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A Review of Bipedal Walking Robots: History, Design, and Control Approaches

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Abstract: The development of bipedal robots has been a significant milestone in the field of robotics, aiming to replicate human-like walking, balance, and mobility. This research paper presents a comprehensive study of the evolution of bipedal robots from their inception to the latest advancements. It analyzes various robots based on parameters such as speed, height, weight, degrees of freedom, year of invention, country of origin, and the organizations involved. Early pioneering robots, such as WABOT-1 (1973, Japan, Waseda University), laid the foundation for humanoid robotics, achieving basic walking capabilities. Subsequent innovations introduced highly advanced robots like ASIMO (2000, Japan, Honda), Atlas (2013, USA, Boston Dynamics), and Cassie (2017, USA, Oregon State University), which demonstrated significant improvements in balance, adaptability, and dynamic locomotion. The study highlights how technological advancements in actuators, sensors, artificial intelligence, and control systems have enhanced robot performance, resulting in faster speeds, improved stability, and greater autonomy. Additionally, the paper discusses the global contributions of leading organizations from Japan, USA, China, Korea, and Europe in shaping modern bipedal robotics. This research provides insights into the challenges faced, the breakthroughs achieved, and the future potential of bipedal robots in areas such as healthcare, disaster response, space exploration, and personal assistance.

Keywords: Bipedal Robots, Humanoid Robotics, Degrees of Freedom, Robot Evolution, Walking Mechanism, Human-Robot Interaction.

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1. Introduction

Bipedal walking refers to locomotion using two legs, closely resembling human gait and posture. Since the world we live in is designed around human mobility, robots with bipedal structures are better equipped to navigate staircases, narrow pathways, and uneven terrain, making them highly suitable for civilian, industrial, and healthcare applications [1]. Developing such robots, however, presents complex challenges that span mechanics, control theory, electronics, artificial intelligence, and human biomechanics, making the field inherently interdisciplinary [2]. Although quadrupedal robots can offer greater stability, bipedal robots provide distinct advantages in tasks that require human-like mobility and interaction. This is especially important in caregiving, elderly assistance, and other contexts where familiarity improves acceptance [1]. Beyond practical use, bipedal robots also serve as valuable research platforms for advancing locomotion science, balance control, and human–robot interaction. Building on these motivations, this paper reviews the historical development of bipedal robots, highlighting the key milestones and contributions that have shaped progress in the field.

2. Journey of Bipedal Robot Innovations

The concept of walking machines dates back to ancient times. Homer's Iliad describes an early mechanical device and in 231 CE, a wooden walking contraption called Mu Niu Liu Ma was designed in China. Modern research on humanoid robots began in the early 1960s, initially focusing on artificial hands and arms to support human labor [2]. The first true bipedal robots appeared in the late 1960s. One notable example is Rig, developed in 1968 by Smo-Sher at General Motors, which marked the beginning of systematic bipedal locomotion research. Around the same time, Vukobratović from Yugoslavia proposed the Zero Moment Point (ZMP) stability criterion between 1968 and 1969. This became a foundational concept for bipedal robot control and stimulated research efforts worldwide [3]. In Japan, Professor Ichiro Kato of Waseda University began developing bipedal robots in 1968. He launched the WAP series from 1969 to 1972, progressively emulating human walking [4]. In 1970, he initiated the WABOT project, under which several humanoid robots were developed, including WABOT-1, the first full-scale anthropomorphic robot, and WABOT-2, which performed tasks requiring dexterity and intelligence [5]. In 1984, the WL-10RD achieved the world's first complete dynamic walking using preset walking patterns, completing a step in just 1.3 seconds [6]. Between 1969 and 1984, Kato's lab produced over ten bipedal robots [3].

In 1986, Honda released the E series of experimental bipedal robots, starting with E0, which could walk slowly in a straight line by placing one leg before the other while keeping its center of gravity over the feet. Movements were rigid and limited to straight lines [7]. In the subsequent E1–E3 models (1987–1991), Honda aimed to achieve dynamic walking by studying and programming human walking patterns, but these robots still lacked robust stabilization, making smooth and practical locomotion difficult [8]. Between 1992 and 1993, Zheng et al. applied neural networks to the SD series robots, which allowed them to achieve more stable dynamic walking. This marked the earliest use of intelligent algorithms in gait planning. This work paved the way for later learning and model-based strategies, such as Virtual Model Control (Pratt & Pratt, 1997), which further simplified bipedal locomotion control [3]. Building on these advances, Honda introduced the P series (1993–1997), culminating in P2 (1996), the first humanoid robot capable of fully independent walking. This series laid the foundation for ASIMO, which integrated human-inspired mechanisms to achieve independent walking and stair climbing, marking a milestone in practical humanoid robotics [8]. In Japan, other companies also entered humanoid development. Sony launched the SDR (Sony Dream Robot) project in 1997, which later evolved into QRIO. The enhanced QRIO, announced in 2003, featured advanced motion control for walking, jumping, and running, surpassing standard ZMP-based control. It was recognized by Guinness World Records in 2005 as the world's first running humanoid robot [9].

Humanoid robotics expanded globally in the early 2000s. In 2004, Aldebaran Robotics (now SoftBank Robotics) began developing the NAO robot as an accessible platform for human–

robot interaction [10]. NAO is a small humanoid robot equipped with sensors for walking, dancing, speaking, and recognizing faces and objects. Now in its sixth generation, released in 2016, it is widely used in research, education, and healthcare [11]. In the US, Boston Dynamics began developing humanoid robots in 2008, starting with PETMAN and evolving into Atlas, capable of human-speed walking, climbing, and navigating rough terrain [12]. The hydraulic Atlas (Atlas HD) demonstrated advanced mobility and agility through whole-body skills such as dynamic balancing, running, jumping, and object manipulation [13]. Similarly, the University of Tehran in Iran developed the Surena humanoid series, from Surena I (2008) to Surena IV (2019), progressively enhancing walking, balance, and manipulation capabilities [14]. In China, the Beijing Institute of Technology introduced BHR-5, an adult-size humanoid capable of walking, climbing stairs, and grasping objects, while performing agile tasks such as playing table tennis against a human using a high-speed vision system [15]. Collectively, these developments illustrate the worldwide evolution of humanoid robotics toward assisting humans in daily life, research, and education.

In nature, bipedal locomotion is observed in dinosaurs, birds, and even some insects, providing insights into speed, gait, and energy efficiency. Birds, as evolutionary successors of dinosaurs, employ bent knees and horizontal femurs that allow economical walking and adaptive terrain handling. Studies show that avian locomotion can surpass humanoid models in efficiency, making it an important inspiration for the development of bipedal robots [16]. In 2016, Cassie, developed under the direction of Oregon State professor Jonathan Hurst, features ostrich-like knees and can operate without cameras or external sensors, demonstrating blind yet dynamic locomotion on complex terrain [17]. While its successor Digit made in 2019 extended this non-human inspired walking design by adding a sensor-rich torso and arms for balance and manipulation, making it useful in logistics and research [18]. Alexander conducted a comparative analysis of locomotion patterns across various animal groups, including reptiles, birds, and mammals [16]. His findings indicate that mammals exhibit similar gait behaviors when evaluated using the Froude number, a dimensionless parameter defined as:

$$\mathbf{F = u^2 / (g \cdot h)} \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where ***u*** *represents the animal's velocity,* **g** *is the gravitational acceleration, and* **h** *corresponds to the hip height.*

Advancements in control systems combined with innovative actuation designs have enabled robots such as Cassie and Digit to rapidly achieve performance levels comparable to leading humanoid platforms [16].

These advancements have positioned humanoid robots at the center of practical applications, where they are being increasingly utilized to engage and cooperate more naturally with humans and their surroundings. The rising need for adaptable robotic systems has driven the emergence of commercially available, general-purpose humanoid robots designed with collaborative functionalities [19]. Earlier efforts such as Honda's ASIMO laid important groundwork by demonstrating advanced locomotion and natural human interaction. However, ASIMO was never deployed in real-world manufacturing or service environments, and the project was discontinued in 2018 due to challenges in justifying a profitable business case [20]. This reflects a persistent challenge in humanoid robotics, which is turning research prototypes into solutions that are both technically capable and commercially viable. Another notable example is NASA's Valkyrie, the agency's first bipedal humanoid robot built on nearly two decades of prior research. It is designed for disaster response and to support future space exploration missions. [21]. In 2021, Tesla's Optimus was designed to perform dangerous, repetitive, and monotonous tasks. The prototype features improved dexterity through human-like hands, enhanced mobility, and integration with Tesla's proprietary artificial intelligence tools including self-driving computer systems, neural network planning, and object recognition capabilities. These developments position Optimus as a potential solution for both industrial and domestic environments [20]. Similarly, Figure AI is developing a general-purpose humanoid robot intended to address labor shortages, capable of performing end-to-end operations in industries and household tasks such as doing dishes and laundry [22]. Together, these efforts reflect a growing emphasis on developing versatile, human-compatible robots that can operate reliably in real-world environments across both terrestrial and extraterrestrial settings.

Table 1: Detailed description of the history of bipedal robots

Reference No.	Year	Country	Organization	Robot	Walking Speed (km/h)	Weight (kg)	Height (cm)	DOF
[23]	2000	Japan	Honda	ASIMO	1.6	43	120	26
[19, 24]	2000	Japan	Sony	SDR-3X	0.9	5	50	24
[19]	2000	Japan	University of Tokyo	H7	1.8	58	147	30
[28]	2000	Japan	University of Tokyo	H6	N/A	55	137	35
[25]	2001	Japan	Kawada Industries	Isamu	5	55	146.8	35
[19]	2002	Japan	Kawada Industries, AIST	HRP-2	1.98	58	154	30
[26]	2002	China	Beijing Institute of Technology	BHR-1	2	76	158	28
[27]	2002	South Korea	KAIST	KHR-1	N/A	48	119.3	21
[19]	2003	Japan	Sony	QRIO	1.18	7	58	28

[27]	2003	South Korea	KAIST	KHR-2	1	56	120	41
[19]	2003	Germany	Technical University of Munich	Johnnie	2.2	40	180	17
[27]	2004	South Korea	KAIST	HUBO	1.25	55	125	41
[26]	2005	China	Beijing Institute of Technology	BHR-2	N/A	63	160	32
[27]	2005	South Korea	KAIST	Albert HUBO	1.25	57	125	66
[29]	2005	South Korea	Korea Institute of Science and Technology	Mahru	0.9	67	150	35
[19]	2005	Japan	Honda	ASIMO	2.98	54	130	34
[30]	2007	South Korea	Korea Institute of Science and Technology, Samsung Electronics	Mahru III	1.3	62	150	32
[31]	2008	France	Aldebaran Robotics	NAO	0.3	4.5	57	25
[32]	2008	Iran	University of Tehran	Surena I	N/A	60	165	8
[33]	2008	Russia	Android Technics	AR-600	N/A	56	147.5	36
[34]	2009	The Netherlands	Eindhoven University of Technology	TUlip	1.44	25	125	N/A
[27]	2009	South Korea	KAIST	HUBO 2	1.5	45	125	40
[35]	2009	USA	Boston Dynamics	PETMAN	6.44	79.4	177.8	29

[26]	2009	China	Beijing Institute of Technology	BHR-4	N/A	65	170	46
[36]	2010	German	Technical University of Munich	LOLA	3.34	60	180	25
[37, 38]	2010	Japan	AIST	HRP-4C	1.8	43	158	42
[32, 39]	2010	Iran	University of Tehran	Surena II	0.10	45 []	145	22
[40]	2011	France	Softbank Robotics	NAO 4	0.6	5.2	58	25
[41]	2011	Japan	Honda	ASIMO	N/A	48	130	57
[42]	2011	China	Beijing Institute of Technology	BHR-5	2	65	165	30
[43]	2013	Germany	Institute of Robotics and Mechatronics	TORO	1.8	76	174	39
[44]	2013	Spain	PAL Robotics	REEM-C	2.5	80	165	68
[45]	2013	USA	Boston Dynamics	Atlas	N/A	150	188	28
[46]	2014	Japan	Kawada Industries	HRP-4	1.57	39	151.4	34
[20]	2014	USA	NASA JSC	Valkyrie (R5)	1.8	125	180	44
[47]	2014	France	Aldebaran Robotics	NAO V5	N/A	5.4	57.4	25
[32, 48, 49]	2015	Iran	University of Tehran	Surena III	0.72	98	198	31

[50]	2016	USA	Boston Dynamics	Atlas HD	5.4	80	150	28
[51]	2016	USA	Agility Robotics, Oregon State University	Cassie	5	31	115	20
[52, 53]	2017	Spain	PAL Robotics	TALOS	3	95	175	32
[54]	2017	China	Beijing Institute of Technology	BHR-6	N/A	50	165	23
[55]	2018	France	Softbank Robotics	NAO V6	N/A	5.48	57.4	25
[56]	2018	USA	UT Austin, Meka Robotics, Apptronik	Mercury	4	22	150	6
[57]	2019	USA	Agility Robotics	Digit	5.4	65	175	28
[48]	2019	Iran	University of Tehran	Surena IV	0.7	68	170	43
[58]	2020	Norway	IX Technologies	Eve	14.4	83	183	25
[59, 60]	2022	China	Xiaomi	Cyber One	3.6	52	177	21
[20]	2022	USA	Tesla	Optimus	8	57	173	40
[61]	2023	USA	UCLA	Artemis	7.56	37	142	20
[62]	2023	USA	Figure	Figure 01	4.3	60	168	40+
[63]	2023	China	AgiBot	RAISE A1	7	55	175	49+
[64]	2023	Canada	Sanctuary AI	Phoenix	4.82	70	170	44

[65]	2024	Iran	University of Tehran	Surena V	N/A	73	163	41
[66]	2024	USA	Boston Dynamics	Atlas	2.5	89	150	28
[67]	2024	USA	Figure AI, Inc.	Figure 02	4.32	70	168	16
[68]	2024	Germany	Neura Robotics	4NE-1	4	80	180	25
[69]	2024	China	LimX Dynamics	Tron 1	< 3.6	20	84.5	N/A
[70]	2025	USA	CMU	Zippy	0.89	25 g	3.6	N/A
[71]	2025	China	Unitree Robotics	UniTree R1	2.5	25	121	26
[72]	2025	China	CASBOT	CASBOT 01	N/A	60	179	52
[73]	2025	China	UBTECH	Walker C	6	43	163	20

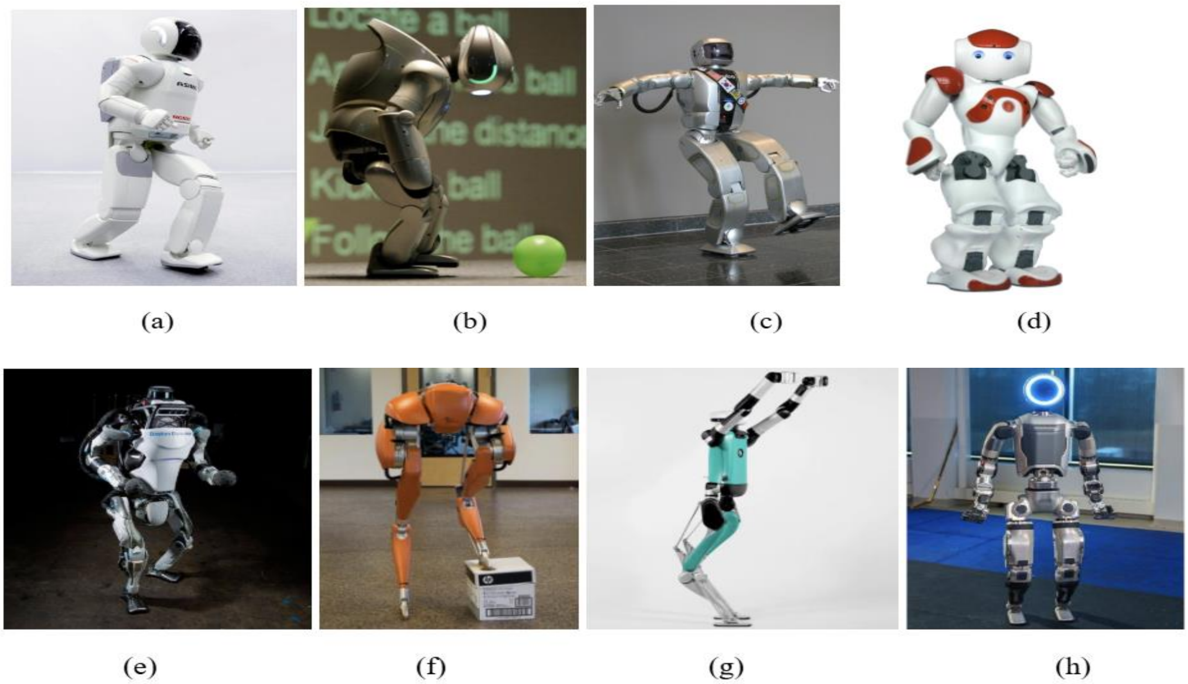
(a) (b) (c) (d)
(e) (f) (g) (h)

Figure 1. The historical development of bipedal robots. (a) ASIMO (2000) [74]; (b) QRIO [75]; (c) HUBO [76]; (d) NAO (2008) [31]; (e) Atlas HD (2016) [50]; (f) Cassie (2016) [51]; (g) Digit (2019) [57]; (h) ATLAS (2024) [77].

3. Methodologies for Bipedal Locomotion

Bipedal robots are often structurally unstable due to passive joints at points of unilateral contact. These robots typically have multiple degrees of freedom, which adds to their mechanical and control complexity [3]. To address this, researchers adopt simplified models to balance system simplicity with the need for dexterous movement. The development of bipedal robots capable of operating in unknown environments with a high degree of autonomy requires knowledge from various disciplines, including advanced mechanics, control theory, electronics, artificial intelligence, and human anatomy. As a result, the research in this area is truly interdisciplinary [2].

3.1 Actuation Systems

Actuators are responsible for generating the forces and torques required for bipedal locomotion. The most commonly employed systems include electric motors, hydraulic drives, pneumatic actuators, and series elastic actuators (SEA). Electric motors, particularly brushless DC and servo motors, are widely used due to their precision and ease of control, though they are limited by the energy density of batteries. Hydraulic systems, used in robots such as PETMAN and Atlas, provide high power density and smooth force generation but add weight, noise, and require bulky pumps. Pneumatic actuators offer low weight and fast response times but suffer from reduced precision due to the compressibility of air. SEAs introduce mechanical compliance, improving safety in human–robot interaction and enhancing energy efficiency by storing and releasing elastic energy.

The choice of actuation is closely linked to the energy source. Most bipedal robots rely on rechargeable batteries, particularly lithium-ion variants, which provide high energy density and low self-discharge but have limited operating times compared to combustion fuels. Larger platforms often employ hybrid solutions, such as hydraulic pumps powered by internal combustion engines or fuel cells, to extend range and performance. Current trends emphasize lightweight, energy-efficient actuators, compliant designs inspired by human musculature, and energy-recovery mechanisms to improve locomotion efficiency and reduce overall power consumption [79].

3.2 Balance and Stability

Balance and stability are paramount in bipedal locomotion. A robot that cannot maintain its balance will fall, rendering it ineffective. The center of gravity (CoG) plays a critical role; it must be kept within the support polygon (the area bounded by the feet) to maintain stability. Advanced control systems are used to adjust the robot's posture and movement in real-time to maintain balance. To further improve balance, especially under external disturbances or when walking on uneven terrain, researchers have developed stability control mechanisms inspired by human sensory reflexes. These include the Zero Moment Point (ZMP) reflex, the landing-phase reflex, and the body-posture reflex. Each of these reflexes operates independently, activating under specific conditions to restore or maintain equilibrium. These mechanisms mimic how humans instinctively adjust their limbs to prevent falling when pushed or destabilized. To maintain the robot’s movements, mainly these 2 walking methods are used. This movement called bipedal locomotion is guided by two main theories.The widely used Zero Moment Point (ZMP) theory, employed by Honda’s ASIMO (2000), allows walking, running (up to 6 km/h), and stair climbing. The other theory, known as Passive Dynamic Walking, is energy-efficient with simple control and enables downhill walking without actuators but requires round feet, which causes instability when standing and dependence on external forces to start or stop walking. Despite progress, challenges remain in achieving human-like motion and behavior in humanoid robots [78]. In addition, trajectory optimization plays a central role in ensuring stability and reducing energy consumption during long-distance walking, with several approaches combining learning-based methods, terrain adaptability, and optimal energy use [79].

3.3 Control Systems

One of the key challenges in biped locomotion is generating an optimal trajectory that ensures stability while avoiding obstacles. In practice, multiple algorithms are often combined to achieve effective locomotion patterns. Control systems serve as the “brain” of bipedal robots, integrating sensor feedback to regulate movement and maintain balance. A typical feedback control loop consists of three stages: state estimation from sensor data, control computation to determine the required inputs, and actuation to apply these inputs to the robot’s actuators [80]. Traditionally, most control systems for bipedal robots have been based on predefined trajectories. Methods for online ZMP compensation are commonly based on preview control, model predictive control, or artificial intelligence, providing flexibility in adapting locomotion strategies to varying terrains and disturbances. In contrast, modern AI-based systems can generate stable walking patterns without explicit physical modelling, though different strategies exist for gait stabilization [79].

4. Conclusion

The development of bipedal robots has progressed from simple walking prototypes to advanced humanoid systems. Foundational concepts such as the Zero Moment Point theory established the basis for stable locomotion. Robots, such as ASIMO, Atlas, and Cassie have advanced agility, adaptability, and efficiency. Despite these achievements, limitations remain in energy efficiency, robustness, and the realization of human-like gait. Addressing these challenges requires continued innovation in actuation, control algorithms, and learning-based approaches Future work should emphasize translating research into practical deployment. Applications in healthcare, logistics, disaster response, and space exploration highlight the need for reliable, adaptable, and commercially viable bipedal robots. Continued integration of artificial intelligence, biomechanics, and energy-efficient design, supported by interdisciplinary collaboration, will guide the next phase of progress in this field.

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