# DESIGNING ROBOTS, DESIGNING HUMANS

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# 1

# *GOTAI*

## Corporeal aesthetics and robotic exoskeletons in Japan

*Jennifer Robertson*

## Introduction

The question that inspired this chapter is "How do robots and robotic exoskeletons reinforce a conception of the 'normal' human body?" The answer, "By promoting a corporeal aesthetics of bipedalism," is elaborated in the pages that follow.

Among the claims for "human exceptionalism" is the fact of bipedalism. Of course, other animals can walk on two legs—birds, kangaroos, and other primates—but much is made of the "unique" type of upright walking practiced by humans, which uses the pendulum motion of the limbs. *Why* humans are bipedal is a subject that has provoked heated debates among paleoanthropologists. Over the past century, about 30 hypotheses have been proposed to account for the evolution and function of human bipedalism (Cartwright 2016: 87–91). By referring to bipedalism in terms of a corporeal aesthetic, my intention is to investigate the designs and applications of humanoid robots and robotic exoskeletons—specifically lower limb exoskeletons (as opposed to full body and/or upper limb exoskeletons). I am using "aesthetics" not as a synonym for things beautiful, but as a mode of knowledge and knowing premised on cultural, sensorial, and emotional values. My focus is primarily on Japanese exoskeletons, although I will make some comparisons with non-Japan-made exoskeletons. I will also note the relationship between bipedal robots and robotic exoskeletons as their technical development intersects in significant ways.

What exactly are exoskeletons? They are wearable devices, made of rigid or soft materials, that work, actively or passively, in tandem with the user. Exoskeletons, which can cover all or part of a body, work to reinforce, augment, and/or restore bodily performance (http://exoskeletonreport.com/what-is-an-exoskeleton/). The field of exoskeletons involves the application of robotics and biomechatronics towards the augmentation of humans in the performance of a variety of tasks, including sports and military deployment (http://exoskeletonreport.com/2016/12/introduction-to-the-commercial-exoskeletons-catalog/).

## Walking

Walking is a feat that many of us humans take for granted—we should not. Every human capable of upright walking has a specific, unique gait, or manner of walking or running. Walking consists of a stable phase, when only the soles of the feet contact the floor, that alternates with an unstable phase, or a "falling forward" phase (Dekker 2009: 4, 6). For this reason, upright walking has been described by biomechanical engineers as "a series of controlled falls"!

Human gait was a topic that attracted significant scientific and popular attention in Japan in the first half of the twentieth century when positive eugenics was promoted as a means to literally grow and strengthen the bodies of citizens.[1] National anthropometric, nutritional, hygiene, and sanitation guidelines were put into effect and the broadcast in public parks of "radio calisthenics" (exercise routines set to music) promoted group exercises throughout the country (which continue today). An article published in a leading weekly in 1940 drew attention to the need for citizens to pay even greater attention to their gait. "True," the author writes,

> calisthenics have been instrumental in improving citizens' physiques, but for the most part, people do not walk properly or efficiently … Too many males walk on the outsides of their feet, and too many females are pigeon-toed … Most people bend at the waist, hunch over, or stare at the ground when they walk.
>
> *(Kurimoto 1940: 18–19).*

The author was a physical fitness expert employed by the Ministry of Health and Welfare to promote a new mind-and-body exercise program called "correct walking technique." He included pictures (Figure 1.1) to illustrate proper and improper postures and gaits, and admonished readers to extend their knees, stretch their feet straight ahead when walking, and to swing their arms from the shoulders naturally to stabilize their gait and establish a rhythm. And, he reminded readers that "we are the leaders of Asia, yet there are Japanese whose sloppy gait befits citizens of a defeated nation! Japanese must begin to throw out their chests and start walking with purpose and spirit!" (Kurimoto 1940: 18–19).

A similar article was published two years later in 1942 in a top news periodical. The author became concerned about the national gait when he watched a newsreel on the 1936 Olympic opening ceremony—a time of global military mobilization. The Japanese athletes paraded haphazardly; they were disorganized and out of step with each other (*barabara*) compared to the orderly marching of the European athletes. He urged readers to pay more attention to the ergonomics of walking, and compared the length of stride and speed of walk of Europeans to Japanese. Recreational walking and hiking, and the creation of public

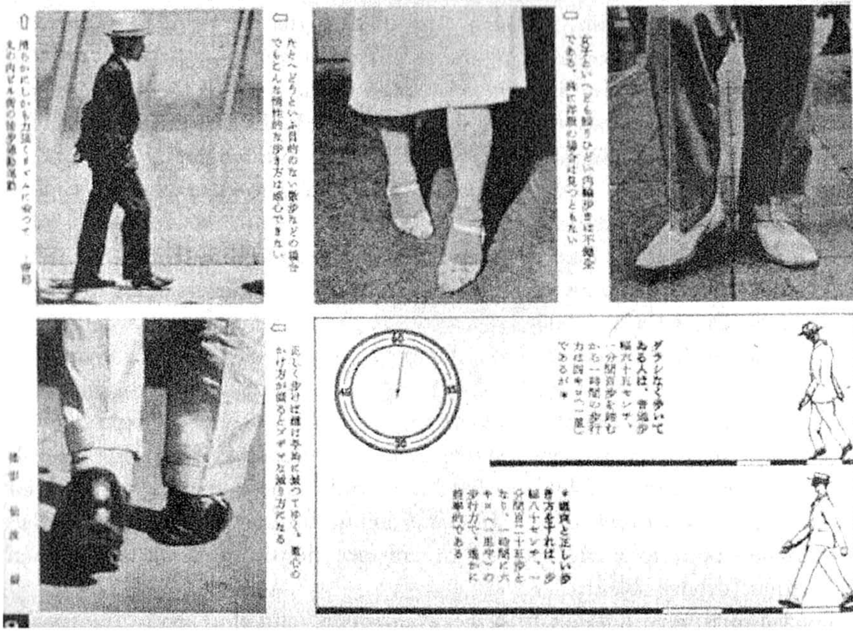

**FIGURE 1.1** Examples of incorrect ways of walking, and a graph showing the efficiency of a proper gait.
Photo from Kurimoto (1940: 19).

parks, were offered as partial solutions (Ashihara 1942:176–181). Today, as evident in the Pyeongchang Winter Olympics (2018) opening ceremony, athletes from all countries enter the stadium in a relaxed mode, smiling, waving, and taking selfies!

This historical backstory about walking and gait as a matter of urgent national interest helps us understand the investment today in Japanese robotics in the development of both bipedal humanoids and robotic exoskeletons. Ironically, in the 1930s when Japanese women and men were being encouraged to improve their gait, the mass media, including advertisements, were filled with representations of bipedal robots, although the first actual robot capable of bipedal locomotion would not be engineered until the late 1960s.

## Gotai

In Japan, the corporeal aesthetics underlying both the ergonomics of human walking and bipedal robots and exoskeletons can be summed up by the term *gotai*, literally "five body." *Gotai* refers to the five body parts that collectively constitute the integral, intact, "normal" body and, by association, a fully *human* being. The most familiar definition of *gotai* names the head, two arms, and two legs. Another names the head, neck, torso, arms, and legs. There is no similar equivalent term in English, although *gotai* invokes the image of the Vitruvian Man, an image also appropriated by the Japanese post office in 1979 for the ¥50 stamp.[2] The *gotai* ideal also links the wholeness of the body to mental, and even spiritual, health; individuals with missing or atypical limbs are thus characterized as helpless and pitiful. Significantly, the bestselling autobiography of Hirotada Ototake, who was born with the tetra-amelia syndrome—caused by a genetic mutation that prevents the arms and legs from developing *in utero*—was titled *Gotai Fumanzoku* (1998), literally "incomplete or unsatisfactory body." The English translation reflects an awareness of disability rights and bears a less discrediting title, *No One's Perfect* (2003).[3]

A robotic exoskeleton can be used only by a *gotai,* or fully limbed human. The objective is to restore the operational integrity of the *gotai* and thus to reintegrate disabled persons—for example, stroke patients or persons who suffered a spinal cord injury—into the larger able-bodied society. Evolutionary forces for bipedalism aside, the majority of humans live in a world where exterior and interior spaces are planned around upright bipedal mobility. In short, robotic exoskeletons are designed both to enable and/or to enhance human walking, a condition I refer to as "cyborg-ableism."

Bipedalism is very difficult to achieve in robots, and thus many humanoids have wheels. Figures 1.2 and 1.3 feature two well-known bipedal robots with different types of gaits: Honda's ASIMO and AIST's HRP-4C, nicknamed Miim.[4] ASIMO's mode of walking is essentially flat-footed, or ZMP (Zero Moment Point) in robotics jargon. This refers to the point at which contact of the robot's foot with the ground does not produce any horizontal movement or slippage allowing ASIMO to maintain his balance. HRP-4C has a more human-like walk—a heel-to-toe-swing that enables her to walk in a more upright manner than ASIMO, whose knees remain bent.

Even though they are more difficult to engineer, many roboticists argue that legged robots are more capable of navigating "extremely cluttered" human environments, which include obstacles like curbs and buildings with stepped entrances (Vincent 2017). Similarly, Ichirō Katō at Waseda University (Tokyo) who designed the first bipedal humanoid, WABOT 1,[5] in 1973, remarked in a 1988 interview that,

> My research is not just in function, but in shape. … In the twenty-first century, I think that human form will be essential in robots. In factories, which are for work, robots can be of any shape, but the personal robot … will have to exist in a regular human environment and be able to adjust to humans.
>
> *(Katō 1973)*

Herein lies a big problem: namely, the normalization of "cluttered human environments" that pose significant barriers for disabled persons in wheelchairs and/or using exoskeletons. Actually, the question is not just whether robots can adjust to humans, but whether robotically assisted humans can function even in *un*cluttered human environments.

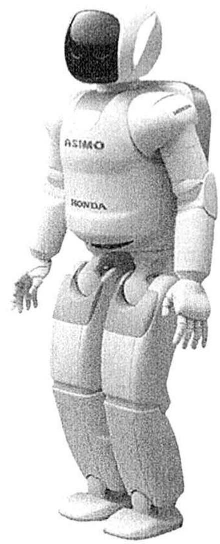


**FIGURE 1.2** Honda's ASIMO. The male-gendered robot is 130 cm tall, weighs 54 kg, and is colored white, with gray and sometimes pastel highlights.

Photo from http://keywordsuggest.org/gallery/100346.html.

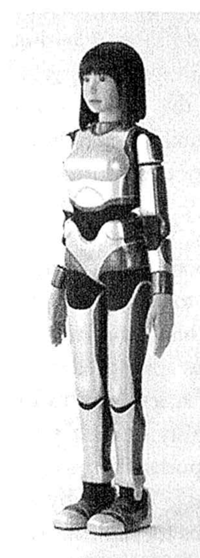

**FIGURE 1.3** AIST's HRP-4C (Miim). The female-gendered robot is 158 cm tall and weighs 45 kg. Her silicon face is based on a composite photograph of female office workers at AIST and her proportions are that of the average Japanese female.

Photo adapted from http://bobstrife.blogspot.com/2011/09/fact-based-fiction-japanese-technology.html

## Exoskeletons

The first robotic exoskeleton and platform for the development of bipedal robots was developed in 1978 by Serbian engineer Miomir Vukobratovic for use by paraplegics. Today, the platforms are reversed; that is, the technology for bipedal robots has been applied toward the development of robotic exoskeletons. A paragraph from a 2015 report on Honda's website is illustrative:

> Striving to offer the joy of mobility to more people, Honda has been continuing the research and development of the Walking Assist Device since 1999 based on the theory of human walking Honda has amassed through research and development of ASIMO, Honda's advanced humanoid robot.
> *(http://world.honda.com/news/2015/p150721eng.html)*

Honda claims that the Walking Assist Device (Figure 1.4) is being used at "250 facilities throughout Japan," although details are not provided. The device was first leased in Japan in 2012 and approved for use within the EU in January 2018 (http://world.honda.com/news/2018/p180118eng.html). Honda's device can only be used by humans with two legs who are already able to walk and who would benefit from additional support.

In Japan, Cyberdyne's HAL (Hybrid Assistive Limb) is the best known and most advanced robotic exoskeleton. The company now focuses mainly on lower-limb exoskeletons (Figure 1.5). The pictorial explanation of "HAL®'s Motion Principle" on Cyberdyne's website illustrates the *gotai* aesthetics of robotic exoskeletons. Not only are the limbs of disabled individuals activated, the company claims that the human brain is also rewired in the process—a state of cyborg-ableism. Because "major causes of lower limb disabilities are disorders of the cerebral and nervous muscular system ... the brain cannot use ordinary neural pathways and cannot order the legs to move."

> Wearing HAL® leads to a fusion of [hu]"man", "machine" and "information." ... The mechanism to move the human body does not end up with only moving muscles. The brain confirms how the body moved on what sort of signals. When HAL® has appropriately assisted the motions of "walking", the feeling "I could walk!" is fed back to the brain. By this means, the brain becomes able to learn the way to emit necessary signals for "walking" gradually. This leads to "the important first step" in walking of the physically challenged person without being assisted by HAL®. The only robot that can provide appropriate solutions for motions to the brain is HAL®.
> *(Cyberdyne 2015).*[6]

The unity between HAL and the human body, including the brain, as evident in the description above of HAL's motion principle, is clear. The robotic exoskeleton reads and amplifies the wearer's intention to walk, translated as bioelectric signals, and, theoretically, not only mobilizes the disabled body but also reconditions the

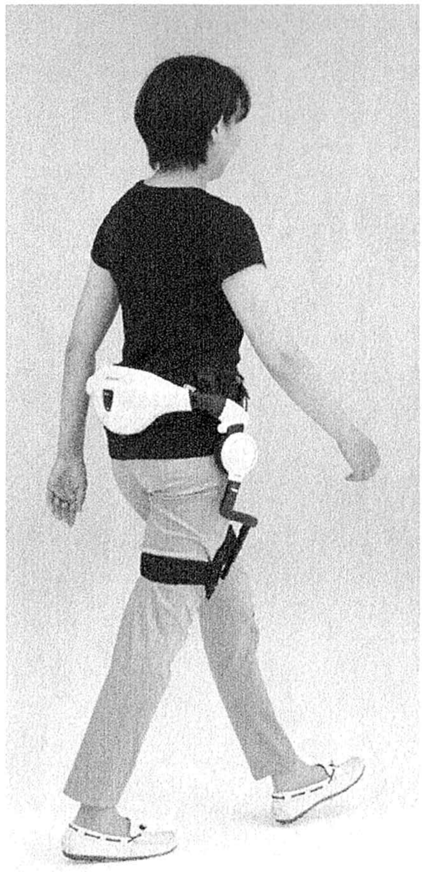

**FIGURE 1.4** Honda's Walking Assist Device.

Photo from www.autoevolution.com/news/honda-walking-assist-device-leasing-debuts-better-chances-for-recovering-riders-98106.html.

brain of the person with the hitherto immobilizing disability. "Theoretically," because there are yet no repeatable, quantitative or qualitative data-based confirmations of neurorehabilitation, or of paralyzed people walking on their own after therapy sessions with HAL.[7]

HAL epitomizes and enables cyborg-ableism. No other exoskeleton maker claims that their product actually changes the brain. In doing so, Cyberdyne implicitly reinforces the *gotai* notion that disability is a body-mind condition, and that both bodies and minds need correcting—and aestheticizing. The fusion of "human," "machine," and "information" in Cyberdyne's PR for HAL could be summarized as "becoming *gotai*."

Exoskeletons were initially developed for use in paraplegics and physically disabled individuals, but all models, including HAL, are still in the prototype phase

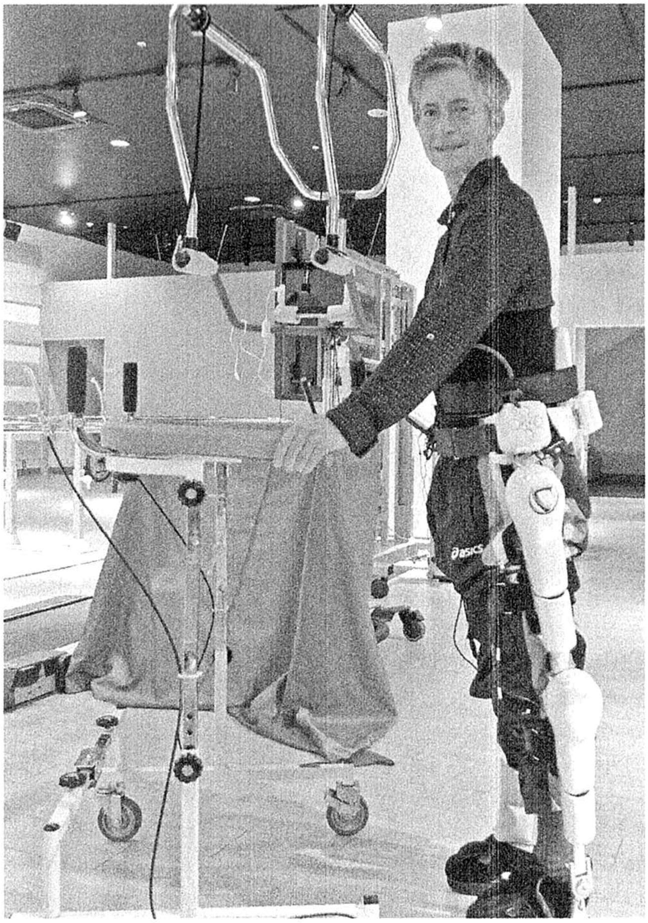


**FIGURE 1.5** The author, wearing a lower-limb HAL exoskeleton at Cyberdynes's Cyber Studio (Tsukuba), November 2015.
Photo by Cyber Studio staff.

and most clinical trials are one-off events. Robotic limbs can only be used in strictly monitored settings, and there are serious drawbacks and risks that are not acknowledged in the public relations literature. I understand "disabled" in the broadest sense of the term as encompassing a diverse array of physical and cognitive "impairments" or "dysfunctions," including those linked to aging, that are associated with some kind or level of personal or social limitation (Wasserman, Asch, Blustein, and Putnam 2016). However, with specific respect to modes of robot-enhanced mobility, I argue that cyborg-ableism is premised on a whole-body ideal (*gotai*) and thus is a condition attainable only by certain types of human bodies (Robertson 2018: 27).

## Risks

Although not mentioned in the promotional literature published by makers of exoskeletons, the robotic limbs carry a lot of risk for the physically disabled user especially. The findings of a 2017 review in the *Journal of Medical Devices*, of risk management and regulations in lower limb exoskeletons are sobering. The review, conducted by engineers at the University of Houston,[8] compares regulations and standards for non-military exoskeleton use in the USA, Europe, and Japan. ReWalk (Israel), Indego (USA), Ekso (USA), Rex (New Zealand), and HAL (Japan) were the exoskeletons examined.[9]

The review's findings contrast with the hyper-optimistic way that robotic exoskeletons are described on the companies' websites, videos, and public relations media. Not included, for example, are such adverse events as falls, bruising, skin damage, joint misalignment, bone fractures, software malfunctions leading to uncontrolled movements, electrical and fire hazards, and user errors (He, Eguren, Luu, and Contreras-Vidal 2017: 91). Depending on the model of exoskeleton, disabled persons must use a walker, harness, or crutches when fitted with the exoskeleton. Crutches especially heavily stress patients' shoulder muscles, and that limits training and rehabilitation sessions as users often need days to recover from muscle fatigue (Dent 2017). Morishita and Inoue further note that although "the advantage of robot rehabilitation is considered to reduce the burden of therapists, at least two therapists are needed to use HAL for ambulation training" (2016: 609).[10] My own experience "test driving" a HAL lower-limb exoskeleton in November 2015 at Cyberdyne's rehabilitation center (see Figure 1.5), confirms that even for healthy, able-bodied individuals, a technician has to help put on the device, and a walker is needed (at the outset, at least) along with the constant presence of trained physical therapists. Also crucial is a software specialist to monitor the interface between the robotic limbs and the human user (Robertson 2018: 163–168).

## Military exoskeletons

It is their perceived usefulness for military use that has attracted the most research and development, and funding, especially in the United States but also in Japan. The wearable robot industry gained traction in the 1980s with American military-funded prototypes. Military exoskeletons are currently being tested in the United States, China, Canada, South Korea, England, Russia, Switzerland, Australia, Israel, and Japan—and these are just the projects that are publicized. Many more projects are classified and off limits to the public. The test subjects are almost all sturdy, physically-fit *gotai* males who appear in public relations photos in military uniforms. Interestingly, in the company's 2017 annual report, Cyberdyne's founder and CEO, Yoshiyuki Sankai, expressed concern about military applications of HAL, but it is not clear how that concern translates into actually refusing to collaborate with Japan's Self-Defense Force

Ministry (Cyberdyne 2017). Much of Japanese technology is of a dual-use nature—civilian and military—and the weapons economy is one of the most lucrative for robotics (Matsuzaki 2018; Robertson 2010a).

Exoskeletons are part of the Pentagon's Third Offset Strategy, which seeks to use robotics and artificial intelligence to enhance humans on the battlefield, rather than to replace them—or to avoid war altogether. There's no area where the need is more acute than in the infantry, which carries the heaviest loads and takes the vast majority of casualties. The average load for an American soldier is over 41 kg compared to 15 kg for a Japanese soldier. An exoskeleton would relieve some of the weight. Japan's defense research organization proposed allocating $7.5 million of its 2015 budget towards research into "highly mobile powered suits," with an emphasis on full-body exoskeletons. This is one-tenth of the $80 million the United States government is spending on exoskeleton research. Of course, military budgets are far from transparent, and robots and exoskeletons are very expensive, so it is safe to assume that both amounts underestimate actual costs (Marinov 2016; Ministry of Defense 2015: 35).

However, not to be ignored is the huge disconnect or gap between actual exoskeletons and public expectations of and for robotic exoskeletons raised by science fiction movies. As an America military robot manager recently declared, movies like *Iron Man* (2008) have hurt exoskeleton development because they create impossible expectations—literally impossible, since the CGI (computer generated image) full-bodied robotic suit routinely violates the laws of physics. "When Iron Man drops from the sky to a neat three-point landing, in particular, the sudden deceleration would liquefy [the human body] inside the suit" (Freedberg 2017). Whether in science fiction or the present reality, it should be quite clear that wearable robots are best suited for *gotai*, or fully limbed physically fit bodies; in both the United States and Japan, soldiers are regarded as ideal users.

Disabled veterans may participate in exoskeleton clinical trials and such events as the recently inaugurated Cybathlon in Switzerland, but these are of limited duration. Launched by Eidegenössische Technische Hochschule (ETH) in Zürich, the first Cybathlon was held in 2016 and included an exoskeleton race (won by Team ReWalk) (Prassler and Baroncelli 2017b: 8). A second event is planned for 2020. The competitors, or "pilots," included amateurs participating in local clinical trials and "top athletes" representing "big industrial players" in the exoskeleton industry (Prassler and Baroncelli 2017a: 8), who underwent a medical evaluation and extensive training for the event. Showcasing currently available and prototypes of assistive technologies, the Cybathlon garnered widespread media coverage[11]; team leaders emphasized that although Cybathlon results could be used for marketing purposes, they should not become a "benchmark" for assistive technologies. As Ottobock's team leader emphasized, users of rehabilitative technologies are individuals whose experiences may not be generalizable.[12] "Benchmarking always comes with standards that limit creativity" (Prassler and Baroncelli 2017a: 8). I will return to the theme of "creativity" below in the next section on the limits of bipedalism.

As evident in images from the Cybathlon and company websites, the exoskeletons do not guarantee solo upright bipedal walking. Used must rely on walkers, harnesses, crutches, and support therapists for stability. Even though the mantra of exoskeleton public relations media is all about "offering the joy of walking" to disabled persons, independent upright walking remains an unrealized (and perhaps unrealizable) corporeal aesthetic.

## Riddle of the Sphinx

Most readers have heard the riddle of the human-eating Sphinx in the play *Oedipus Rex* (the Athenian tragedy by Sophocles that was first performed around 429 BCE): "What walks on four legs in the morning, two legs in the afternoon, and three legs in the evening?" Oedipus survives, and the Sphinx dies, because he answers correctly, "a human." A human being crawls on all fours as a baby, walks on two legs as an adult, and uses a cane in old age.

In terms of the human life-cycle then, there are several corporeal modalities, or sensorial states, involving locomotion, and bipedalism is just one. It may be that the design of future of robotic exoskeletons lies in the hands of "imagineers" willing to break out of the limitations posed by both upright two-legged walking and the corporeal aesthetics of *gotai*. What other modes of locomotion, bipedal and otherwise, would facilitate the navigation of environments designed for *gotai* humans?

A small number of creative roboticists are now realizing the need to think outside the box of "upright bipedalism" when designing exoskeletons—and effective bipedal robots for that matter. Perhaps walking per se is less important than warranted. Innovative, non-anthropomorphic mobility devices able to navigate existing human environments are being developed. I introduce a few of them in the conclusion.

## Beyond human-like bipedalism

One of the most challenging problems for roboticists since the late 1960s has been to accurately replicate in robots the exact mechanism of upright human walking, or "heel strike, foot roll, and toe lift." The human pelvis and hip joints, which enable incredible, energy-efficient bipedal movement, are especially hard to replicate in robots. According to roboticist Dennis Hong,[13] "One of the reasons bipedal walking is difficult is because of an offset in the hip joints. This creates undesirable oscillatory moments that force the robots to take small, calculated steps," and if kicked in the side, to lose their balance and fall over (Gault 2016).

Hong found that by taking steps side to side, a robot is more stable, and moves faster and more smoothly. Declaring humanoid robots "too slow, too unstable, too expensive, too complicated, and too dangerous," Hong and his colleagues developed a prototype NABiRoS (Non-Anthropomorphic Bipedal Robotic

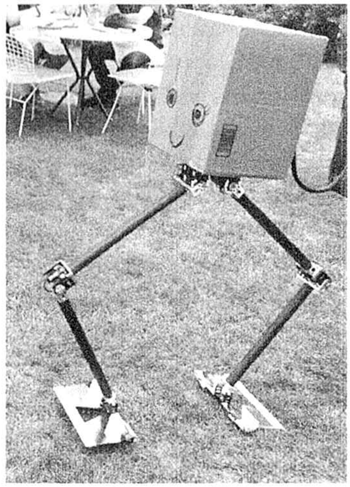

**FIGURE 1.6** RoMeLa's NABiRoS (Non-Anthropomorphic Bipedal Robotic System), sideways walker.
Photo from Ackerman (2016).

System) robot (Figure 1.6). A sideways walker with a circular knee and a lower leg that swings a full 360 degrees is able to climb over the lip of a windowsill and even climb stairs. "Instead of mimicking human walking," Hong notes, "we provide an elegant solution by proposing a novel configuration utilizing 'mechanical intelligence' for speed, stability and simplicity, enabling practical and effective robot mobility for real life applications" (Ackerman 2016; Gault 2016).

Another non-anthropomorphic bipedal robot is nicknamed Cassie. It was built by Agility Robotics (USA) whose design was based on the cassowary, a large ostrich-like bird from New Guinea. Like humans, Cassie has hips with a three-degrees-of-freedom, which allow it to move its legs forward and backward, side to side, and also rotate them at the same time (Ackerman 2017). Agility Robotics notes that Cassie's walking abilities could be productively integrated into the exoskeleton market (www.roboticsbusinessreview.com/rbr/cassie_bipedal_robot_wants_to_deliver_your_packages/).

What if, in addition to sideways moving and bird-inspired bipedal robots, a sideways moving wheelchair or walking device were created? The "climbing wheelchair" designed several years ago by roboticists at the Chiba Institute of Technology (Japan) is one such device. The wheelchair consists mainly of a seat mounted on top of four wheels that are attached to front and back sets of "legs." Sensors locate approaching obstacles and edges. When arriving at a curb or step, the legs can swivel and tilt—in effect, "climb." The legs move independently of the seat to keep it level at all times. They can also swivel into a roller blade formation allowing the wheelchair to make a zero-radius turn (www.universaldesignstyle.com/climbing-wheelchair-by-chiba-tech/; Owano 2012).

## Concluding thoughts

Debates among roboticists that are relevant to bipedalism have revolved around two basic, overlapping questions: why should robots resemble humans? and Why should humanoids be bipedal? I suggest that two additional, overlapping questions could be posed. The first is why the *gotai* ideal of human upright walking should pose design limitations on both bipedal robots and robotic exoskeletons. The second asks why the changeability of human environments is left out of the discussion of accessibility.

Robotic mobility devices call both for innovative, outside-of-the-box designs and for changes in human social infra- and super-structures. With the advent of trains, railroad tracks were laid; with the mass production of cars, train tracks (in the United States at least) were dismantled and highway systems were created. And yet, when it comes to robots and exoskeletons, the "human environment" is treated as a fixed, unalterable condition. Barrier-free mobility for robots and disabled humans is as much an urban/environmental design challenge as it is a technological challenge.

As the Agility Robotics advocates, robot designers must move beyond human exceptionalism and the fixation with upright walking. Science writer Matt Simon extends this point: "Designing a bipedal bot to work well in human environments is not necessarily about designing something that looks exactly human. It's about building the most effective platform that the laws of physics allow" (Simon 2017). New approaches to diverse body types and modes of locomotion are likely to produce more efficient mobility devices along with environmental innovations.

## Acknowledgements

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## Notes

1 For detailed information on eugenics movements in Japan, see (Robertson 2010b).
2 The stamp celebrated the centenary of biomedicine.
3 The author, Hirotada Ototake (b. 1976), has enjoyed a diverse career as a sports journalist, elementary school teacher, actor, and aspiring conservative politician in the

ruling Liberal Democratic Party. An "unfailing optimist," he is one of the very few Japanese celebrities with a visible disability living a very public life. He was recently outed in the press for several extra-marital affairs.

4 ASIMO is an acronym for Advanced Step in Innovative Mobility. ASI (pronounced "ahshi") is the Japanese word for legs and feet. HRP-4C refers to Humanoid Robotics Project-Fourth Cyborg, and AIST to National Institute of Advanced Industrial Science and Technology (Tsukuba, Japan). For more information on ASIMO and HRP-4C, and their gendering, see Robertson (2018). Miim may be a reference to "meme" (Robertson 2018: 117–118).

5 WABOT stands for Waseda Robot.

6 Currently, three types of HAL exoskeletons are available for rehabilitation: a bilateral leg type (BL), a single leg type (SL), and a single joint type (SJ) (Morishita and Inoue 2016: 605). A definition of HAL for medical specialists describes the exoskeleton as follows: "HAL for Medical Use (Lower Limb Type) is a bilateral lower limb exoskeleton with two active degrees of freedom at the hip and knee, and a passive degree of freedom at the ankle joint of each leg. Its control system processes data from surface electromyography (EMG) sensors, angle/acceleration sensors, and force sensors to estimate the necessary forces to assist-as-needed the user's intended actions. The use of EMG signals in HAL's shared control system to help detect the user's intent represents a type of hybrid peripheral neural interface" (Contreras-Vidal, Kilicarslan, Huang, and Grossman 2015; He, Eguren, Luu, and Contreras-Vidal 2017: 93).

7 One of the few studies of neurorehabilitation using HAL notes that "it is difficult to conclude that HAL-assisted rehabilitation is superior to conventional [manual] rehabilitation therapies due to a paucity of evidence," and that "no published data has demonstrated the facilitative effect of HAL therapy." Also emphasized in the study is the importance of identifying suitable patients; patients with "complete paralysis" and "severe motor weakness" are inappropriate as bioelectrical signals generated by voluntary muscle movement are needed to activate HAL (Morishita and Inoue 2016: 605, 608, 609).

8 Laboratory for Noninvasive Brain-Machine Interface Systems, Department of Electrical and Computer Engineering.

9 As of February 2018, Rex is the only exoskeleton in the group that has not been cleared for marketing in the United States or Europe.

10 It is also worth noting that rising health care costs internationally tend to limit access to rehabilitation facilities and trained clinicians are not always available (He, Eguren, Luu, and Contreras-Vidal 2017: 89).

11 For extensive coverage of the 2016 Cybathlon, see the December 2017 (Vol. 24, No. 4) issue of *IEEE Robotics & Automation Magazine* that was devoted to the event.

12 Ottobock is a German company that makes the C-Brace, a computer controlled knee ankle foot orthosis. See Ottobock (2018).

13 Hong is based at the Robots and Mechanics Lab (RoMeLa), University of California at Los Angeles.

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