users tend to remain in control and do not lose the "human-added value" in action [31,46]. Being in control of the device may lead to a decreased level of mistrust if the child does not trust himself or herself to operate the device competently. Nevertheless, for their safety, the system should be prepared for such unpredictable behavior to react in time to prevent harm to children.

Design for safety in exoskeletons may refer to preventing the person from falling and avoiding other related harms during its use. Safety, in this sense, dissociates in certified and perceived safety, that is, a "certified robot might be considered safe objectively, but a (non-expert) user may still perceive it as unsafe or scary." The latter is tightly associated with trust, in trusting that the device will not make a user fall [40,47]. Trust is one of the leading values in human-robot interaction (HRI) [48–51]. A lack of trust in robotics often relates to the technical functionality and the perception of safety the user has. Ideally, an exoskeleton should be reliable and trustworthy [8]. Besides safety, trust also depends on how the designers have adequately addressed other aspects, such as privacy, robustness, security, and data protection [52]. Age and cultural preferences also affect trust. For instance, there are situations where older adults were less receptive to robots as compared to younger adults [51,53]. Because of these multiple and multifaceted design considerations, it is not difficult to understand how design challenges could present a barrier, albeit surmountable, to commercial production.

4.3 Implementation challenges: the importance of trust

Trust in an HRI relationship also has a moral dimension. It connects to vulnerability because the trustor is dependent on the trustee and may not necessarily know whether the trustee is trustworthy [51]. In the philosophical debate on trust, trust has been analyzed as an attitude of optimism toward others, assuming their goodwill, when we rely on them in the face of uncertainty and risk of harm or exploitation. Baier [54] highlights that trust is inherently risky and makes visible the subject's vulnerabilities: "[w] here one depends on another's goodwill, one is necessarily vulnerable to the limits of that goodwill." Trust is of particular importance in the context of pediatric exoskeletons wherein the trust ecosystem might involve a child with a specific motor or cognitive impairment, parents, caregivers, and technology developers (including manufacturers or companies), and trustworthiness must be negotiated among and between all of these parties [54,55]. Moreover, the relationship between trust and expectations may complicate the trust ecosystem, as, for example, when parents base their expectations from industry on overhyped and unrealistic claims that appear in the media or self-promoting advertising literature that are far from the current technological feasibility.

Children with acquired or developmental disorders are especially susceptible to the risks posed by overtrust

because children cannot adequately assess the hazards of using sophisticated technological devices [56]. Parents, who would usually be relied upon to provide this kind of assessment, are also often themselves very much emotionally invested in the technology as a potential solution or treatment for their child, such that they may not adequately identify and evaluate the risks associated with the use of a robot. Moreover, children are more likely to conform to robots [57], and in a worst-case scenario, robot designers and producers may exploit this “defenselessness” [58,59].

Trust and, eventually, acceptance also depend on one’s perceptions and attitudes toward robots [60]. Negative perceptions, such as the users perceiving technology as too complicated and costly, may lead to non-acceptance [60,61] and a related lack of trust. One solution to the acceptance issue might lie in the neglected niche of the personalization of robotics. Design that adopts a person-centered approach might reduce device complexity for the user, increase the ease of use, and foster positive experiences [62].

Design plays a crucial role in the personalization of the exoskeletons for children, as it presents an opportunity to decrease the feeling of being ostracized by the stigma of being different. The personalization of technological artifacts has four effects: (1) perceived ease of use, (2) recognition of “mine” versus “others,” (3) reflection on personal identity, and (4) feeling in control [62]. Personalization has demonstrated positive effects in the design of different technological devices, including mobile phones [62] and PCs or Roomba robots [63], and provided a hopeful perspective for socially assistive robotics (SARs) as well [61]. Personalization is an extension of the so-called *customization needs*, where robot design demonstrates an understanding of the users’ individual needs [61,64,65]. In this way, customization contributes to the well-being of users without restricting their rights [65].

Personalization can contribute to the development of the long-term trust relationship between humans and robots, an aspect that has been recognized in the domain of SARs [51,66–68]. As well, personalization has been found to encourage user acceptance among adults [51,69]. This trust relationship is also crucial for children, given their increased vulnerability as compared to adults. Pino and colleagues argue that personalization could overcome individual differences and provide the user with a sense of autonomy and control over the robot, facilitating the appropriation and embodiment of the exoskeleton as an extension of the user’s body [61].

The question of costs and profits remains a crucial consideration for the industry. The duty to deliver on the bottom line requires that production be efficient and capable of yielding a profit. Customized exoskeletons for

a dynamic population present multiple challenges for the industry, even if they are convinced of its merit. Strategies need to be developed that make the design and production of pediatric exoskeletons not only effective and safe but also attractive from a market perspective. Among the avenues that could be pursued is the use of emerging 3D printing technologies [70]. Already in use in several other industries, such as housing [71], 3D printing could provide cost-efficient means to produce parts for personalized exoskeletons for growing pediatric populations and, at the same time, expand options for adults who may benefit from more personalized features [72,73]. Other alternatives might include exploring the limits of modularity in designing such that exoskeletons could be modified rather than replaced to accommodate a growing young body. Finally, the ability to offer an effective therapeutic product for this vulnerable and highly sympathetic population may meet with increased receptivity from institutional customers like hospitals and insurance providers, further enhancing its market viability.

5 Theoretical basis for a new design approach

Technology has always been a supportive means for people to realize their life goals and to improve their lives by making it more comfortable. Such technology’s impacts can also be found in the domain of pediatric exoskeletons. However, to develop a technology that will improve the lives of children, we must understand what a good life means for them. A useful answer to that inquiry can be found in the application of the LBD framework that seeks to accommodate children’s life context, needs, values, and acceptance of pediatric exoskeleton. The starting point of the design process should, therefore, be based on familiarity with the target children population, their needs, limitations, desires (what “a good life” means to a child and expectations of how the exoskeleton would improve his/her life). To that end, we find that perhaps the most suitable approach to use in the development of pediatric exoskeletons would be an LBD rather holistic approach in which a whole “life” becomes a central referral point for technology implementation for improvement of the individual well-being, introduced by Jaana Leikas in the field of gerontechnology [74]. We propose that the LBD approach with respect to the current state of the art would give importance to the children’s everyday life requirements consisting of daily activities and leisure time.

The LBD is not a purely theoretical approach but a practical process consisting of four phases relying on conceptual methodology of “unified systems of action” (called “forms of life”). According to this approach, designers or engineers must understand the segregated “systems of action” among the target population; in this case, children [75]. By understanding these “unified systems of action” within a given domain or section of the child’s life, the new technology can be designed to accommodate the needs of the child in different segments or facets of his/her world. People can participate in the unlimited number of “systems of action,” voluntarily or involuntarily, e.g., in regards to a hobby or other recreational activity, profession, family status, or a situation [76].

1) The first phase in the LBD process is to recognize the “unified systems of action” of a particular group of children using a *form-of-life analysis*, which will help to develop pediatric exoskeleton solutions. Such a pre-design investigation will contribute to discovering the human requirements of the technical artifact, the *reasons, and motivations* that will guide the design process of the technology that should improve human life. The development of the pediatric orthosis is different from the development of adult orthosis because children will need not only much smaller orthoses that are lighter and less robust but also flexible enough to accommodate perhaps less predictable behavior. Additionally, the orthosis should enable them to move by walking upright like adults but also enable them to engage in a range of motions necessary to play with other children [77]. Applied here, the concept of LBD becomes a tool that identifies the differences in different life settings and entities within children’s everyday life. Participating in “systems of action” for different life domains, people generally follow different rules and regularities, e.g., child’s school day consists of waking up, getting washed, having breakfast, going to school, taking part in schoolwork, meeting classmates during breaks, returning home, and doing their homework. These represent rule-following actions that provide meaning in their form of life, and they can also give a sense of technological ideas in the technology design. The form of life mostly focuses not only on the individual but on the group of people, e.g., children [76].

To understand the rules and regularities not only means having an adequate picture of an individual’s “unified systems of action” for each domain but also an understanding of facts and values, i.e., why people pursue specific actions. In this case, children embody many factors such as age, gender, health status, education, and so forth that explain and determine goals of

rule-following actions and even provide limits by restricting what they can do in their lives. Ascertaining a child’s set of “unified systems of action” enables understanding of that individual’s everyday context and real needs that arise in this context [76]. The facts and values facilitate understanding of the needs of the people, including biological, psychological, or socio-cultural [75]. Most of the children who require pediatric exoskeleton are affected by different musculoskeletal disorders, as a biological fact that practically shapes their “unified systems of action” present alongside this is the desire of these children to walk normally and to run or to play with their peers. Therefore, besides facts within the design process, attention should also be given to the values that people follow in their life, by providing the information necessary for analyzing and understanding their “form of life.” The importance of value understanding might assist in identifying the kind of “worth” the technology might bring [76]. Knowledge of a child’s values helps develop meaningful, supportive technologies in actions and things that are valuable to them, like walking freely and playing with their peers. Understanding of facts and values and with them the associated rule-following actions forms the *design-relevant attributes* that can enhance the outlining of pediatric design goals [76].

2) In the second phase of the LBD process, the technology is designed to support rule-following actions becoming the technology-supported actions (TSAs) [76]. For example, walking is a rule-following action, but walking with the support of exoskeleton would be a “TSA.” In the LBD approach, the design of every TSA should be crafted with reference to a desired action and its goals, the agent, the context, and possible technology. Before designing a pediatric exoskeleton, it is then necessary to understand the child’s need for such supportive service; in other words, the *goals* of using it. To discover the children’s goals and values can only be achieved by including the user from the beginning of the design process, regarding children as experts of their everyday life, essentially involving them into *co-designers* [78]. This may also have the benefit of addressing some of the implementation challenges if this early involvement in design facilitates a greater understanding of and comfort with the limitations of the technology.

3) The third phase of the LBD process includes *fit-for-life design*. This phase inquires about the impact of the developed solutions on the quality of life. In our case of pediatric exoskeletons, we inquire about the outcomes that the exoskeletons will provide and evaluate whether they genuinely satisfy the child’s needs. This stage mostly

refers to the previously addressed issue of acceptance and trust, where using different survey methodologies, various factors can be assessed, such as perceived ease of use, usefulness, or enjoyment (attitude) toward particular technology from the children (user) and parent perspective [79].

- 4) After the evaluation of the impact, if the design of an exoskeleton meets the children's needs, the fourth phase of the LBD process – *innovation design* – takes place. This final phase aims to export the design outcome into general use by incorporating the technology into human life settings, ensuring that children use the future product [80]. To facilitate the uptake of the technology by those who could most benefit from it, health-care systems and other societal institutions, in addition to the producers, may be called upon to contribute to the appropriate integration of this technology.

The above-structured process represents a person-centered approach where the design of exoskeletons is not only how to produce a functional exoskeleton, but an exoskeleton that will improve the quality of the child's life. In its primary focus, the LBD design strives to understand what the good life of a child would be and to promote it within the design of the technological artifact. LBD applied to the context of pediatric exoskeleton development by promoting the good of the child accomplishes multiple goals: first and foremost, it supports the child's capacity to flourish. Such an approach requires a morally virtuous action from the designers and engineers, promoting and integrating Aristotelian virtues such as *phronesis* in the form-of-life analysis, or virtue of justice when the exoskeleton adequately responds to the child needs, reducing the prevalence of unmet needs and inequalities among their peers. Pediatric exoskeletons will facilitate a “good life” for children with impairment in the form of *best possible life* [81], taking situation and context into consideration. Personalized exoskeletons built with an LBD approach further enhances the possibility for human flourishing among children with neuromusculoskeletal disorders. It is essential to acknowledge that although the exoskeleton will improve the child's quality of life, it will also modify their “form-of-life” demanding from them the virtue of temperance (self-restraint) in accommodating and accepting the exoskeleton in their everyday life, especially after noting the differences in abilities between them and their peers' abilities.

6 Conclusion

Our primary aim with this article is to identify and address challenges and barriers of pediatric access to

exoskeletons and promote inclusiveness by design. In the field of exoskeleton development, children and their needs appear to be substantially overlooked, with some few exceptions presented in our overview. We identify three reasons for this paucity of pediatric products: (1) a lack of market appeal because of the investment or costs associated with product development for such a complex target population, (2) design challenges for pediatric exoskeletons in comparison to the design for adults. This is due in part to children's physical growth and the variability of learning abilities. Finally, we attribute this phenomenon also to (3) implementation challenges related to trust.

We conclude that the unmet health needs of the pediatric patient group who would benefit in a myriad of ways from the use of exoskeletons, justify and demand a more nuanced approach to the design of pediatric exoskeletons. We suggest that design approaches must balance market realities with the health and life needs of this segment of the population. The neglect of children's needs and the failure to provide adequate technological solutions represent a major barrier to accessing the benefits that the technological advances bring about. Both as a matter of policy and moral commitment to the well-being of all members of society, we propose the application of the LBD in pediatric exoskeleton design. Promotion of inclusivity and, specifically, pediatric access using a variety of institutional and policy mechanisms will further our collective well-being by contributing to more inclusive health care.

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