Reimagining robotic walkers for real-world outdoor play environments with insights from legged robots: A scoping review

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ABSTRACT
Purpose: For children with mobility impairments, without cognitive delays, who want to participate in outdoor activities, existing assistive technology (AT) to support their needs are limited. In this review, we investigate the control and design of a selection of robotic walkers while exploring a selection of legged robots to develop solutions that address this gap in robotic AT.
Method: We performed a comprehensive literature search from four main databases: PubMed, Google Scholar, Scopus, and IEEE Xplore. The keywords used in the search were the following: “walker”, “rollator”, “smart walker”, “robotic walker”, “robotic rollator”. Studies were required to discuss the control or design of robotic walkers to be considered. A total of 159 papers were analyzed.
Results: From the 159 papers, 127 were excluded since they failed to meet our inclusion criteria. The total number of papers analyzed included publications that utilized the same device, therefore we classified the remaining 32 studies into groups based on the type of robotic walker used. This paper reviewed 15 different types of robotic walkers.
Conclusions: The ability of many legged robots to negotiate and transition between a range of unstructured substrates suggests several avenues of future consideration whose pursuit could benefit robotic AT, particularly regarding the present limitations of wheeled pediatric robotic walkers for children’s daily outside use.

KEYWORDS
assistive technology; robotics; mobility; pediatric rehabilitation; walker; rollator; smart walker

1. Introduction

Mobility is vital for children with lower limb disabilities considering their need to explore their environment (e.g. homes, playgrounds, and daycare centers) to develop key motor skills and functions for independence in adulthood [1–3]. AT designed to increase mobility is highly desired and valuable in lower-extremity rehabilitation because it allows a person with a disability to travel independently [4]. Traditional AT options include crutches, walkers, wheelchairs, and prostheses. The efficacy of each option is strongly influenced by the individual's level of function and the environment in which it is used. The selection of each option depends on a diverse set of factors such as age, illness type, location of impairment, portability, and cost [5,6].

Crutches and walkers are favorable because they are lightweight, portable, and height-adjustable [7]. Crutches provide assistance to mobility by broadening pediatric users' base of support and improving their balance. They are completely in the control of the user, and therefore demand substantial coordination, muscle memory, and balance to avoid slipping or falling. Children are also at-risk for muscle wear and tear if the crutches are placing too much strain on their upper extremities [8]. Crutches cannot be used if a child requires underarm support or is unable to bear weight on the hands [9]. Walkers are commonly used in the early stages of mobility training if one or both of a child's legs are so disabled that full weight bearing is not possible. One even has the option of having wheels on the walker (i.e. rollator) to reduce the child's force contribution and eliminate constant lifting while walking [9]. However, the design and control of standard walkers make them unsafe to use in outdoor unstructured environments (e.g. parks, forests). Standard walkers and crutches are "not smart." Any information they provide about the environment is transmitted at the moment of contact and they cannot receive or process information from the environment (i.e. no feedback or feedforward control). This limitation of walkers and crutches presents a "tipping over" hazard if the walker were to become unbalanced while the child is applying force to generate motion. Both walkers and crutches require energy exerted by the child to execute movement. When children become too fatigued to support their own body weight with their upper limbs, they must rely on an alternative care option to address their mobility needs such as manual or powered wheelchairs—a care option outside the scope of this paper [8,10,11]. The challenges for existing AT that support children with ambulatory disabilities center around two themes: control and design. Control challenges of crutches and walkers include maintaining balance and coordinating movement. Design challenges of crutches and walkers include body support, poor performance on uneven terrain, and device mass.

We envision applying ideas from the control and design of legged robots that enable them to work well in complex environments to the control and design of robotic walkers for disabled children. The aim of this review is to present approaches to the design and control of legged machines that might be able to assist mobility in a far broader environmental context than current robotic walkers without adding greater complexity in design and product. Robotic assistive technologies (robotic AT), a subclass of AT, are defined as robots used to increase, maintain, or improve the function capabilities of persons with disabilities [12]. For patients with lower limb disabilities, robotic ATs have historically been designed to perform well in flat, obstacle-free, and static environments [13,14]. However, children desire increased mobility in a broad range of diverse settings, which today's robotic AT cannot deliver. To meet this need, robotic AT for children with lower limb disabilities should be designed to be safe and work well in dynamic surroundings. In the field of legged robots, there is a vast amount of literature that deals with developing robots with the ability to continuously traverse complex dynamic environments [15–19]. Although we do not want to necessarily replace robotic walkers with legged machines, we do want to investigate the design and control aspects of these systems for inspiration and insights to develop robotic walkers that can achieve locomotion on uneven surfaces for our target pediatric population.

1.1. Target Population

Pediatric rehabilitation research aimed at improving mobility typically focuses on children with Cerebral Palsy (CP), which is the most common motor disability in childhood with approximately 1 in 323 American babies being diagnosed annually [20,21]. CP is defined as a disorder of posture and movement due to a defect or lesion in the immature brain [22]. In other words, this disease impacts children physically and mentally. Still, there are other common disabilities in children that impede their mobility, but do not affect their cognition. These types of childhood disabilities can also benefit from this area of research. The American Census Survey (ACS) defines ambulatory disabilities as motor impairment in individuals 5 or more years old that causes "serious difficulty walking or climbing stairs". In 2016, about 0.6% of the 5.6% of people ages 5-17 with disabilities in the United States (US) fell into this category of disability [23]. Ambulatory disabilities include Congenital Limb Defect (CLD) and Spina Bifida as well as CP. CLD occurs when a portion or the entire upper or lower limb fails to form normally when the baby is developing in the uterus. Researchers estimate that about 1 in every 1,900 babies is born with a limb reduction defect in the US [24]. Spina bifida is a birth defect that occurs when the spine and spinal cord do not form properly [25]. Each year, about 1,645 American babies are born with spina bifida [26]. Note that the formal definition of ambulatory disability excludes children who have "difficulty walking or climbing stairs" between the ages of 2 and 5 as well as those who did not participate in the survey. Therefore, the statistic given by ACS on children with ambulatory disabilities is potentially a gross underestimation of the amount of children presently in the US with at least one ambulatory disability. The statistics on the individual types of ambulatory disabilities (e.g. CLD), however, include all children under the age of 18 years old.

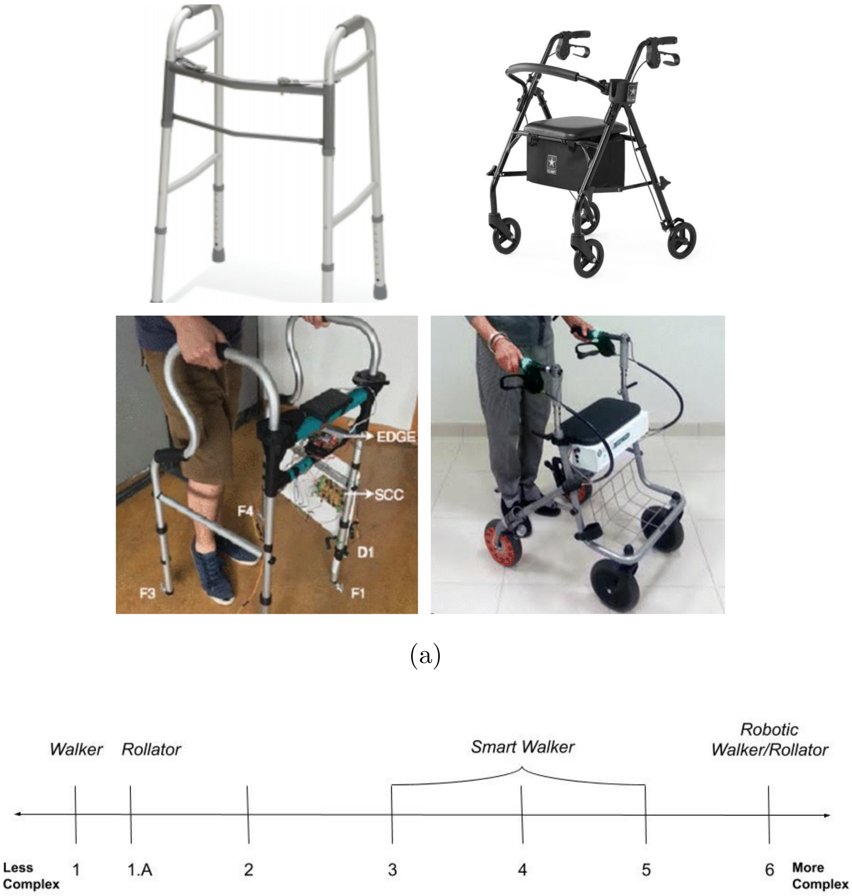
This review addresses strategies for developing a robotic walker that can traverse complex and dynamic areas for children with mobility impairments who have mild to no cognitive impairment and are of early school-age. We define the term "early school-age children" as designating children between the ages of 3 and 8 years old. During the pre-school years (ages 3 to 5), children grow more and more independent and capable. To assist with growth, the Center for Disease Control and Prevention (CDC) recommends parents supervise their child in outdoor play spaces such as playgrounds and theme parks. In the early school years (ages 6 to 8), children gain independence and competence quickly. This includes practicing physical skills (e.g. walking) to get better at them [27]. Based on developmental milestones [28], we selected a target demographic of early school age children for which a robotic walker for outdoor exploration would aid their individual growth. The paper is organized as follows. Section II describes the methodology used for the literature search. Section III provides an analysis of the robotic walkers in the selected literature and discusses their limitations in outdoor dynamic environments. Section IV offers a brief review of legged robots that operate in complex and dynamic environments. Section V concludes this paper with future considerations.

2. Methods

2.1. Existing literature for robotic walkers

We performed a comprehensive literature search up to August 2020 from four main databases: PubMed, Google Scholar, Scopus, and IEEE. The keywords used in the search were the following: “walker”, “rollator”, “smart walker”, “robotic walker”, “robotic rollator”. See Fig. 1 (a) for examples. A rollator is defined as a wheeled walker. A “smart walker” is described as a non-motorized standard walker with intelligent functionalities such as computer vision and voice recognition [29,30], however during this search, we noticed that there are a handful of publications that use the term “smart walker” for devices that contain both motorized wheels and intelligent capabilities. All the publications written in the English language and published in the period between 2015 and 2020 that discussed the control or design of robotic walkers (i.e. smart walkers, robotic rollators) were considered. Additional works from the references of the selected papers in the search were also included.

A total of 159 papers were analyzed using the aforementioned approach. From the initial 159 papers, 127 papers were excluded since they failed to meet some inclusion criterion. Fig. 1(b) lists the AT that the keywords of our literature search describes in order of increasing overall system complexity (see Appendix A for more details). The total number of papers analyzed included publications that utilized the same robotic walker, therefore we classified the remaining 32 studies into groups based on the type of robotic walker used; this results in a review of 15 different types of robotic walkers. In the review, we explore how robotic walkers combined with the underlying legged robotics technology could provide potential solutions to meet the needs posed by the target population. With that in mind, we determined the inclusion criteria that allowed us to compare and contrast physical robot to physical robot. The inclusion criteria are outlined in the flowchart in Fig. 2. We characterize a working prototype to be a power autonomous physical machine that represents all or nearly all of the functionality of the final product. To support our target population during outdoor activities, we require that the prototype be non-stationary and contain motorized wheels. If users are stationary, they are restricted to playing in one location and are unable to explore their surroundings. The use of actuated wheels assists with muscle weakness and fatigue that children with ambulatory disabilities typically suffer from after prolonged use of non-motorized walkers [7]. A key feature distinguishing robotics from merely powered devices is the ability to sense and act in consequence. Robotic AT must offer performance and safety beyond the capabilities of a simple push button power assist but targeting child users further requires simplicity and reliability of operation independent of the specific surroundings or available adult attendants. The significant complexity of designs capable of such operational independence discourages confidence in the value of retrofitting for unstructured outdoor settings devices designed for indoor clinical rehabilitation centers. One of the unexpected outcomes of this literature review reveals that few robotic mobility devices are designed for use outside a clinical setting. Restricting focus to devices whose designers explicitly target assistance of day-to-day mobile activities of our intended audience — and who can report clinical or controlled trials establishing that goal — results in the surprisingly small final sample of papers we review. All of the systems examined in this paper are classified as robotic walkers or robotic rollators. Section 3 will review them in detail.



(a)

(b)

Figure 1.: (a) Examples of the AT described by our chosen keywords from the literature search - *Top Left*: Traditional (Standard) Walker [31], *Top Right*: Rollator [32], *Bottom Left*: Smart Walker [33], *Bottom Right*: Robotic Walker/Rollator [34] (b) Ranking of the AT described by the keywords based on overall system complexity (see Appendix A for details).

2.2. Existing literature for legged robots in dynamic environments

To help us highlight the appropriate legged robots from the wide range of literature available, we performed a less comprehensive search from three databases: IEEE, Google Scholar, and Scopus. Based on the selected robotic walkers and the intended environment for daily use, we developed the following inclusion criteria:

(1) Included a working prototype (i.e. no simulations or proof-of-concept platforms).
(2) Performed controlled experiments showing their working prototype executing a gait over two or more uneven surfaces in an outdoor environment.
(3) Exclusively used internal sensing to support the gait used in their controlled

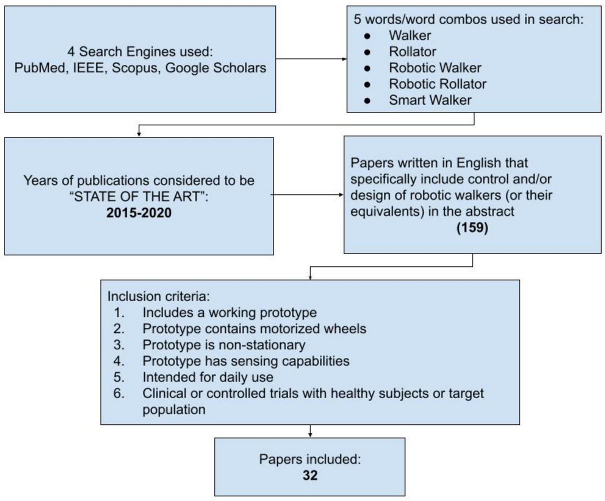


Figure 2.: Flowchart of the search and inclusion process.

experiments.

We use the same definition for a working prototype as in the robotic walkers' literature search. To verify that legged robots can provide a potential approach to balanced motion in outdoor environments that we claim existing robotic walkers should negotiate, we require that repeated experiments demonstrate one specific task. The task is balanced movement through several types of uneven terrain (e.g. wood chips, grass, rubber mulch) commonly found in playgrounds. Although not every legged robot can execute the desired task, including one target assignment does little to reduce the amount of literature we need to consider. To limit our inquiry while maintaining the relevancy to robotic walkers, we focus on legged robots that can traverse complex environments exclusively using proprioceptive and vestibular sensing, which we will designate as "internal sensing". In this paper, we follow the traditions of the locomotion neurophysiology literature [35] and use the term "proprioception" in analogy for robotics to denote sensory measurements originating within the robot's actuator drive train or physical limb structures, distinguishing these from internal measurement units (IMUs) that are analogous to the biological vestibular sensory pathways. In contrast, the term "exteroception" will denote sensing modalities entailing remote, contact-free measurement (e.g., vision or lidar) that do not fall under proprioception or vestibular sensing. From the current literature, it seems that developing a controller for a robotic walker that can handle such environments would require a great deal of sensing capabilities (proprioceptive, vestibular, and exteroceptive) and custom hardware, therefore increasing the complexity of the device. We expect disabled children to utilize these devices daily, so a large, heavy, or highly complex robot is not ideal. We also want the device to be safe during operation as well as in the event of a system failure. Therefore, we look at the development of a robotic walker that requires a minimal amount of mechanical and electrical components that is also stable, dynamically and statically, in uneven outdoor settings. We found a selection of legged robotic platforms in the literature that can carry out or be extended to perform this task under this condition. There are commercially available legged robots that also claim to exhibit such capabilities under similar conditions. However, due to the absence of publications to support their claims, we are unable to analyze their approaches in detail. Thus, the ensuring review of legged technologies is a much more notional account of a rapidly emerging technology, the choice of whose exemplars relies as much on the background and judgment of the authors as on a formal search methodology.

3. State of the Art Robotic Walkers

Generally, robotic AT is tailored to a variety of disorders and addresses a range of needs such as mobility, self-care, cognition, etc. Even fixating on robotic AT for people with ambulatory disabilities, the state of the art does not primarily focus on solutions for one specific type. Of the robotic AT created for children, however, the state of the art is predominantly focused on addressing the needs of children with CP. These robots, developed to support motor functions, are quite often aimed at gait training in children [13,36] only a few are intended to improve their day-to-day experience while exploring their environments [2]. When we specifically look at robotic walkers, we see that regardless of the target population, this type of robotic AT is primarily designed to rehabilitate the patient in a clinical setting [36–39], not to support the daily mobility activities of its user. As mentioned in Section 2.1, an important finding of this review is the lack of robotic walkers that can be used daily by disabled children outside of a clinical setting. Table 1 provides a summary of the systems that were included in this review.

3.1. What makes a robotic walker complex?

We have chosen to compare each walker based on how the device is mechanically structured and controlled as well as provide a discussion of the usability and performance of each walker on either non-disabled or disabled subjects. Fig. 3 arranges the selected robotic walkers based on their control and mechanical complexity. First, we consider the simplest controller to be low-level, direct drive. One turns the system on and the system immediately receives power to begin a task it was programmed to do. With that in mind, we define control complexity by four components: supervisory control, automatic safety features, internal sensing, and exteroceptive sensing. The addition of any of these components requires the controller to do more than immediately supply power to the system which increases the difficulty of developing it. Looking at the structure of each walker, we consider the standard walker in Fig. 1(a) as the simplest base frame. We define mechanical complexity by five components: portability, mobility on uneven surfaces, mobility on smooth surfaces, traversing steps, and additional wearable equipment. The addition of any of these components requires modifying or redesigning the standard walker frame, increasing the effort and hardware necessary to build. See Appendix B for a detailed explanation of the components that define control and mechanical complexity used to develop the graph in Fig. 3. For each walker listed above, the paper selected had to contain a detailed description of the mechanical design, the control framework, and the controlled experiments. In the event that more than one paper contained this information, we chose the most recent publication.

Table 1.: Summary of the State of the Art Robotic Walkers/Rollators

Device	**Target Population**	**Hardware Components**	**Controller Used**	**Mechanical Complexity Score**	**Control Complexity Score**
Active Posterior Walker (ragaja 2019) [40]	Children with walking disabilities	This walker contains a U-shaped metal base frame with four wheels and the opening is in the front. Only the two rear wheels are motorized, and it has an array of 5 infrared (IR) position sensors mounted on top of the walker frame located behind the user.	force sensing	-25	-55
A novel human-robot interaction system (wang 2018) [41]	Adults with mobility needs and upper limb weakness	This walker is a mobile device with 2 motor-driven wheels and 2 universal wheels. A handle is installed on the top of the walker. A linear slideway with a spring is installed between the handle and the walker along the anterior-posterior direction. Additionally, there are 4 IMUs attached to the 2 shanks and 2 thighs by elastic bands while a pressure sensor is placed on the end of the spring.	force sensing	-120	-55
i-Walker (morone 2016) [34]	Adult Persons with mild/moderate subacute stroke	A standard 4-wheel rollator frame is modified with integrated sensors and actuators. The actuators are 2 hub motors integrated in the rear wheels, used for braking or helping the user walk. The device has 2 modified handlebars with brake handles and force measurement. 32 strain gauges are mounted in 8 bridges to measure forces and several sensors are arranged in the frame.	force sensing	-75	-10
i-Go (lu 2015) [42]	Elderly persons	This walker consists of a support frame as the main body, 2 force-sensing grips on the handles, 2 wheels equipped with servo brakes and encoders, a controller installed in the notebook, and sensors for obstacle and slope detection. The support U-shape frame is made of aluminum. It also has an adjustable rod for height adjustments.	force sensing	-110	-25
A novel assistive walker robot (oigawa 2019) [43]	Elderly persons	This walker has 2 caster front wheels and 2 actuated rear wheels with an in-wheel motor on each side. Its body size is small enough for practical use in a typical Japanese house. The user is able to adjust the height of the walker. The handle grips contain force sensors as well as a lever to activate the mechanical parking brake. Additionally, there are two laser range finders on the frame.	force sensing	-75	-25
Chaoyang University of Technology (CUT)'s smart walker (cheng 2017) [44]	Elderly persons	This is a commercial smart walker with 4 wheels. The 2 front wheels has 12 V DC motors. Also included on the walker's frame is a wireless inductive charging module, an Arduino microcontroller, a motor driver, a RFID reader, an IR tracking sensor and a battery.	force sensing	-75	-40
UFES Smart Walker (jimenez 2015) [45]	Elderly persons	This walker consists of a base frame with 3 wheels. The front wheel is caster and the 2 rear wheels are DC motorized. It also has an embedded computer, a microcontroller, a wireless sensor network, 2 laser range finders, 2 3D force sensors in the handle bars, and an IMU sensor in the front of the base.	force sensing, autonomous navigation, and motion captured by LRF	-110	-110
JaRoW II (ohnuma 2017) [46]	Elderly persons	JARoW-II consists of a base frame and upper frame. The upper frame is supported by the base frame and is positioned at the center of the base frame. The base frame consists of a leg frame having 2 front legs and 1 rear leg extending in 3 directions from frame center. The tip of each leg features an omni-wheel unit. Lastly, the rear leg is equipped two LRFs and the main controller and battery unit are installed at the rear of the base frame.	motion captured by LRF	-110	-65

MOBOT rollator (werner 2018) [47]	Elderly persons who are frail with and without cognitive impairment	A 4-wheeled rollator is equipped with 2 high-precision quadrature optical encoders on the 2 rear driving wheels, a laser range finder at the front of the rollator facing towards the motion direction, and an IMU mounted on its chassis.	autonomous navigation	-75	-110
SmartWalker (shin 2015) [48]	Elderly persons	The SmartWalker had a front wheel, two motorized rear wheels, and two sensors. The front wheel had no motor and the rear wheels were powered with e-bike motors. It had a RGBD camera attached to a motor and placed below the handlebar. This device also had a laser sensor sat the bottom of the frame in addition to a tablet-PC and an on-board processing computer.	manual and autonomous navigation	-110	-125
SLAM walker (kashyap 2018) [49]	Elderly persons and individuals with movement disorders	This rollator-type device has 2 fixed wheels in the rear and caster wheels in the front. Mechanical encoders are mounted to the rear wheels. The motors are connected to a motor shield. The motor shield and the encoders are then connected to an Arduino. Additionally, the device includes a lidar sensor, a microphone, and a wearable accessory for fall detection.	autonomous navigation	35	-40
Little Keepace (matsumoto 2017) [50]	Elderly Persons	A rollator-type device with 4 wheels that consists of a six-axis gyro sensor and 4 wheel rotation sensors. It has both a horseshoe handle and a normal handgrip handle. The front wheels are caster and the rear wheels are motor-driven. It also comes with a seat, a storage bag on the front of the frame, and manual handbrakes.	force sensing	-40	-40
Flatia (matsumoto 2017) [50]	Elderly persons	A rollator-inspired device with four wheels. The front wheels are caster and the rear wheels with manual brakes are motor-driven. The base frame contains a large basket between the handlebars and a force sensors in each of the handle grips.	force sensing	-40	-25
RT.1 and RT.2 (ogata 2017) [51]	Elderly persons	RT.1 and RT.2 are a 4-wheeled trolley and rollator respectively. The front wheels are caster and the rear wheels are motor-driven. Each has a 2-axis (x and y axes) acceleration sensor, a 3-axis gyroscope sensor, a GPS sensor, a cellular device, and a touch sensor on the handle. Only RT.1 has 2 additional force sensors in the handle.	RT.1- force sensing, RT.2 - manual	-15	-40
Agile Walker (katz 2015) [52]	"Active-agers"	This walker has a 3-wheel configuration: a front wheel and 2 rear wheels. These 3 large diameter wheels with inflatable tires are motorized using electric wheel hub-geared motors. The walker has oval-cross section handlebars and a control panel in the middle of the handlebars presents the speed of the walker, distance traveled, and slope of the ground. It can be folded to fit in a typical sport utility vehicle (SUV).	force sensing	-85	-65

3.2. Development of Robotic Walkers for Children

Out of all the papers considered, only one robotic walker, that explicitly states its target population are children with disabilities, met our inclusion criteria. The key criterion that separates this paper is the fact that their proposed device was intended for daily use. Ragaja et al. [40] presented the Active Posterior Walker, a robotic walker designed for children with walking disabilities. The Active Posterior Walker was an adaptation of an existing commercially available passive walker. It consisted of a metal base frame with four wheels with the opening in the front. Only the two rear wheels were motorized, and it had an array of five infrared (IR) position sensors mounted on

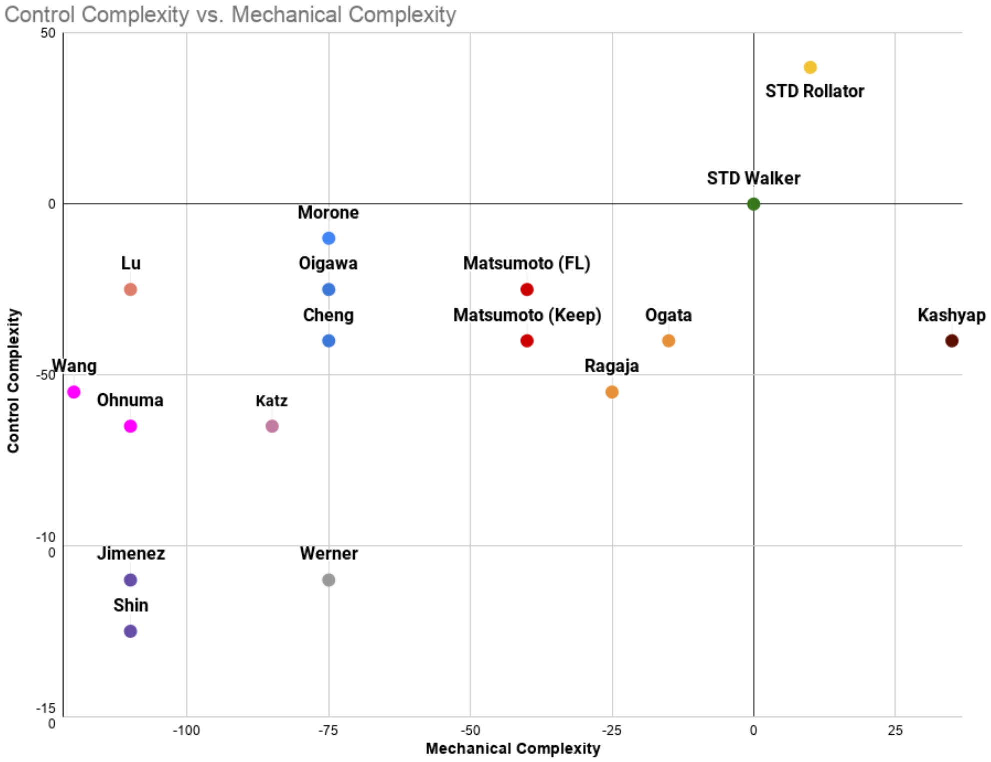


Figure 3.: This plot is a result of analyzing the 15 robotic walkers/rollators based on mechanical and control complexity (see Appendix B for more details). Each device is labeled by the first author's last name. Devices that were very similar in complexity are marked with the same color. The datum is marked green.

top of the walker frame positioned behind the user. The walker's motion was controlled according to the gait intention of the user such that the walker followed the user's waist position while maintaining a distance gap between the user's body and the walker's frame. The gait intention of the user was derived from the measured waist position. Given that the base frame is a modified standard walker, the complexity of the structure is minimal, receiving a score of -25. On the other hand, the controller is more sophisticated, incorporating exteroceptive sensing data, earning a score of -55. So this result places this device not too far from the standard walker on the graph of Fig. 3.

3.3. Development of Robotic Walkers for Adults

While the robotic walkers intended for adults vary in the medical conditions they address, they predominantly target the geriatric population. Several of these devices are intended for indoor use only (i.e. in the home, at a retirement center). Wang et al. [41] developed a human-robot interaction system for human walking companion based on force sensing. Their device was developed for elderly adults with mobility needs that lack upper limb strength. The walker was presented as a mobile device with two motor-driven wheels and two universal wheels. A handle was installed on the top of the walker. A linear slideway, with a spring and pressure sensor attached, was installed between the handle and the walker along the anterior-posterior direction. There were also four IMUs attached to the two shanks and two thighs by elastic bands. A customized system was used to process the data collected by the sensors, and then provided control signals to the robotic walker. With the support of a gait detection algorithm, the device could detect human walking phases (e.g. heel-strike, mid-stance) in real time while the user was walking. Although this walker is manually driven, it has substantial sensor data to process, resulting in a control complexity score of -55. Additionally, the extensively customized frame makes it increasingly complicated to build, earning the largest (in magnitude) mechanical complexity score of -120. Similarly, Morone et al. [53] presented a study that evaluated the effects of human-robot walking training performed with a robotic rollator. The i-Walker was developed for adults in the subacute phase after a mild or moderate stroke. The authors modified a standard four-wheel rollator frame by incorporating sensors and actuators. The actuators were two hub motors integrated in the rear wheels. The device had two handlebars with brake handles and force sensors to detect the force imposed by the user. Thirty-two strain gauges as well as several unnamed sensors were arranged in the frame to detect force, tilt, and movement. A network of distributed microcontrollers drove the system while a battery supplied power. The walker provided no pulling force, but assisted in pushing the device forward with the user. This device gets a -10 in control complexity because it is primarily manually driven with only one type of sensor data being processed. However, the inclusion of several intricate pieces of hardware substantially boosted the effort needed to construct this walker, resulting in a mechanical complexity score of -75.

Continuing with force sensing, Lu et al. [42] proposed a motion guidance system equipped upon a robotic walking assistant for the elderly to emulate the biological rhythm of its user for practical daily use. The i-GO consisted of a support frame as the main body, force-sensing grips on the handles, two wheels equipped with brakes and encoders, a laptop, and sensors for obstacle and slope detection. The aluminum support frame consisted of an adjustable rod for height adaptation. The controller contained a machine learning algorithm to derive the force necessary to assist the user's motion. The fact that the controller is limited to processing only one type of sensor data (i.e. the force) to operate the device, making it slightly more complicated than a traditional walker, earns it a control complexity score of -25. The same cannot be said about its mechanical design, which requires more effort to construct since it's highly specialized, resulting in a score of -110. Similarly, Oigawa et al. [43] proposed using force-sensing grips in their assistive walker robot, which considers its user's gait. This unnamed walker had two caster front wheels and two actuated rear wheels. Its body size was small enough for practical use in a typical Japanese house and included height adjustability. The handle grips contained force sensors as well as a lever to activate the mechanical parking brake. There were also two laser range finders (LRFs) on the frame. While the user applied force to initiate motion, the controller measured the right and left foot gait of its user and estimated its user's body balance by calculating their position of center of gravity (COG). When the COG was unbalanced, the walker activated the motors of each wheel and tried to coordinate the body balance of its user. As with the i-GO, this device's controller is only processing applied force giving it the same control complexity tally of -25, however, size considerations and materials make it less complex to build. Resulting in a mechanical complexity record of -75. Both walkers land far from the standard.

Moving away from using force sensing to pressure sensing, Cheng et al. [44] developed a user's intention detection algorithm for their proposed smart walker to assist home care for the elderly. The authors modified a four-wheeled commercial smart walker. The unnamed walker's frame consisted of a wireless charging module, a microcontroller, a motor driver, a RFID reader, an IR sensor, a battery, and a DC motor in each front wheel. The authors installed three pressure sensors on both sides of the smart walker's handles to extract the user's force application, which were taken as input signals. Then through a classifier, input signal recognition took place and controlled the device, moving it forward or backward. The user was required to apply pressure to the handles to direct the walker. Mechanically, this device's base frame is not very complex since it utilizes a traditional rollator but it does contain an ample amount of hardware. So it earns a mechanical complexity tally of -75. To control the device, sensor data must be processed in a timely fashion, which complicates controller development. Being that there are only two sensors, so the control complexity score lands at -40. Likewise, Jiemenz et al. [45] stepped away from force sensing alone to incorporate LRFs. The authors presented a smart walker with an admittance controller for guiding visually impaired individuals along a desired path. This walker consisted of a base frame with three wheels. The front wheel was caster and the two rear wheels were motorized. It also had an embedded computer, a microcontroller, a wireless sensor network, a LRF, several 3D force sensors in the handle bars, and an IMU sensor in the front of the base. The controller used the physical interaction between the user and the walker as inputs to provide haptic feedback hinting the path to be followed. With haptic feedback providing intuitive information, the user was expected to manage the smart walker. For this device, both the controller and the structure are very complicated to put together. The incorporation of haptic feedback combined with the customized three-wheel frame increase the difficulty of developing this walker substantially, in comparison to traditional walkers, resulting in a control and mechanical complexity score of -110 each.

Investigating motion tracking without force sensing, Ohnuma et al. [46] developed a motion-based controller for walking assistance that considered pelvic movements for the JAIST Active Robotic Walker II (JARoW-II). The JARoW-II was designed for elderly people in need of supervision. Its frame consisted of a base frame and upper frame. The upper frame was supported by and positioned at the center of the base frame. The upper frame was supported by and positioned at the center of the base frame. The base frame consisted of a leg frame having two front legs and one rear leg extending in three directions from the frame's center. The tip of each leg featured an omni-wheel unit. When the user took a step forward in a certain direction, the role of this system was to read that movement with LRFs and facilitate walking based on the user's intent. The wheel driven system determined the speed and direction of the walker in response to foot movements accompanying user walking. Although the unique framework dominates the complexity scoring of this device (mechanically scoring a -110), the motion-based controller is not simple to implement either, resulting in a control complexity score of -65.

Under the assumption that their device will only be used indoors, there were several robotic walking devices designed for autonomous navigation. Werner et al. [47,54,55] designed, built, and evaluated a robotic rollator (RR) that provides navigation assistance for frail older adults with (CI) and without cognitive impairment (NCI). The MOBOT rollator was an assistive device which included a main frame, two actuated handles, four active wheels, a user interface, an electronic control unit and various sensors. The platform consisted of two robots, a rollator-type robot for walking and a nurse-type robot for sit-to-stand (STS) assistance. The navigation based controller consisted of three components: map-building, odometry, and localization. Likewise, Shin et al. [48,56] presented the SmartWalker, a high-tech extension of a regular walker aimed to assist its user intelligently and navigate around its environment autonomously. The SmartWalker had a front wheel, two motorized rear wheels, and two sensors. It had a RGBD camera attached to a motor and placed below the handlebar. This device also had a LRF at the bottom of the frame as well as a tablet-PC and an onboard processing computer. It could function in two different modes: assistive and autonomous. In the assistive mode, the frame was driven by the user and it provided support to the user during movement. In the autonomous mode, the walker operated as an autonomous robot, without any physical exertion by the user. The walker navigated around its environment and executed the user's commands given through gestures. These two robotic walkers' autonomous ability comes at a cost of increasing control complexity because the device is expected to operate effectively in any given setting without the user's input. Each control system is expected to process a large amount of sensory information, earning complexity scores of -110 and -125 respectively. With that in mind, notice that Shin et al. and Werner et al. also designed and constructed very intricate mechanical structures to compliment their controllers, resulting in high complexity scores of -75 and -110. These devices land the furthest from the traditional walker on the graph of Fig. 3. Kashyap et al. [49] also proposed an autonomous walker as a tool for the elderly and individuals with movement disorders. This rollator-type device had two fixed wheels in the rear and two caster wheels in the front. Mechanical encoders were mounted to the rear wheels only. The motor and the encoders were then connected to an Arduino. Additionally, the device included a lidar sensor, a microphone, and a wearable accessory for fall detection. The walker could be controlled by voice commands to create location markers and navigate the user in an indoor environment while avoiding obstacles. The walker utilized SLAM techniques using a lidar sensor to map the environment the user was located in. Mechanically, this device is based on the standard rollator framework and requires few lightweight hardware add-ons, resulting in a complexity score of 35. From a control standpoint, autonomous navigation, even with few sensors, is complicated to develop and maintain, earning the device a control complexity tally of -40.

Activities of daily living are not restricted to indoor environments, therefore robotic walkers should be able to provide walking assistance outdoors. Matsumoto [50] described three robotic rollators that were designed for the elderly to use outdoors on ramps, streets, and sidewalks. The Little Keepace was a rollator-type device with four wheels that consisted of a six-axis gyro sensor and several wheel rotation sensors. It had both a horseshoe handle and a handgrip handle. The front wheels were caster and the rear wheels were motor-driven. It also consisted of a seat, a storage bag on the front of the frame, and manual handbrakes. The user controlled the device by applying a pushing force to the handgrip in the desired direction of movement. The Flatia was another rollator-inspired device with four wheels. The front wheels were caster and the rear wheels with manual brakes were motor-driven. The base frame contained a large basket between the handlebars, and two force sensors were placed in the handle grips. Similar to the Little Keepace, Flatia was activated via the handlebars when the user applied a pushing force. Unlike the other devices, Flatia had a “safe stop” function that was activated when a user moved too far away from the device while walking (i.e. “separate braking” function). The RT.1 and RT.2 were a four-wheeled trolley and rollator respectively. Like the Flatia, their front wheels were caster and rear wheels were motor-driven. Each device had an acceleration sensor, a gyroscope sensor, a GPS, a cellular device, and a touch sensor on the handle. Only RT.1 had additional force sensors in the handle. The motors in each device were activated when the user applied force, initiating movement of the walker’s frame. As a safety precaution, they could also recognize a state of danger such as a fall and notify the management center, caregivers, etc. The control strategy for RT.1 and RT.2 was extended by Ogata et al. [51], who proposed an algorithm for estimating the condition of the road surface using only internal sensors. The estimations were used alongside the force sensing controller to improve the walking assistance of the robotic device in nursing care communities. All three devices are pretty similar in control and mechanical complexity, not straying too far from the traditional walker. The slight difference can be contributed to the number of sensors as well as the different types of sensing capabilities required of each walker. The control complexity scores are -40, -25, and -40, while their mechanical complexity scores are -40,-40, -15, respectively.

Likewise, Katz [52] presented a newly developed, all-terrain walker, the Agile Walker, to improve the outdoor mobility of elderly people with some mobility limitations. The author defined the target group of “active agers” as those who were able to walk and were fit enough to hike and to travel outdoors. The walker had a three-wheel configuration: one front wheel and two rear wheels. These three large diameter wheels with inflatable tires were motorized using electric hub-geared motors to allow the device to travel on uneven ground. The walker had oval-cross section handlebars and a control panel in the middle of the handlebars that presented the speed of the walker, distance traveled, and slope of the ground. It could be folded to fit in a typical sport utility vehicle (SUV). The walker was powered by a LiPo battery. When the user applied force to the device, the motors turned on to assist the user’s movement. The user could select the speed by pressing their thumb on the right on the speed lever. From a control perspective, a walker having these sensing capabilities in their controller will present more complication than implementation of a direct-drive controller, resulting in a complexity score of -65. Mechanically, the environment-tailored design is very customized and not simple to construct, earning a complexity tally of -85.

A more general observation arising from this literature is that the majority of robotic walkers have been designed for disabled adults. It lies well beyond the scope of this review to examine in detail the modifications to these adult devices that would make them more suitable for our targeted population. However, in considering their adaptation for disabled children, certain common broad features readily come to mind, including size, durability, safety, and usability. Evidently, typical adult mass and length scales greatly exceed those of youngsters and the mismatch with early school-aged children in particular likely precludes the utility of such devices for those still physically developing bodies. While all use eventually degrades even the most durable designs, children’s less experienced body awareness and less focused attention suggests the need for considerably more robust versions of juvenile re-targeted assistive devices. Similar reasoning applies to safety considerations, refocusing the worry about device damage on elevated dangers to the environment or the immature users themselves. Regarding usability, it is again well understood that children and adults learn differently. Adults' more fully developed brains and prior knowledge accrued from more extensive life experience contrast with children's typically greater proclivity for experimentation. Such relative fearlessness can have both positive and negative implications when learning how to use a robotic device [57], impacting the prospects for redesign in a complicated manner that begs for substantial further study.

In summary, this review has identified two robotic walkers [40,51], that invite adaptation for use by disabled children, exhibiting both relatively reduced mechanical complexity (between -25 and 0) while achieving moderate control complexity (between -50 and 0), as depicted in Fig. 3. Notwithstanding the relevance of their designers' motivation to the focus of this review article, we have identified several aspects of the control schemes (e.g. absence of safety features) and mechanical structures (e.g. operation restricted to smooth surfaces) of these robotic devices that still do not address the specific daily needs of children with ambulatory impairments to participate in outdoor activities.

3.4. Assessing the effectiveness of robotic walkers

We examine whether the proposed robotic walkers performed as expected with users. All studies reviewed had some type of performance evaluation study completed where the number of subjects enrolled ranged from 1 to 44 and consisted of non-disabled subjects only [41,44–46,49,51], disabled subjects only [40,42,52], or a mixture of disabled and non-disabled subjects [34,43,47,50,56]. Evaluation tasks required subjects to walk at different walking speeds over a variety of surfaces while their interaction forces and various gait kinematic parameters were measured. Although the assistive devices reviewed are considered robotic walkers or robotic rollators, there was a lack of consistency across validation procedures used. Specifically, there was a lack of consistency in the type of walking tests used in addition to the absence of a standard usability or performance metric. Given that many studies had a small number of subjects, we focus in this section on briefly examining the key findings and features which contributes to the effectiveness of each device's evaluation while reporting the associated difficulties.

3.4.1. Performance Validation

Four robotic walkers were assessed on flat surfaces with non-disabled subjects with the aim of evaluating their control strategies for assisted walking and navigation using interaction forces, path accuracy, or # of steps. Five non-disabled subjects were recruited for the evaluation of the Novel Human-Robot Interaction System [41]. Each subject performed 3 trials, for a distance of 15 m across a flat indoor surface, in each of the following cases: walking at preferred speed, at slower speed, and at faster speed. Performance was measured by the root-mean-square (RMS) of the difference between the measured pressure while operating and the reference pressure from standing still. The authors claim their walker reduced the force needed to operate the walker since the RMS was less than 8 N. Similarly, to evaluate the response time of CUT's smart walker [44] to its user's applied force as well as the classifier's ability to select the correct direction of movement, several non-disabled adult subjects were asked to use the walker to travel a 30 m flat path inside of the Senior Home of CUT. An indicator was used to guide the subject to move forward. Without considering the response time of the subject when seeing the indicator, the authors recorded the time from the moment when the indicator was turned on to the moment the device starts to move. Each respondent conducted the experiment 20 times. The results showed the system response is not real-time. The authors then changed the placement of the classifier and repeated the experiment. In comparison to the first, the results of the second experience showed the response time is greatly shortened.

Reduced steps and divergence off target path were the key criteria for evaluating the JaRoW-II [46] and SLAM walker [49]. In JaRoW-II [46], five non-disabled subjects were asked to walk a 15 m long, flat, stone-paved surface with and without this robotic walker. They defined ideal walking performance as walking with a fewer number of steps over a fixed traveling distance even at the same walking speed. Based on this metric, the authors confirmed that JaRoW-II improved walking behavior of its user by facilitating pelvic movements while walking. In the study by Kashyap and colleagues [49], after mapping the environment made up of flat and smooth surfaces, one non-disabled subject walked with the SLAM walker from the set origin in one room to the destination in another room to capture the ideal path. Navigation was tested with 3 different SLAM algorithms to determine the best algorithm with the least divergence from the desired x-position. Since these walkers were only tested on flat surfaces and with only non-disabled users, it is difficult to determine the generalization of these four robotic walkers' [41,44,46,49] structure and control algorithms, to walking over uneven surfaces or to disabled users.

Three walkers were tested with non-disabled subjects on flat and mildly irregular surfaces to validate control algorithms for assisted walking using kinematic variables. In [51], one non-disabled subject used the walker on several paths which included several long slopes (both up and down), a few small slopes between the sidewalk and road and a slope on the sidewalk; irregular surfaces were between the sidewalk and the road. The algorithm estimated the surface conditions on the path using acceleration and orientation measurements. The validity of the proposed algorithm was confirmed by comparison with the video data taken during the experiments. For the UFES SmartWalker (SW) [45] fifteen non-disabled participants performed guided walking with and without a blindfold. The designed path, composed of three straight line segments linked by soft curves, requires the subject to go over 2 different surfaces (rug and corridor floor). Subject's force signal, subject's torque signal, SW linear velocities and SW angular velocities were measured, but only the mean velocity errors and orientation position errors were used to assess performance. Mean velocity and orientation errors were small indicating that all participants followed the desired path but the velocities tend to increase in the blindfold condition. Lastly, the Agile Walker [52] was tested for operational performance only with one non-disabled subject. The author tested the walker's ability to climb and support the subject walking up and down a hill (about 5 degrees slope) as well as ability to travel on gravel and grass. The author claimed the walker assisted the participant while he walked up the hill by pulling up when necessary. However, the authors provided no quantitative performance metrics to support their claims. Since these walkers were only proven effective with non-disabled users on flat and mildly irregular surfaces, it is difficult to determine the generalization of their structure and control algorithms for assisting disabled users.

Two walkers were evaluated by walking experiments conducted with non-disabled and disabled subjects on flat or irregular surfaces. In [40], three non-disabled subjects were chosen to assess the Active Posterior Walker's tracking performance. Each child walked over an indoor flat surface, outdoor pavement surface and over a wheelchair ramp of slope around 6 degrees. The walker tracked the user's trunk position only when the user's lumbar region was within the tracking range of the walker and the walker stopped when the user went beyond tracking range. The performance was quantitatively evaluated using the position difference between the left side of the user's lumbar region and the walker frame. The same authors then had ten disabled subjects perform walking tests on a known path with a passive walker and the Active Posterior Walker on 3 different surfaces: a 50 m flat indoor corridor, a 50 m outdoor pavement, and a 10 m ramp with a 15 degree incline. Based on measured Physiological Cost Index (PCI), which indicates the energy cost of the child for the walking test, the authors claimed that the energy cost of walking with their device was half of the energy cost of walking with a passive walker. Similarly, one non-disabled and two disabled subjects performed walking tests on a flat and smooth indoor path for evaluation of the i-GO [42]. Each participant performed one trial with the walker guiding them along the path from the given start point to the desired end point. All three subjects were able to complete the task with position error less than 0.65 m. The authors claimed the position discrepancy most likely results from the miscoordination between the subject and i-GO assistive robot.

Six robotic walkers were evaluated with only disabled subjects on flat surfaces and ramps. Three disabled subjects with minimum care requirements were selected to test the Novel Assistive Walker Robot [43]. Each participant tried 2 cases: one with the proposed assistance and the other without it. During these trials, the authors measured the position of COG and concluded that their walker shrunk the range of the position of COG. They claimed these results meant the device successfully balanced the participants' bodies while walking. Similarly, one disabled subject with minimum care requirements tested the basic functions of Flatia [50]. The forces on both the hand grips were measured as the subject walked while pushing a traditional rollator, with or without baggage, on a flat surface or on an upslope with an inclination angle of 7 degrees, then repeating this experiment with the robotic walker. The results concluded that the average force on the hand grips decreased to half that on traditional rollators in both cases. Likewise, to test the average force exerted using the Little Keepace [50], ten disabled adults performed walking tests. In the experiments, myoelectric sensors were attached to 8 parts of the bodies of the participants. They were asked to walk using a traditional rollator and the Little Keepace on a flat path, upslope, and downslope with an inclination angle of 4 or 10 degrees at the same speed. Their results demonstrated the reduction in the use of the muscles in the lower body while walking with assistance from the motor driving force.

These three walkers not only performed evaluations on disabled adults in clinical settings, but also included a diverse set of disability levels. To gauge the effects of navigation assistance and cognitive status on the target population's navigation performance, twenty disabled subjects were included in the evaluation of the MOBOT rollator [47]. Participants were matched for cognitive status (CI vs. NCI) and randomized to one of two conditions: RR (1) with or (2) without activated navigation system. All subjects had to complete a 100 m navigation path with the RR in an unfamiliar, real-life environment. The results of the study concluded that only during complex path (section 2), both the NCI and CI group benefited from the navigation assistance because the completion and stopping time were reduced. Similarly, twenty-one disabled subjects evaluated the SmartWalker [56] by walking around with it; two of the wheelchair users could not participate in this portion of the test. All 23 participants tested the device's gesture-based interface by calling it towards them and sending it back to a predefined location. To evaluate the i-Walker [34], forty-four disabled subjects were randomly assigned to 2 different groups that received 40 sessions of the same therapy. First, 20 sessions of standard therapy were performed by both groups. In another 20 sessions, the subjects enrolled in the i-Walker-Group (iWG) performed with the i-Walker and the Control-Group subjects (CG) performed the same amount of conventional walking oriented therapy. Clinical and instrumented gait assessments were made pre- and post-treatment. The follow-up observation consisted of recording the number of fallers in the community setting after 6 months. Their results suggested that the device improved walking performance and balance in subjects affected by mild stroke because the iWG had a reduced number of falls compared to the CG. Unlike the previously discussed robotic walkers, the i-Walker was only evaluated for therapy use. However, the authors state that the device can be used for daily activities and claim their results support this statement. Although these assistive devices have been proven to achieve good performance with several levels of cognitive or mobile impairments, they have not been tested on surfaces common to unstructured outdoor environments and therefore we have no evidence to suggest that they would perform well for daily outdoor activities.

3.4.2. User Validation

Majority of the papers evaluate their proposed robotic walkers exclusively on performance, only one paper (Shin et al. [56]) surveyed the users to get their individual perspectives on using the SmartWalker. Twenty-one participants evaluated the walker's potential as a mobility aid by walking around with it; two of the wheelchair participants could not participate in this portion of the test however they were able to test the gesture interface. In general, the participants liked the device, finding it comfortable to use and easy to control. They also found the walker exciting and useful; however, they were reluctant to replace their walker with a robotic one, possibly because the SmartWalker is bulkier and heavier than traditional walkers and many elderly are unfamiliar with technology.

3.5. What causes robotic AT to fail in dynamic outdoor environments?

Fifteen different walkers from the literature were presented, describing their structure, control, and effectiveness at providing mobility assistance to their intended users. Next we discuss the limitations of these walkers and highlight factors that make them less adequate for the daily outdoor activities of children with ambulatory disabilities. In most cases, we find that the additional electronic components necessary for supporting sensing capabilities do not add much competency in mobility beyond what is already found on standard walkers or rollators. We also note the various consequences associated with developing a structure that can support additional hardware components and the user.

In the selected literature, robotic solutions that advance existing AT for mobility are primarily focused on developing controllers centered on the user's interaction with the system then modifying the layout of the traditional walker to implement their proposed method on. Controllers found in several robotic walkers [58,59] and crawling devices [2] often rely on mechanisms that utilize force and/or pressure sensors to initiate and drive the device to assist the user's intended movement. There are a few obstacles that arise using these methods such as not all the pressure sensors can be used for detection [44] or the user applying too much or too little force to the handlebars, which resulted in either the device not working at all or the device moving dangerously too fast for the user [49]. Several of the walkers incorporate IMU sensor data in their controller. The downfalls to these methods are that the accuracy of the sensing depends on the location of the IMUs with respect to the user's lower limbs, this factor has led some researchers to pair wearable IMU devices onto the user in order for their gait detection algorithms to work [41]. Having to keep track of and maintain additional equipment to operate one's walker could be seen as a burden on the user.

A handful of the robots we discussed have at least one safety feature such as manual or automatic braking [34,49,50] and emergency stop buttons [43]. While being able to stop or shut off the device when a problem occurs may reduce the likelihood of the user being harmed, the complete reliance on either the user or the robot to react at the right time can be seen as risky. Several devices include obstacle avoidance in their navigation controlled systems [42,44,46,47,56]. However, this safety measure depends on the accuracy of the various sensors working together to create the right map. If the map built is incomplete or imprecise, the user could walk right into an obstacle with their device. For this selection of robotic walkers, we find that the main determinant in developing the controller for each system is the level of autonomy that the authors deem adequate for mobility aid. On one end of the spectrum is full autonomy, where the robotic walker is expected to drive the user to a pre-specified location and activate all safety features. On the other end of the spectrum is full dependence, where the user is expected to push the robotic walker and manually initiate safety features. Most of the devices fall somewhere in between the two extremes. Therefore we can assume that there are benefits to incorporating dependency and autonomy into a controller for a robotic walker. However, there is still a need to find a combination of these two elements that does not significantly increase the control complexity of the system.

Fixating on the structure of these robotic walkers, we find that each device is an extension of the traditional walker. Several systems have been presented as a modified version of a commercial available walker [34,40,44,48], while others have cited the heavy influence of the traditional walker in the various elements of their systems [42,45,52]. The standard walker has its advantages such as portability, partial body weight support, height variability, and affordability [7]. Presently, the selected robotic walkers excel at partial body weight support, height variability, and body stability during operation. However, they consistently fail at other key benefits because they tend to be heavier, bulkier, and more expensive than the standard walker while providing the same amount of mobility [47,56]. These restrictions are amplified when we consider the daily use of robotic walkers in outdoor settings. Existing robotic walkers are not restricted to indoor environments, however, the majority of authors state that their devices are designed and tested for indoor use only. The lack of consideration for daily outdoor activities in the building phase makes these devices a liability for users who would like to incorporate them in their day-to-day routine outside of their homes and rehab facilities. There are several walkers presented that do provide some walking assistance outdoors [40,50–52]. They have been shown to assist non-disabled or disabled subjects traveling short distances up and down slopes up to 10 degrees. They have also been evaluated in controlled walking trials on various surfaces such as concrete sidewalks and pavements, grass, and fine gravel.

We notice that missing from the selected literature was a discussion about the maintenance and durability of robotic walkers. With the exception of the Agile Walker [52], where the authors mention considering ease of maintenance in their design but do not provide any details on how that objective could be achieved. We define durability by specific properties that allow the structure of the robotic walker to have longevity such as waterproof, dust proof, and the ability to withstand "wear and tear" from multiple uses. In regards to maintenance, we must consider what is practical for a caregiver (e.g. a relative, a spouse, etc.) to be able to do. In reality, we expect that most instances will require the walker to be sent back to the manufacturer for repairs. The ideal situation is to minimize those instances, once again emphasizing the need for the system to be durable. One element that all of the systems in this review have in common are wheels. This component can be seen as a challenge in environments that are very irregular or cluttered (e.g. a playground, a ballpark). Only one of the robotic walkers performed evaluations with continuous transitions between different surfaces in an outdoor setting [51], while none of them address traversing steps or curbs even when their intended users specifically requested this feature [56]. From the discussion of the selected systems so far, there suggests a need for a modified wheel or other alternative that significantly increases the mobility capacity of the intended user beyond that of the traditional wheeled walker (i.e. rollator). It seems that incorporating key elements of the standard walker in the mechanical design of a robotic walker has its advantages, however, the main considerations for the structure needs to focus on overground dynamics. With that in mind, this review will analyze potential approaches to the proposed problem found in the field of legged robotics.

4. Legged robots designed for complex and dynamic environments

4.1. Motivation and Organization

4.1.1. Why Should Robotic AT Consider Legs?

From the very inception of legged robotics research, the notion of an "adaptive suspension" has been central in the minds of roboticists [60]. In this point of view, a key advantage of legs over wheels is their far greater range of control over a mobile platform's ground reaction forces (GRFs): wheels can address only shear forces whereas legs' more variable manner and direction of contact yield GRFs whose direction as well as magnitude may be substantially controlled [15]. Of course, the greater control affordance comes at the cost of considerably greater mechanical design and control complexity.

This article does not necessarily advocate the replacement of walkers by legged machines because the desired capabilities or applications that motivate the development of legged robots go beyond the scope of what one imagines robotic walkers might target in the near term. Since roboticists in this field have been developing solutions to the problem of traversing complex environments for quite some time, it seems appropriate to examine the extent to which their approaches to design and control are applicable to robotic walkers. An overarching theme of this paper is the motivation to support mobility across various types of complex terrain commonly found in playgrounds. Supporting such advanced mobility introduces considerations of sensing and control as well as mechanical design whose role in legged locomotion has a bearing on some of the challenges associated with the AT reviewed in the previous section. In the following sections, we will discuss key observations from the legged robotics literature based on the theme, examine a selection of legged machines that illustrate these observations, and address the limitations of such machines while concluding with some potential implications for innovation in the development of robotic walkers.

4.1.2. Translation of Insights from Legs into Robotic AT

This section will examine the prospects for translating some of the lessons learned from research on legged machines into the framework of robotic AT. In imagining how such lessons might carry over, it seems necessary to add one new feature to the set developed in section 4 to characterize the state of the art robotic walkers. Namely, in this section, beyond the two aspects of design and control introduced above (morphology—degrees of freedom (DoFs) and their distribution; and the extent of sensing required for operation), in considering the value of legged designs and controls it proves necessary to add a further dimension: the energetic operating regime for locomotion.

Regarding morphology, the robotic walkers, depicted in Fig. 1, offer either rigid frames with no DoFs or rigid frames with four DoFs all committed to wheels. In contrast, the most common legged robots generally have far more than four DoFs, all committed to internal joints between multiple limbs with no wheels. Thus, while legs offer rich possibilities for varied combinations of leg contacts, these aspects of limb coordination (typically gathered under the rubric of "gait" control) seem out of reach for the near future of the far more constrained contact patterns of robotic walkers. Instead, given the unavailability of gait level control (i.e., the strategy for making and breaking ground contact with different combinations of limbs), our assertion is that the near-term translation of insights from legged robotics to robotic AT may likely be most usefully anticipated by considering their approaches to "adaptive suspension" [60]. Intuition suggests that this carry-over is likely strongest for limbed machines whose locomotion capabilities have given rise to wheeled hybrid versions.

Regarding sensing, we will continue to focus on proprioceptively controlled legged robots and present a few examples along a spectrum of alternatives ranging from "preflexes" (no active sensory feedback at all) to actuator-generated feedback to hardware for measuring reaction forces acting on the limbs. A "preflex" is defined as an inherent mechanical response of the musculoskeletal system whose intrinsic material properties reject disturbances with greatly reduced time delay relative to active sensorimotor feedback. [61]. Such a sensor-free, mechanically engaged [62] feedback mechanism has been identified as playing a key role in the stabilization of rapid animal locomotion over rough terrain [63], and preflexive control can be mathematically shown to stabilize gait stability [64] in suitably simplified models of the feedforward controlled RHex robot [65] to be discussed below. When such a mechanical closed-loop is paired with an open-loop control input modified by sensory information, a robot can adjust its behavior to adapt to extremely rough [66] or changing conditions [67].

Finally, legged mobility operates across a range of energetic regimes depending upon the degree to which forces and their consequent accelerations feature in the behavior of interest. The term “quasi-static” is applied to mechanics phenomena wherein there is relatively little kinetic energy, hence for common locomotion settings (e.g., motion along constraining surfaces exhibiting dry friction), velocities instantaneously align with the externally applied forces [68]. In contrast, dynamical locomotion refers to settings where external forces excite substantial kinetic energy, typically yielding pogo-stick like behavior in running animals [69] or dynamically active robots [70]. It is presumed that disabled children may well prefer to operate in the quasi-static regime, but this becomes increasingly difficult as the terrain roughens (assuming reasonable speeds of traversal) until, eventually, complex enough environments completely defeat their negotiation except possibly by dynamical operation [71]. Thus, we include a mix of legged machines, some purely quasi-static, some capable of mixed operation, and others that must intrinsically operate in the dynamical regime.

4.1.3. Rationale for the Selected Legged Designs

Prior to discussing specific legged platforms, it remains to describe how the general search criteria presented in Section 3.2 yield the examples below. Exploring their implications for robotic walkers seems most usefully presented along the dimension of energetic operating regime since that aspect plays a major role in their design and control. This discussion progresses from purely quasi-static machines to more energetic platforms, ending with intrinsically dynamic legged robots.

Wheeled hybrids have been proposed for many high DoF, completely actuated, purely quasi-static designs [72] and we will use the Weaver [73] as a modern day representative of such legged designs. Weaver’s quasi-static control is predicated on the notion of “impedance control”, a term denoting the design of a compliant mechanical system that accepts motion inputs and returns force outputs in some prescribed manner [74]. On the spectrum of proprioception, Weaver implements this control strategy using feedback from its actuators’ control loops, suffering thereby from the lack of transparency of their highly geared drivetrains. The concept of “mechanical transparency” suggests that the appropriate system must be able to not only perform work on the environment but also reflect back to the operator the work the environment imparts back to it [75]. The notion of actuator transparency finds its place in high performance robots by motivating the design of machines that can receive from and impose work upon their environment through either ungeared [76],[77] or very lightly geared [78] transmissions, thereby “feeling” the world even in the absence of any dedicated force sensor [79]. The last statement gives an example of where Weaver falls short.

RHex [15], the first legged machine to run untethered in outdoor environments, is capable of both dynamical [80] as well as quasi-static [15] operation. Quattroped [81], a wheeled hybrid vehicle derived from RHex, suggests its potential relevance for near-term robotic AT. RHex perceptual resources have run the range from its initial purely “preflexive” operation [82] to adding feedback sensing of leg contacts [66], through vestibular feedback of body pose [83] to eventually include exteroceptive feedback for global navigation [84]. This article focuses on the preflexive versions of the machine because implementation minimizes the amount of mechanical and electrical components required, while maintaining stability dynamically and statically, to operate in uneven outdoor environments.

The MIT Cheetah 3[85] is a popular contemporary quadrupedal robot that operates almost exclusively in the dynamical regime. The Cheetah family of machines pioneered a new emphasis on joint proprioception via highly transparent actuators [78], which was taken to the extreme limit of direct drive legged locomotion in the *Minitaur* [77] it inspired. Generally speaking, a quadrupedal machine cannot be quasi statically stable unless its moving with a “crawl” gait (where at least three toes are touching all the time).

Cassie, a dynamic bipedal robot built by Agility Robotics [86], was designed to walk and run in a fashion similar to that of humans or animals to handle diverse and complex terrain. It has a 3 DoF hip like humans do, allowing the robot to move its legs forward and backward, side to side, and also rotate them at the same time. Small-footed bipedal machines are intrinsically always dynamical, unless they have huge ankle motors. For example, Cassie also has powered ankles, which it uses to stand in place without having to constantly move (i.e. quasi-static stability) [86].

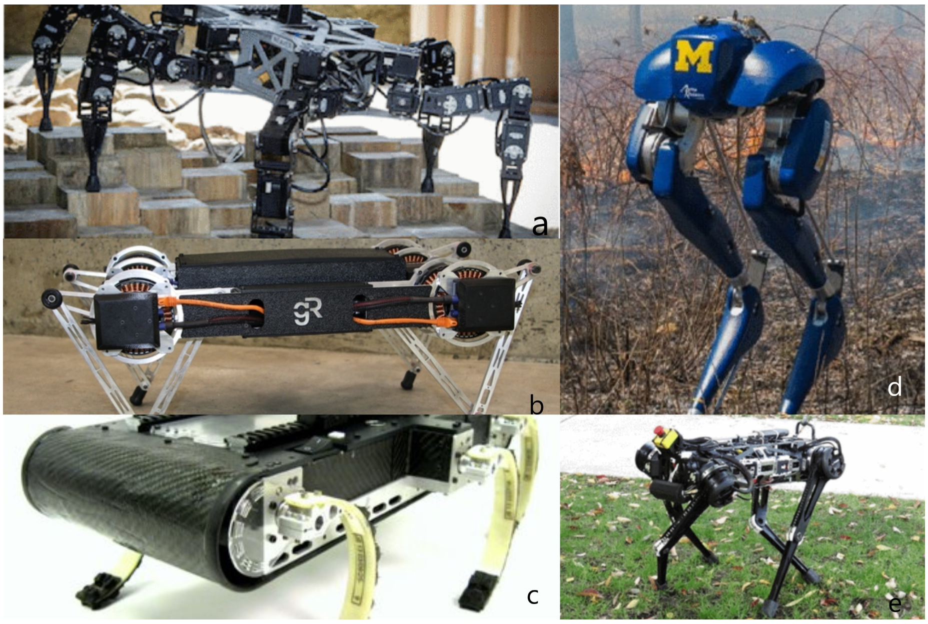


Figure 4.: Images of the selected legged robots (top to bottom, left to right) - (a) Weaver [87] (b) Minitaur [77] (c) X-RHex [88] (d) Cassie [89] (e) MIT Cheetah 3 [85]

4.2. Illustrative Legged Robots: Control & Design

Having established the relative place of these legged machines along the spectrum of energetic operating regime, this section will now discuss in that same order aspects of their design and control which bear closer correspondence to the features of the robotic walkers reviewed above.

Bjelonic et al. [87] developed a hexapod robot, Weaver, and implemented a low-level controller on Weaver that added virtual elastic elements to a second order mechanical system. Weaver’s control framework consists of an overactuated dynamic model and virtual second order compliance. Their control scheme consists of a high-level and low-level controller. The high-level component consists of three planners: body path, gait pattern, and foot path. The low-level component consists of two sub-controllers: inclination and impedance. The impedance controller enables the robot to adapt to uneven terrain and the inclination controller increases the stability of the robot's gait by shifting the CoM. The 7.03 kg 30 DoF robot has five DoF per leg. It is powered by Lithium Polymer (LiPo) batteries and contains IMU sensors. Weaver was experimentally evaluated with the proposed controllers and demonstrated effective walk on a multi-terrain testbed and high gradient slopes up to 30 degrees.

Progressing along the spectrum of energetic operation to consider machines that can operate either quasi-statically or dynamically, the discussion next turns to a pair of legged robots that rely upon preflexes to support their locomotion. Insights from biomechanics heavily influenced the design of RHex [80]. This robot has been developed and refined since its introduction as a research platform in 2001. The latest in the series of RHex-style platforms developed at the University of Pennsylvania, X-RHex was conceived as a hexapedal laboratory on legs [88,90]. The robot's body features a bottom frame and a top plate constructed from aluminum. Carbon fiber panels side panels increase frame stiffness and for protection from outside obstacles. The 9.5 kg 6 DoF robot has an actuator per leg and is powered by LiPo batteries. It also contains several encoders as well as a hall sensor inside each actuator. X-RHex operates by tracking, at each hip joint, a copy of the given reference trajectory known as the "Buehler clock" [15] that enforces an alternating tripod gait through body- and leg-open loop control. The two tripods are driven out of phase relative to each other. This control framework has been extended to allow RHex-styled platforms to perform tasks in indoor and outdoor settings such as leaping [91], stair-climbing [92,93], self-righting [49], carrying modular payloads [88], rapid running on challenging terrain [94], and automated gait adaptation [95].

Similarly, De et al. [96] presented a quadrupedal robot, Minitaur, exhibiting preflexive stability in its gaits. This 5 kg 8 DoF robot, developed in [77], has two actuators per leg and is powered by LiPo batteries. The leg design incorporates closed kinematic chains, which consist of two revolute-revolute (RR) chains closing at the toe. Minitaur is equipped with encoders on each of its motors, as well as an IMU. The authors presented a method for implementing all the virtual bipedal quadruped gaits (e.g. bounding, pacing, pronking, and trotting) on Minitaur. The overall implementation of this method proceeds as follows: (a) a virtual leg grouping is selected; (b) physical touchdown and liftoff detection is implemented; (c) the controller is used to formulate the stance control signal; (d) this control signal is applied to the stance leg. Minitaur has also previously been shown to execute other dynamic behaviors such as climbing stairs and opening doors [71].

The latest in a series of agile legged robots [85,97–100] designed and built at Massachusetts Institute of Technology (MIT), the MIT Cheetah 3 is a power autonomous, quadrupedal robot that implements simple control strategies for dynamic locomotion and features high bandwidth custom proprioceptive actuators to manage physical interaction with the environment [85]. The 45 kg 12 DoF robot is powered by one LiPo battery, yet has internal space to carry an additional backup battery. Two actuators are located between each pair of legs, and are coupled to the legs by linkages. The end of each leg has a cover made from urethane rubber, providing cushioning and traction. Its control architecture consists of 3 components: gait planning, leg and body control, and state estimation. The robot's gait is defined by a finite state machine (FSM) [101] that uses a phase variable to schedule nominal contact and swing phases. This virtual leg compliance [78,102] allows for flexible gait definitions and fluid transitions between gaits as well as gait modification in the presence of unexpected disturbances. The authors conducted experiments that successfully showed the Cheetah 3 walking, trotting, pacing, and bounding on a treadmill and on grass.

Gong et al. [89] implemented feedback control on a bipedal robot, Cassie, for standing and walking using a mixed approach of virtual constraints and gait libraries. The 31 kg 20 DoF robot has 10 actuators, 10 joint encoders, a battery located in the torso, and an IMU sensor. There are 7 joints in each leg, 5 of which are actuated by electric motors while the other two are passive joints realized via a four-bar linkage with one of the links being a leaf spring. There have been control laws proposed to produce stable walking and several other gait behaviors for this robot in indoor and outdoor settings [89,103–106]. For example, the authors of [89] utilized the full dynamic model of the robot in conjunction with optimization to design 7 gaits for walking in place, forward, and backward, while meeting key physical constraints. In this work, they were able to implement an agile walking gait that allowed Cassie to traverse over grass, sidewalks, snow, soft sand, and burning brush.

4.3. ***What lessons from legged robotics can help improve robotic AT?***

At the quiescent end of locomotive operation lie quasi-static legged machines whose adaptive suspension seems more immediately practical for the applications of current robotic mobility aids. However terrain negotiation and, consequently, mobility tend to increase with more dynamical operation, hence it seems worth continuing to explore the full spectrum of legged insights for potential advantageous application to robotic walkers. Following the previous scheme, this section will proceed along the axis of dynamical operation starting from the least energetic (purely quasi-static) to the most energetic (exclusively dynamical) regime.

Weaver's pairing of an impedance controller with a high DoF, highly actuated morphology exemplifies the notion of an "adaptive suspension". The impedance controller is not only designed to enforce a preferred upright posture but also to identify and reject disruptive forces arising from broken and unstable surfaces that might destabilize subsequent movements. Implementing a similar architecture in robotic walkers could help users keep their body perpendicular to the surface they are traversing, enhancing balance and promoting traction throughout movement. Challenges to the adoption of this robot's architecture for AT lie in both its impedance controller and its implementation via conventional actuators. Impedance control assumes the environment (in this case including the surface and the human leaning on the device) can always be modeled as an admittance (i.e. a physical system that accepts force inputs and returns motion outputs [74]). This formal assumption ignores the complexities of terrain and intricacies of human movement: such "environments" are likely sources of unmodeled forces (e.g. due to surface constraints or human intentions) as well as reactive motions. Moreover, such an architecture assumes the robot's hardware can support the multiple actuators and high bandwidth required to achieve the desired impedance for a given surface. Highly geared actuators lack mechanical transparency making them much less sensitive to the environment.

Situated midway along the energetic spectrum is RHex. RHex's minimal actuator endowment, physical springy legs, and six-legged alternating tripod gait ensures quasi-static stability at low speeds and achieves preflexive dynamical stability at higher speeds, mitigating the need for any body and leg sensors. In contrast, Weaver's programmable virtual springs incur much greater mechatronic complexity whose limited sensorimotor bandwidth nevertheless cannot readily confer dynamical stability. More analysis and considerable empirical work will be required to understand which approach is likelier to support assistive mobility at moderate speeds on marginally uneven surfaces.

Departing from the quasi-static regime, the Minitaur and MIT Cheetah quadrupeds can crawl (lifting no more than one leg at a time) but are more typically operated using higher energy gaits. At the extreme dynamical regime considered in this review, bipeds like Cassie must always be balancing, even at slow speeds. The ability of these robots to operate in regimes of high energy allows them to perform vigorous gaits in unstructured environments. As the surroundings increase in complexity (becoming more challenging to traverse), more dynamic gaits, as opposed to quasi-static gaits, perform better but are also more dangerous. A major obstacle to the relevance of legged robots for AT is the danger that highly energetic limbs or bodies might injure people or damage the environment when some aspect of their control goes awry. Even in lower energetic regimes, the increased mobility of intrinsically dynamical machines may not justify their additional risks. For example, if a dynamically balancing robot loses power, its fall may be injurious and would almost surely precipitate a dangerously uncontrollable tumble on sloping or highly irregular terrain. Despite these very real challenges, intuition suggests that there is a significant opportunity in developing more dynamical robotic AT. As discussed in section 5.1, the value of dynamic machines lies in their ability to quickly sense and respond to disturbances in the environment, allowing them to expand the range of surfaces they can traverse as well as their speeds of traversal.

In summary, discerning which aspects of legged robot architectures may best advance AT appears to require balancing the benefits of increased mobility against the risks of more dynamical operation. It seems likely that adding some appropriate mix of active and passive components as exemplified by the Weaver and the RHex machines, respectively, can endow contemporary rollators with some of the "adaptive suspension" capabilities that might afford safe traversal of less structured terrain in the quasi-static regime. However, as the complexity of substrate geometry and mechanics increases, rejecting environmental disturbances will require evenly increased complexity (i.e., more sensitive, higher bandwidth actuation). Eventually, negotiating broken and unstable terrain will require a departure from today's fixed leg designs to achieve the agility and stability afforded by the energetic gaits of highly dynamic legged robots. We have presented a selection of present-day legged robotic research platforms that can provide a foundation for the initial control and design aspects we would like our proposed robotic walker to consist of. The desired behavior and design requirements are not exhaustive, so there is room for a future extension that includes more tasks and features.

5. Conclusion and Future Considerations

This article has reviewed the potential of robotic walkers for use in the daily outdoor routines of children with ambulatory disabilities. A systematically representative selection of state of the art robotic walkers exhibits varied control and design strategies that reveal a range of limitations with respect to the target population and activity. Most surprisingly, this review reveals the very limited availability of any contemporary robotic AT that can be used by children outside of clinical settings. Specifically, extant devices are challenged to offer a portable and durable structure that can support both their own hardware and the weight of the user while also incorporating a stable control architecture that appropriately balances dependency and autonomy for the needs of the target population. The review then turns attention to a more notionally representative group of legged robots, exploring their potential relevance for helping better address these challenges.

The capacity of many emerging legged designs to negotiate and transition between a diverse range of unstructured substrates suggests several avenues of future consideration whose pursuit might benefit robotic AT, particularly regarding the present limitations of wheeled pediatric robotic walkers for children's daily outside use. Specifically, wheeled versions of the RHex-style platforms stand out as potential first points of departure in considering the adaptation of legged technology to robotic assistive mobility. Actively compliant wheels at the base of a robotic walker might better conform to uneven surfaces while adjusting to unexpected user inputs and rejecting environmental disturbances. Incorporation of "preflexive" proprioception — i.e., reliance upon suitably tuned intrinsic material properties in sensorimotor feedback loops — could offer relatively cheap and high bandwidth implementation of such stabilizing controllers, building upon decades of previous work along these lines [15,85,87,89,97,103].

All children with ambulatory disabilities without cognitive delays (e.g. osteoporosis [107], muscular dystrophy [108], congenital limb defect [109]) could benefit from a robotic walker capable of travel in natural, unstructured outdoor environments. But promoting autonomous exploration of different surfaces in a manner that supports and expands motor function and development requires that AT be directly usable by such children without further assistance. Thus, adapting techniques of legged locomotion to robotic AT, while offering novel approaches to areas of control and design brings the further challenge of maintaining an intuitive user interface. Such an integration of advanced technology with a generalized, ubiquitous user interface would greatly impact the future of robotic AT, lending both increased mobility as well as expanding access to and use of these devices.

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References

[1] Prosser LA, Ohlrich LB, Curatalo LA, et al. Feasibility and preliminary effectiveness of a novel mobility training intervention in infants and toddlers with cerebral palsy. Dev Neurorehabil. 2012;15(4):259–266.

[2] Ghazi M, Nash M, Fagg A, et al. Novel Assistive Device for Teaching Crawling Skills to Infants. In: Field and service robotics. University of Oklahoma, Norman, USA: Springer; 2016. p. 593–605.

[3] Fernandes T. Independent mobility for children with disabilities. International Journal of Therapy And Rehabilitation. 2013;.

[4] Cook AM, Polgar JM, Cook AM, et al. Cook & hussey's assistive technologies: principles and practice. 2nd ed. Mississippi, USA: Mosby Elsevier; 2008.

[5] Johnson MJ. BE 514: Rehabilitation Engineering & Design ; 2018. Last accessed 31 August 2020; Available from: https://catalog.upenn.edu/courses/be/.

[6] Prosser LA. Introduction to pediatric rehabilitation presentation; 2018.

[7] Lam R. Choosing the correct walking aid for patients. Can Fam Physician. 2007; 53(12):2115–2116.

[8] Barnard AM, Nelson NG, Xiang H, et al. Pediatric mobility aid-related injuries treated in US emergency departments from 1991 to 2008. Pediatrics. 2010;125(6):1200–1207.

[9] Farmer LW. Mobility devices. Bull Prosthet Res. 1978;1:47–118.

[10] Johnson KL, Dudgeon B, Kuehn C, et al. Assistive technology use among adolescents and young adults with spina bifida. Am J Public Health. 2007;97(2):330–336.

[11] Maher C, Crettenden A, Evans K, et al. Fatigue is a major issue for children and adolescents with physical disabilities. Developmental Medicine & Child Neurology. 2015; 57(8):742–747.

[12] Encarnação P. Fundamentals of robotic assistive technologies. In: Robotic assistive technologies: Principles and practice. 1st ed. Taylor & Francis Group; 2017. p. 24.

[13] Koenig A, Keller U, Pfluger K, et al. PASCAL: Pediatric arm support robot for combined arm and leg training. IEEE International Conference on Biomedical Robotics and Biomechatronics. 2012;:1862–1868.

[14] Bayón C, Martín Lorenzo T, Moral B, et al. A robot-based gait training therapy for pediatric population with cerebral palsy: Goal setting, proposal and preliminary clinical implementation. Journal of NeuroEng and Rehabil. 2018;15.

[15] Saranli U, Buehler M, Koditschek DE. RHex: A Simple and Highly Mobile Hexapod Robot. The International Journal of Robotics Research. 2001;20(7):616–631.

[16] Valdastri P, Webster III R, Quaglia C, et al. A new mechanism for mesoscale legged locomotion in compliant tubular environments. IEEE Transactions on Robotics. 2009; 25(5):1047–1057.

[17] Kimura H, Fukuoka Y, Cohen A. Adaptive dynamic walking of a quadruped robot on natural ground based on biological concepts. International Journal of Robotics Research. 2007;26(5):475–490.

[18] Mcgeer T. Passive dynamic walking. The International Journal of Robotics Research. 1990;9(2):62–82.

[19] Manchester I, Mettin U, Iida F, et al. Stable dynamic walking over uneven terrain. International Journal of Robotics Research. 2011;30(3):265–279.

[20] for Disease Control C, Prevention. Data and Statistics for Cerebral Palsy [Internet] ; 2018. USA: American.

[21] Foundation CPAR. Facts about cerebral palsy [internet] ; 2018. New York (NY): American.

[22] Bax M, Goldstein M, Rosenbaum P, et al. Proposed definition and classification of cerebral palsy. Dev Med Child Neurol. 2005;47(8):571–576.

[23] Kraus L, Lauer E, Colemen R, et al. 2017 disability statistics annual report. American Census Survey. 2018;:48.

[24] Mai CT, Isenburg JL, Canfield MA, et al. National population-based estimates for major birth defects, 2010–2014. Birth Defects Research. 2019;111(18):1420–1435.

[25] for Disease Control C, Prevention. What is spina bifida? [internet] ; 2019. Atlanta (GA): American.

[26] Williams J, Mai CT, Mulinare J, et al. Updated Estimates of Neural Tube Defects Prevented by Mandatory Folic Acid Fortification — United States, 1995–2011. Morbidity and Mortality Weekly Report (MMWR). 2015;64(1):1–5.

[27] Stanborough RJ. Ages and Stages: How to Monitor Child Development [Internet] ; 2019. San Francisco(CA): American.

[28] Dosman CF, Andrews D, Goulden KJ. Evidence-based milestone ages as a framework for developmental surveillance. Paediatrics & Child Health. 2012;17(10):561–568.

[29] Goddard NDR, Kemp RMJ, Lane R. An overview of smart technology. Packaging Technology and Science. 1997;10(3):129–143.

[30] Frizera-Neto A, Elias A, Cifuentes C, et al. Smart walkers: Advanced robotic human walking-aid systems. In: Mohammed S, Moreno JC, Kong K, et al., editors. Intelligent assistive robots: Recent advances in assistive robotics for everyday activities. Springer International Publishing; 2015. Springer Tracts in Advanced Robotics; p. 103–131.

[31] Equipment AM. Medline Guardian Adult Walker, 2 Button, 300 lb capacity ; 2020. Last accessed 10 Feb 2021; Available from: https://www.accessibilitymedical.org/medline-guardian-adult-walker-2-button-300-lb-capa.html.

[32] AtHome M. Medline Basic Steel Rollator US Army Camo Green 1Ct ; 2020. Last accessed 10 Feb 2021; Available from: https://rb.gy/uujdvn.

[33] Nave C, Postolache O. Smart walker based IoT physical rehabilitation system. In: 2018 International Symposium in Sensing and Instrumentation in IoT Era (ISSI); 2018. p. 1–6.

[34] Morone G, Annicchiarico R, Iosa M, et al. Overground walking training with the i-walker, a robotic servo-assistive device, enhances balance in patients with subacute stroke: a randomized controlled trial. Journal of NeuroEngineering and Rehabilitation. 2016;13(1):47.

[35] Rossignol S, Dubuc R, Gossard JP. Dynamic sensorimotor interactions in locomotion. Physiol Rev. 2006;86(1):89–154.

[36] Michmizos KP, Rossi S, Castelli E, et al. Robot-Aided Neurorehabilitation: A Pediatric Robot for Ankle Rehabilitation. IEEE Transactions on Neural Systems and Rehabilitation Eng. 2015;23(6):1056–1067.

[37] Agrawal SK, Kang J, Chen X, et al. Case studies of a robot enhanced walker for training of children with cerebral palsy. In: International Conference on Intelligent Robots and Systems; Tokyo, Japan; 2013. p. 4243–4248.

[38] McCormick A, Alazem H, Morbi A, et al. Power walker helps a child with cerebral palsy. International Conference of Control, Dynamic Systems, and Robotics. 2016;.

[39] Raya R, Rocon E, Ceres R, et al. A mobile robot controlled by an adaptive inertial interface for children with physical and cognitive disorders. In: International Conference on Technologies for Practical Robot Applications (TePRA); 2012. p. 151–156.

[40] Ragaja SR, Dinesh NS, Madhuri V, et al. Development and clinical evaluation of a

posterior active walker for disabled children. J Intell Robot Syst. 2019;97(1):47–65.

[41] Wang L, Yi J, Liu T. Gait adaptable human-robot interaction system and its application to a robotic walker. In: 2018 IEEE 8th Annual International Conference on CYBER Technology in Automation, Control, and Intelligent Systems (CYBER); 2018. p. 707–712.

[42] Lu CK, Huang YC, Lee CJ. Adaptive guidance system design for the assistive robotic walker. Neurocomputing. 2015;170:152–160.

[43] Oigawa K, Chugo D, Muramatsu S, et al. An assitive walker considering with its user's gait difference of both feet. In: 2019 12th International Conference on Human System Interaction (HSI); 2019. p. 231–236.

[44] Cheng WC, Wu YZ. A user's intention detection method for smart walker. In: 2017 IEEE 8th International Conference on Awareness Science and Technology (iCAST); Taichung, Taiwan; 2017. p. 35–39.

[45] Jiménez MF, Mello RC, Bastos T, et al. Assistive locomotion device with haptic feedback for guiding visually impaired people. Med Eng Phys. 2020;80:18–25.

[46] Ohnuma T, Lee G, Chong NY. Development of JARoW-II active robotic walker reflecting pelvic movements while walking. Intel Serv Robotics. 2017;10(2):95–107.

[47] Werner C, Moustris GP, Tzafestas CS, et al. User-Oriented Evaluation of a Robotic Rollator That Provides Navigation Assistance in Frail Older Adults with and without Cognitive Impairment. Gerontology. 2018;64(3):278–290.

[48] Shin J, Itten D, Rusakov A, et al. SmartWalker: Towards an intelligent robotic walker for the elderly. In: 2015 International Conference on Intelligent Environments; 2015. p. 9–16.

[49] Kashyap P, Saleh M, Shakhbulatov D, et al. An autonomous simultaneous localization and mapping walker for indoor navigation. In: 2018 IEEE 39th Sarnoff Symposium; 2018. p. 1–6.

[50] Matsumoto O. Development of robotic rollators and walking trolleys in japan. Stud Health Technol Inform. 2017;242:457–464.

[51] Ogata K, Matsumoto Y. Estimating road surface and gradient using internal sensors for robot assist walker. In: 2020 IEEE/SICE International Symposium on System Integration (SII); 2020. p. 826–831.

[52] Katz R. Agile walker. Stud Health Technol Inform. 2015;217:455–460.

[53] Morone G, Paolucci S, Cherubini A, et al. Robot-assisted gait training for stroke patients: current state of the art and perspectives of robotics. Neuropsychiatr Dis Treat. 2017; 13:1303–1311.

[54] Efthimiou E, Fotinea SE, Goulas T, et al. The MOBOT platform – showcasing multimodality in human-assistive robot interaction. In: International Conference on Universal Access in Human-Computer Interaction; Vol. 9738; 2016. p. 382–391.

[55] Efthimiou E, Fotinea SE, Goulas T, et al. The MOBOT rollator human-robot interaction model and user evaluation process. In: 2016 IEEE Symposium Series on Computational Intelligence (SSCI); 2016. p. 1–8.

[56] Shin J, Rusakov A, Meyer B. SmartWalker: An intelligent robotic walker. Journal of Ambient Intelligence and Smart Environments. 2016;8:383–398.

[57] McDonough D. Similarities and differences between adult and child learners as participants in the natural learning process. Psychology. 2013;04:345–348.

[58] Lee G, Ohnuma T, Chong N, et al. Walking intent-based movement control for JAIST active robotic walker. IEEE Transactions on Systems, Man, and Cybernetics: Systems. 2014;44(5):665–672.

[59] Chuy O, Hirata Y, Wang Z, et al. Motion control algorithms for a new intelligent robotic walker in emulating ambulatory device function. International Conference Mechatronics and Automation. 2005;3:1509–1514.

[60] Waldron K, McGhee R. The adaptive suspension vehicle. IEEE Control Systems Magazine. 1986;6(6):7–12.

[61] Loeb G. Control implications of musculoskeletal mechanics. Proceedings of 17th Interna-

tional Conference of the Engineering in Medicine and Biology Society. 1995;2:1393–1394.

[62] Jindrich DL, Full RJ. Dynamic stabilization of rapid hexapedal locomotion. J Exp Biol. 2002;205:2803–2823.

[63] Full RJ, Autumn K, Chung J, et al. Rapid negotiation of rough terrain by the death-head cockroach [internet] ; 1998. USA: American.

[64] Ghigliazza R, Altendorfer R, Holmes P, et al. A simply stabilized running model. SIAM J Appl Dyn Syst. 2003;2:187–218.

[65] Altendorfer R, Koditschek DE, Holmes P. Stability analysis of a clock-driven rigid-body SLIP model for RHex. The International Journal of Robotics Research. 2004; 23(10):1001–1012.

[66] Weingarten JD, Groff RE, Koditschek DE. A framework for the coordination of legged robot gaits. In: IEEE Conference on Robotics, Automation and Mechatronics, 2004.; Vol. 2; 2004. p. 679–686 vol.2.

[67] Cham JG, Bailey SA, Clark JE, et al. Fast and robust: Hexapedal robots via shape deposition manufacturing. The International Journal of Robotics Research. 2002;21(10):869–882.

[68] Peshkin MA, Sanderson AC. Minimization of energy in quasi-static manipulation. IEEE Transactions on Robotics and Automation. 1989;5(1):53–60.

[69] Blickhan R, Full RJ. Similarity in multilegged locomotion: Bouncing like a monopode. Journal of Comparative Physiology A. 1993;173(5):509–517.

[70] Raibert MH. Legged robots that balance. Massachusetts Institute of Technology; 1986.

[71] Topping TT, Kenneally G, Koditschek DE. Quasi-static and dynamic mismatch for door opening and stair climbing with a legged robot. 2017 IEEE International Conference on Robotics and Automation (ICRA). 2017;:1080–1087.

[72] Granosik G. Hypermobile robots – the survey. Journal of Intelligent & Robotic Systems. 2004;75(1):147–169.

[73] Buchanan R, Bandyopadhyay T, Bjelonic M, et al. Walking posture adaptation for legged robot navigation in confined spaces. IEEE Robotics and Automation Letters. 2019;4(2):2148–2155.

[74] Hogan N. Impedance control: An approach to manipulation: Part i—theory. Journal of Dynamic Systems, Measurement, and Control. 1985;107(1):1–7.

[75] Lawrence D, Pao L, Salada M, et al. Quantitative experimental analysis of transparency and stability in haptic interfaces. Fifth Annual Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. 1996;:441–449.

[76] Asada H, Youcef-Toumi K. Direct-drive robots: theory and practice. MIT press; 1987.

[77] Kenneally G, De A, Koditschek DE. Design principles for a family of direct-drive legged robots. IEEE Robotics and Automation Letters. 2016;1(2):900–907.

[78] Seok S, Wang A, Otten D, et al. Actuator design for high force proprioceptive control in fast legged locomotion. In: 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems; 2012. p. 1970–1975.

[79] Kenneally GD, Chen WH, Koditschek DE. Actuator transparency and the energetic cost of proprioception. ISER. 2018;.

[80] Altendorfer R, Moore N, Komsuoglu H, et al. RHex: A biologically inspired hexapod runner. Autonomous Robots. 2001;11(3):207–213.

[81] Shen S, Cheng-Hsin Li, Cheng C, et al. Design of a leg-wheel hybrid mobile platform. In: 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems; 2009. p. 4682–4687.

[82] Koditschek DE, Full RJ, Buehler M. Mechanical aspects of legged locomotion control. Arthropod Structure & Development. 2004;33(3):251 – 272.

[83] Pei-Chun Lin, Komsuoglu H, Koditschek DE. Sensor data fusion for body state estimation in a hexapod robot with dynamical gaits. IEEE Transactions on Robotics. 2006; 22(5):932–943.

[84] Lopes GAD, Koditschek DE. Visual servoing for nonholonomically constrained three degree of freedom kinematic systems. The International Journal of Robotics Research.

2007;26(7):715–736.
[85] Bledt G, Powell MJ, Katz B, et al. MIT cheetah 3: Design and control of a robust, dynamic quadruped robot. International Conference on Intelligent Robots and Systems (IROS). 2018;:2245–2252.
[86] Ackerman E. Agility robotics introduces cassie, a dynamic and talented robot delivery ostrich. IEEE Spectrum. 2017;Automaton:1.
[87] Bjelonic M, Kottege N, Beckerle P. Proprioceptive control of an over-actuated hexapod robot in unstructured terrain. International Conference on Intelligent Robots and Systems (IROS). 2016;.
[88] Galloway K, Haynes GC, Ilhan BD, et al. X-RHex: A highly mobile hexapedal robot for sensorimotor tasks. University of Pennsylvania; 2010.
[89] Gong Y, Hartley R, Da X, et al. Feedback control of a cassie bipedal robot: Walking, standing, and riding a segway. American Control Conference (ACC). 2019;:4559–4566.
[90] Haynes GC, Pusey JL, Knopf RR, et al. Laboratory on legs: an architecture for adjustable morphology with legged robots. Defense, Security, and Sensing. 2012;.
[91] Johnson AM, Koditschek DE. Toward a vocabulary of legged leaping. International Conference on Robotics and Automation. 2013;.
[92] Moore E, Campbell D, Grimminger F, et al. Reliable stair climbing in the simple hexapod 'RHex'. International Conference on Robotics and Automation (ICRA). 2002;3:2222–2227.
[93] Johnson AM, Hale MT, Haynes GC, et al. Autonomous legged hill and stairwell ascent. International Symposium on Safety, Security, and Rescue Robotics. 2011;:134–142.
[94] Spagna JC, Goldman DI, Lin PC, et al. Distributed mechanical feedback in arthropods and robots simplifies control of rapid running on challenging terrain. Bioinspir Biomim. 2007;2(1):9–18.
[95] Weingarten J, Lopes G, Buehler M, et al. Automated gait adaptation for legged robots. International Conference on Robotics and Automation (ICRA). 2004;3:2153–2158.
[96] De A, Koditschek DE. Vertical hopper compositions for preflexive and feedback-stabilized quadrupedal bounding, pacing, pronking, and trotting. The International Journal of Robotics Research. 2018;37(7):743–778.
[97] Di Carlo J, Wensing PM, Katz B, et al. Dynamic locomotion in the MIT cheetah 3 through convex model-predictive control. International Conference on Intelligent Robots and Systems (IROS). 2018;:1–9.
[98] Seok S, Wang A, Chuah M, et al. Design principles for highly efficient quadrupeds and implementation on the MIT cheetah robot. IEEE International Conference on Robotics and Automation. 2013;:3307–3312.
[99] Bosworth W, Kim S, Hogan N. The MIT super mini cheetah: A small, low-cost quadrupedal robot for dynamic locomotion. SSRR 2015 - 2015 IEEE International Symposium on Safety, Security, and Rescue Robotics. 2016;.
[100] Park HW, Park S, Kim S. Variable-speed quadrupedal bounding using impulse planning: Untethered high-speed 3D Running of MIT Cheetah 2. IEEE International Conference on Robotics and Automation. 2015;2015-June:5163–5170.
[101] Carroll J, Long D. Theory of finite automata with an introduction to formal languages. Prentice-Hall, Inc.; 1989.
[102] Hyun DJ, Seok S, Lee J, et al. High speed trot-running: Implementation of a hierarchical controller using proprioceptive impedance control on the MIT cheetah. The International Journal of Robotics Research. 2014;33:1417 – 1445.
[103] Reher J, Ma WL, Ames AD. Dynamic walking with compliance on a cassie bipedal robot. European Control Conference (ECC). 2019;:2589–2595.
[104] Xiong X, Ames A. Bipedal Hopping: Reduced-Order Model Embedding via Optimization-Based Control. IEEE International Conference on Intelligent Robots and Systems. 2018;:3821–3828.
[105] Xiong X, Ames A. Coupling Reduced Order Models via Feedback Control for 3D Underactuated Bipedal Robotic Walking. IEEE-RAS International Conference on Humanoid

Robots. 2019;2018-November:67–74.
[106] Clary P, Morais P, Fern A, et al. Monte-Carlo planning for agile legged locomotion. Proceedings International Conference on Automated Planning and Scheduling, ICAPS. 2018;2018-June:446–450.
[107] Yasar E, Adigüzel E, Arslan M, et al. Basics of bone metabolism and osteoporosis in common pediatric neuromuscular disabilities. European Joul of Pediatric Neurol. 2018; 22(1):17–26.
[108] Spurney C, Rabin J. Pediatric Muscular Dystrophies | Children's National[Internet] ; 2019. Washington, D.C. |American.
[109] Bass PF, Turley RK, Joseph TN. Congenital Limb Defect in Children [Internet] ; 2020. Rochester (NY): American.
[110] Pugh S, Clausing D, Andrade R. Creating innovative products using total design: The living legacy of stuart pugh. Addison-Wesley Publishing Company; 1996. Engineering Design.
[111] Ulrich K, Eppinger S, Yang MC. Product design and development. 7th ed. McGraw-Hill; 2020.
[112] Dennis R. ME450: PUGH CHART WORKSHEET ; 2001. Last accessed 13 October 2020.
[113] Pearson KG. Common principles of motor control in vertebrates and invertebrates. Annu Rev Neurosci. 1993;16:265–297.
[114] Tuthill JC, Azim E. Proprioception. Curr Biol. 2018;28(5):R194–R203.

Appendix A. One-Dimensional System Complexity Plot

In this plot, we define the system complexity of our keywords by the number of design and control functionalities each particular device possesses. Levels are listed below from less complex to more complex:

- Level 1 (No Functionalities): no sensing, no central processing, no actuation, no wheels
  - Level 1.A: no sensing, non-motorized wheels
- Level 2: no sensing, motorized wheels
- Level 3: proprioceptive or vestibular sensing, processing to interpret sensor data, no actuation
- Level 4: exteroceptive sensing, processing to interpret sensor data, no actuation
- Level 5: proprioceptive, vestibular, and exteroceptive sensing, processing to interpret sensor data, no actuation
- Level 6 (All Functionalities): proprioceptive, vestibular, and exteroceptive sensing, processing to interpret sensor data, actuation

Appendix B. Mechanical Complexity Vs. Control Complexity Explained

To group the 15 different types of robotic walkers, we put together a Pugh chart [110,111]. A Pugh chart is a simple design tool for comparing design ideas against your design criteria early in the design process [112]. The purpose of the Pugh chart is to get you to systematically think of the pros and cons of each design alternative relative to your design criteria. To draw a Pugh chart, first list the design criteria in the left-most column. Using any scale you like, weigh each criterion according to how important it is. Then, across the first row, list the design options. Choose one of your design options as a datum. The datum should be an average design option (i.e. not the best or worst idea). Then, rate how well each design option meets each criteria relative to the datum. The symbols used to rate are given as: plus (positive), zero (neutral), and minus (negative). Lastly, total the points for each design option by multiplying +'s and –'s by the selected weights and sum to get the net score.

Based on the target task of the desired robotic AT, we selected several features to include in the design criteria based on how each feature affected the mechanical or control complexity of the system. A description of each feature included in the design criteria is provided below. Next, we grouped the features as either mechanical or control complexity. Lastly, we filled out a section of the Pugh chart for the mechanical features and a section of the Pugh chart for the control features so that we had two separate net scores to use in our 2D clustering graph. Description of each factor of mechanical complexity listed in Table A1:

- Portability: This feature considers three aspects of the device: size, weight, and foldability. A robotic walker is not expected to be used in a singular setting, therefore it must have the ability to be transported via vehicle to different locations. If a device is too large or too heavy, it falls on the lower end of this feature because it cannot be transported. On the higher end, a device must be lightweight and able to fit easily in a home or car.
- Mobility on uneven/irregular surfaces: The locations in which a robotic walker can be utilized by a person with disability depends on the mechanical properties of the surface such as traction and compliance. Ideally, the robotic walker would traverse various surfaces without becoming stuck or dangerously imbalanced. On the lower end, the device is limited to relatively flat uneven surfaces (e.g. grass, concrete) that remain static throughout movement. While a higher ranking for this feature requires the device to continuously move on dynamic uneven surfaces.
- Traversing steps: This feature is more straight forward. Either the robotic walker can climb steps or it cannot.
- Mobility on smooth or flat surfaces: The locations in which a robotic walker can be utilized by a person with disability depends on the mechanical properties of the surface such as traction and compliance. Ideally, the robotic walker would traverse various surfaces without becoming stuck or dangerously imbalanced. On the lower end, the device is limited to flat and smooth surfaces that remain static throughout movement. While a higher ranking for this feature requires the device to continuously traverse smooth dynamic surfaces such as ramps.
- Additional wearable equipment: Wearable equipment is defined as any hardware that the user must wear on their body while operating the robotic walker.

Description of each factor of control complexity listed in Table A1:

- Supervisory Control: The user interface that translates the user's (high level) commands into low level commands. This feature ranges from the simplest direct drive controllers to the more complex feedback controllers.
- Automatic Safety Features: There is not one way to make a robotic walker safe for its intended user, therefore there are various features that have been developed with safety. We categorized safety features by their level of autonomy. Low ranked safety features include manual braking and emergency stop buttons. High ranked safety features include automatic braking and fall detection.
- Exteroceptive Sensing: We define exteroception as the perception of sensory in-

put originating outside or at a distance from the body [35,113]. An example of exteroception is the perception of light, sound, or heat. Adding exteroceptive sensing to a robotic walker means that additional sensor data needs to be processed and incorporated into the control system. In other words, adding any amount of exteroceptive sensing increases the complexity of the controller. Therefore, we consider incorporating any exteroceptive sensing into a robotic walker a liability.

- Internal Sensing: We designate the term “internal sensing” to refer to proprioceptive and vestibular sensing. We define proprioception as the perception of sensory inputs originating within the robot’s actuator drive train or physical limb structures about its body position and movement [35,114]. Examples of proprioception are the perception of joint forces, torques, or contact. We define vestibular as the perception of sensory input from the “brain” about motion, head position, and spatial orientation [35]. An example of vestibular sensing is an IMU. Like exteroceptive sensing, adding any amount of proprioceptive sensing increases the complexity of the controller. However, we find that the information provided by proprioception is more valuable to monitoring the system as well as maintaining the user’s safety. Therefore, we consider incorporating any internal sensor into a robotic walker a benefit.