COMMENTARY

Journal of Climbing and Walking Robots
2026, Vol. 00(00) 1–6
DOI: 10.47852/bonviewJCWR62029537

BON VIEW PUBLISHING

A Commentary on the Evolution of Legged Robots

Abstract: This article explores the evolution of legged locomotion in both animals and robots, drawing parallels and contrasts between biological adaptation and technological innovation. It examines the transition from quadrupedal to bipedal motion in animals, highlighting the anatomical, neurological, and evolutionary challenges and advantages of bipedalism. In robotics, the development of both bipedal and quadrupedal walking machines is discussed, with attention to the engineering trade-offs, control strategies, and the influence of artificial intelligence (AI). The article analyzes key concepts such as gait cycles, stability, and the role of hardware and software, supported by mathematical models and schematic diagrams. By reflecting on philosophical perspectives and recent advances in AI-driven robotics, the commentary provides insights into the dynamic interplay between biology and engineering in the quest for agile, adaptive, and robust legged robots.

1. Introduction

Considering the evolutionary history of animals, the transition from quadrupedal to bipedal motion stands out as one of the most remarkable adaptations for species survival. This shift, observed in the lineage leading to humans and some other animals, required profound anatomical, neurological, and behavioral changes. Bipedalism offered distinct evolutionary advantages, such as freeing the forelimbs for tool use, increasing the field of vision, and improving energy efficiency during long-distance travel. However, it also introduced new challenges, particularly in maintaining balance and stability, which were addressed through gradual modifications in skeletal structure, muscle coordination, and neural control.

In contrast, the evolution of legged robots has followed a very different trajectory. Rather than progressing from four-legged to two-legged designs, robotics has often moved in the opposite direction. Early milestones in humanoid robotics, exemplified by ASIMO [1], showcased the ambition to replicate human bipedal walking. Similarly, robotic pets like Sony's Aibo [2] captured public imagination with their animal-like quadrupedal gaits. However, as research and development advanced, the field saw a proliferation of quadrupedal robots, such as Boston Dynamics' Spot [3] and ANYbotics' ANYmal [4], which demonstrated superior stability, robustness, and adaptability compared to their bipedal counterparts. This trend reflects a pragmatic engineering response: while bipedal robots are impressive feats of design and control, quadrupeds currently offer greater reliability and performance, especially in unstructured or challenging environments. As a result, there is still no clear advantage for two-legged robots over four-legged ones, particularly regarding stability, dynamic locomotion, and energy efficiency.

This divergence between biological and robotic evolution invites a broader reflection, one that can be illuminated through the lens of philosophy. In ancient Greek philosophy, reality was considered the primary substance—what exists independently of perception or thought. In contrast, modern philosophy, particularly since Descartes, has often emphasized the primacy of thought and subjective experience in constructing reality. This philosophical dualism finds a parallel in the evolution of robotics. The early decades of robotics were dominated by tangible progress in hardware (mechanical structures, actuators, and electronic control systems), mirroring the ancient focus on physical reality. As the field matured and reliable hardware platforms became commonplace, the emphasis shifted toward the intangible: sophisticated software, advanced algorithms, and, more recently, artificial intelligence (AI). Today, the "mind" of the robot (its control software, perception algorithms, and learning capabilities) has become the defining factor in its performance and adaptability, echoing the modern philosophical focus on thought as the creator of reality.

This interplay between hardware and software is especially evident in the latest generation of robots. Once the challenges of building stable, robust mechanical platforms were largely overcome, the bottleneck shifted to the development of efficient, adaptive, and intelligent control systems. The advent of AI-driven robotics has accelerated this trend, enabling robots to learn from experience, adapt to new tasks, and operate autonomously in complex environments. Recent breakthroughs, such as the capabilities demonstrated by advanced AI models like Gemini ER 1.5 [5] and the integration of large language models with embodied robots, highlight the growing importance of software in shaping the future of robotics. These developments suggest that, much like in philosophy, the evolution of robotics is increasingly defined by the dynamic interplay between the material and the immaterial, the body and the mind, and the hardware and the software.

2. Animal Locomotion

2.1. Bipedal motion in animals

Walking on two legs, or bipedal motion, is a remarkably complex yet fluid activity that involves careful coordination between the brain, the muscles, and the skeleton. Although it may appear simple and automatic once learned, every step we take is the result of a finely tuned interaction between our nervous system, our muscles, and the structural framework of our bones and joints.

At the heart of bipedal walking is what's called the gait cycle, which refers to the sequence of movements that occur as one leg supports the body while the other swings forward. This cycle is divided into two main parts. First is the stance phase, which takes up about 60% of the cycle and happens when the foot is in contact with the ground, bearing the body's weight. The second is the swing phase, where the foot leaves the ground and moves forward in preparation for the next step.

The process begins in the brain. The motor cortex initiates the intention to move, while deeper brain structures such as the basal ganglia help set the rhythm of walking. The cerebellum plays a crucial role in maintaining balance and coordinating timing, ensuring that the left and right sides of the body move in harmony. Once the brain has issued its command, the networks within the spinal cord, known as central pattern generators (CPGs), take over much of the control. These spinal circuits can produce the rhythmic patterns of walking with minimal input from the brain. They are largely based on real-time feedback from the body, including signals from joints, muscles, and the inner ear, to adapt to changes in terrain and balance.

As the gait cycle progresses, specific muscle groups are activated in a predictable sequence to move the leg and support the body. When the heel first hits the ground, muscles such as the tibialis anterior help control the position of the foot, preventing it from falling. At the same time, the gluteus maximus stabilizes the hip, and the quadriceps keep the knee extended so that the leg can support body weight.

As the body shifts over the standing leg, smaller muscles such as the gluteus medius work hard to stabilize the pelvis and prevent it from tilting. The quadriceps continue to engage slightly to absorb shock, while the calf muscles begin preparing for push-off. Just before the foot leaves the ground, these calf muscles contract strongly to propel the body forward.

During the swing phase, the focus shifts to lifting and moving the leg forward. The hip flexors, especially the iliopsoas, begin to pull the thigh upward. The knee bends, allowing the leg to swing through without dragging the toes. Meanwhile, the tibialis anterior contracts again to keep the toes lifted and prevent tripping. As the leg moves forward and prepares for the next heel strike, the hamstring muscles begin to slow down the movement, preventing the leg from swinging too far, while the quadriceps help extend the knee in preparation for landing.

Behind the scenes, the skeleton acts as a system of levers. The hips, knees, and ankles all flex and extend at different moments in the cycle, allowing for shock absorption, forward propulsion, and smooth transitions. The spine and pelvis also move subtly, rotating and shifting just enough to keep our center of gravity balanced and to help transfer energy efficiently across the body. The arches of the feet play a quiet but vital role by absorbing shock and storing elastic energy that is released during the push-off.

Throughout this entire process, the body continuously monitors its own movements. Sensors in muscles, tendons, and joints send feedback to the spinal cord and brain. These signals help fine-tune each step, maintain balance, and adapt to unexpected changes in surface or direction. The inner ear contributes information about head position and movement, while the eyes scan for obstacles and changes in terrain, adjusting the body's movement accordingly.

In summary, walking on two legs is not just a mechanical process but a deeply integrated system of control and movement. The nervous system plans and regulates each step, the muscles execute the motion, and the skeleton supports and channels the forces needed for balance and forward progress. Together, these systems allow bipeds to move with remarkable stability, adaptability, and efficiency.

2.2. Quadrupedal motion in animals

Walking in four-legged animals like dogs, cats, horses, or elephants follows the same general principle as in bipeds: a highly coordinated system involving the nervous system, muscles, and skeleton working together to produce smooth and efficient movement. However, because quadrupeds use all four limbs to support and propel the body, their movement patterns and control strategies are different and, in some ways, more stable and versatile than those of bipeds.

Just like in humans, the movement in quadrupeds is organized around a gait cycle, but here, it applies to each of the four limbs and the way they interact. Quadrupeds can use various gaits like walking, trotting, pacing, and galloping depending on speed, terrain, and purpose. Each gait has a specific pattern of limb movement and timing. For example, in a walk, the limbs move in a sequence, typically starting from a hind limb, followed by the forelimb on the same side, then the opposite hind limb, and finally the opposite forelimb. This creates a stable, four-beat rhythm in which at least two or three feet are on the ground at any time, providing excellent balance.

The control of this movement begins in the brain, particularly in motor centers that plan voluntary motion. As with bipeds, much of the rhythmic control of walking comes from CPGs located in the spinal cord. These are networks of neurons that can produce the basic rhythm of walking even without input from the brain, although they usually operate under the brain's guidance. They ensure that the limbs move in the correct sequence and rhythm for a given gait. The cerebellum plays a critical role in coordinating the movements of all four limbs and adjusting for balance and terrain, while proprioceptive feedback from muscles and joints provides moment-to-moment updates about limb position, load, and speed.

Muscular coordination in quadrupeds is more distributed than in bipeds because both the forelimbs and hindlimbs must share the task of propulsion, support, and balance. Generally, the hindlimbs provide most of the propulsive force, pushing the body forward, while the forelimbs play a bigger role in support and shock absorption as the body's weight shifts forward.

During the stance phase of a limb (when the foot is on the ground), powerful muscles like the gluteal group and hamstrings in the hindquarters generate the force needed to push off. In the forelimbs, muscles around the shoulder and elbow, such as the triceps, stabilize the limb and support the body's weight. As the limb enters the swing phase (when the foot is lifted and moves forward), hip and shoulder flexors help lift and advance the limb, while muscles like the tibialis anterior or its analogs help clear the ground.

The skeleton plays an essential role in translating muscle contractions into movement. In quadrupeds, the spine is more flexible and dynamic compared to that of humans. In many species, such as cats and cheetahs, the spinal flexion and extension during running or walking contribute significantly to stride length and speed. The limb bones act as levers, while joints such as the hips, knees, shoulders, and elbows flex and extend at the right moments to absorb impact and provide thrust. The scapula (shoulder blade) in quadrupeds is often not directly attached to the skeleton by a joint like in humans; instead, it floats within a muscular sling, allowing for a greater range of motion and shock absorption in the forelimbs.

Another key aspect of quadrupedal motion is interlimb coordination. Unlike bipeds, who must constantly shift balance from one leg to the other, quadrupeds benefit from having a much wider base of support. This allows them to be naturally more stable, especially at slower speeds. The nervous system takes advantage of this by coordinating diagonal or lateral pairs of limbs, depending on the gait, to keep the center of gravity balanced and prevent falling.

Throughout the movement, sensory feedback from the skin, muscles, and inner ear continuously informs the nervous system about limb position, body orientation, and contact with the ground. This allows for real-time adjustments, such as stepping over an obstacle, changing direction, or stabilizing after a stumble. Vision also contributes, especially in navigating complex terrain.

In summary, walking in quadrupeds is a product of integrated systems working together. The brain and spinal cord create rhythmic signals and adjust for environment and balance. Muscles contract in specific patterns to lift, stabilize, and push the limbs. The skeleton provides the structure and mechanical advantage for movement. Thanks to the use of all four limbs and a more stable base, quadrupeds can maintain smoother, more energy-efficient locomotion across a wide range of terrains and speeds. This system gives them both power and agility, essential for survival in diverse environments.

2.3. Evolution of walking

The evolution from quadrupedal to bipedal motion in animals is one of the most fascinating transitions in vertebrate history. It reflects a deep interplay between environmental pressures, anatomical changes, and functional adaptations. While bipedalism is rare in the animal kingdom, it evolved independently in several groups, most notably in humans, birds, and some extinct species like non-avian dinosaurs.

The earliest vertebrates to walk on land, such as early tetrapods over 350 million years ago, moved on four limbs. Quadrupedal locomotion was effective for stability, especially on uneven or slippery terrain, and allowed the body's weight to be distributed across all limbs. Most land animals today, from reptiles to mammals, continue to walk on all fours for precisely these reasons.

For many species, quadrupedal motion was not just a trait but an efficient evolutionary solution. It allowed for balance, support of a heavy trunk, and ease of movement over various surfaces. However, under certain conditions, evolution began to favor upright walking. This behavior appeared at first temporarily to address specific tasks such as reaching for food (e.g., chimpanzees reaching into trees), carrying objects (e.g., gorillas using hands to carry), displaying dominance, or scanning for predators.

This kind of occasional bipedalism did not require dramatic anatomical changes but began to shift behaviors and selective pressures when these movements became more advantageous or frequent.

Over time, especially in certain environments, natural selection began to favor animals that could spend more time on two legs. Walking upright provided a few key advantages to the early human ancestors. Bipedal walking uses less energy over long distances compared to quadrupedal knuckle-walking; standing upright allowed early humans to see over tall grass and spot predators or resources, and two freed hands meant that hominins could carry food, infants, and tools, a major survival benefit.

Eventually, bipedal walking became the primary and exclusive mode of locomotion in certain species. Once walking upright became the standard, the body further adapted for endurance and upright balance. Humans became capable of walking long distances and even running efficiently, a feature that likely played a role in hunting and migration.

In parallel, in other groups, the forelimbs were gradually freed from locomotion and adapted to wings, while the legs evolved for fast bipedal movement and balance.

However, despite its advantages, bipedalism is relatively rare in the animal kingdom. That is due to several issues. It makes balance more difficult, especially on uneven terrain, it places more stress on the lower back and knees, and it requires major structural changes that were not always favored by evolution unless there was strong environmental pressure.

3. Walking Robots

Figure 1 shows a hypothetical evolution of legged robots mirroring the evolution of animal locomotion. Walking in bipedal and quadrupedal robots mimics many of the same goals as biological locomotion: stability, efficiency, adaptability, and forward movement. However, to achieve these goals, animals rely on evolved biological systems (nerves, muscles, bones), whereas robots rely on artificial control systems, actuators, sensors, and mechanical linkages.

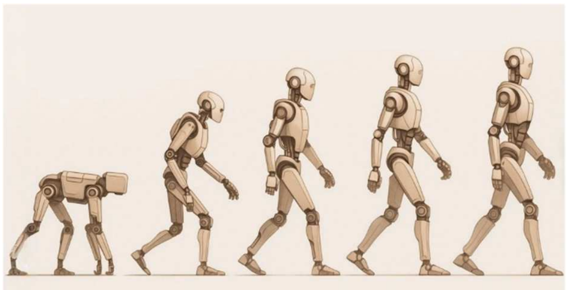

Figure 1
Hypothetical evolutionary pathway for legged robots

3.1. Bipedal robots: Walking on two legs

Walking in bipedal robots is one of the most complex challenges in robotics because it requires constant balancing, just like in humans. Unlike quadrupeds, bipeds have a narrow base of support, which makes them inherently unstable, especially during the single support phase (when only one foot is on the ground).

To walk, a bipedal robot starts by performing Motion Planning and Trajectory Generation. The robot's software generates a gait pattern: a sequence of joint angles and foot placements that will move the robot forward. These movements must be carefully timed and coordinated to prevent falls. Often, the gait is based on inverted pendulum models, where the robot's torso is treated like a pendulum swinging over its leg.

During the motion, the control system must assure balance and stability. Bipedal robots use algorithms to stay upright, adjusting their posture in real time. This involves managing the center of mass (CoM) and the zero moment point (ZMP), a point on the ground where the total forces acting through the robot's body cancel out, ensuring it doesn't tip over. If the ZMP moves outside the support area (the foot), the robot can fall.

The following equations form the mathematical basis for generating and controlling gait patterns in bipedal robots using the inverted pendulum model.
Let:

- m = mass of the robot's torso
- g = acceleration due to gravity
- z_c = constant height of the center of mass (CoM)
- x = horizontal position of the CoM
- u = position of the foot (pivot point)

The equation of motion for the Linear Inverted Pendulum Model is:

$$\ddot{x} = \frac{g}{z_c}(x - u)$$

The ZMP is defined as:

$$u = x - \frac{z_c}{g}\ddot{x}$$

The general solution for the CoM trajectory is:

$$x(t) = Ae^{wt} + Be^{-wt} + u$$

where $w = \sqrt{\frac{g}{z_c}}$ and A and B are constants determined by initial conditions.

The first equation describes the horizontal acceleration of the CoM as a function of its displacement from the foot.

The second equation relates the ZMP to the CoM position and acceleration.

The third equation gives the general solution for the CoM trajectory during a step.

Figure 2 shows a schematic diagram of the inverted pendulum model.

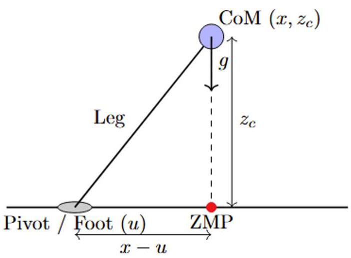

Figure 2
Schematic of a biped robot leg showing the center of mass (CoM), zero moment point (ZMP), pivot point (foot), and variables x, u, Z_c, and g

Electric motors, hydraulic actuators, or pneumatic systems drive the joints of the robot (hips, knees, ankles). These actuators must be precisely controlled to reproduce the planned motions while adapting to disturbances or uneven terrain.

The control of these actuators is typically achieved through a combination of open-loop and closed-loop control strategies (Figure 3), allowing for both precise trajectory tracking and real-time adjustments based on sensor feedback. The choice of actuators and their control algorithms is crucial for achieving smooth, stable, and efficient walking in bipedal robots.

Bipedal robots rely on a suite of sensors, including gyroscopes, accelerometers, force sensors, and cameras, to detect their

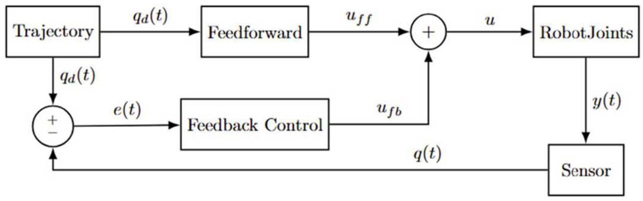

Figure 3
Mixed closed-loop and open-loop control architecture for a robot joint. The feedforward (open-loop) path provides planned input, while the feedback (closed-loop) controller corrects errors based on sensor measurements

orientation, foot contact, and surroundings. These sensors feed into a control system that can adjust gait and posture in real time.

Modern bipedal robots, like Boston Dynamics' Atlas [6], use machine learning and reinforcement learning to improve their walking ability. They can learn from trial and error, gradually improving their gait stability and energy efficiency.

However, bipedal robots typically walk more slowly and cautiously than humans, and their walking often looks mechanical and deliberate, although newer designs are approaching natural human-like motion.

3.2. Quadrupedal robots: Walking on four legs

Quadrupedal robots are generally more stable and robust than bipeds, thanks to their wider base of support and ability to keep at least three feet on the ground at any time. Their walking mechanisms are inspired by four-legged animals, and they often use gait patterns such as walk, trot, gallop, or pace.

Quadruped robots can switch between different gait patterns depending on speed and terrain. A walk involves moving one leg at a time (Figure 4) while a trot involves moving diagonal pairs of legs together (Figure 5). These gaits are pre-programmed or learned through AI algorithms.

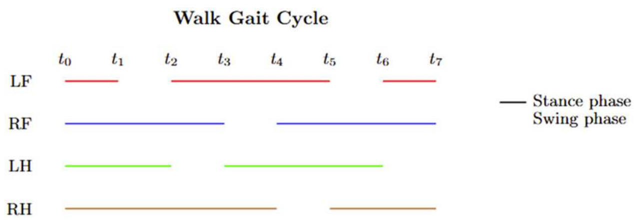

Figure 4
Exemplary footfall diagram for a quadruped robot in a walk gait. Each bar shows when a foot is on the ground (stance phase). LF: left front, RF: right front, LH: left hind, RH: right hind

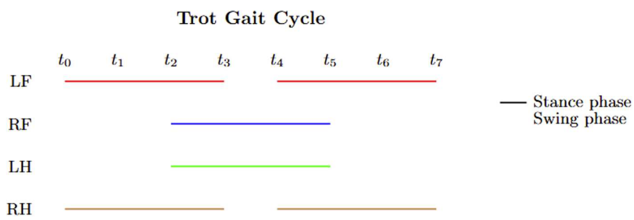

Figure 5
Possible footfall diagram for a quadruped robot in a trot gait. Diagonal pairs (LF + RH, RF + LH) are in stance together

Each leg is controlled independently but coordinated centrally. The control system ensures that the phase offset between each leg is just right to keep the robot balanced and moving smoothly. This coordination can be modeled after CPGs, similar to those found in animals.

Quadrupeds maintain stability by keeping their CoM within the polygon of support formed by the feet on the ground (Figure 6). If one foot slips or encounters an obstacle, the robot can quickly adjust the other legs to compensate. Advanced quadrupeds like Spot by Boston Dynamics or ANYmal by ANYbotics can walk on rough terrain, climb stairs, and even recover from pushes or falls.

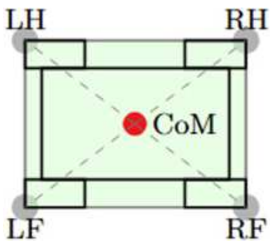

Figure 6
Top view of a quadruped robot showing the support polygon (green area) formed by the feet in contact with the ground and the center of mass (CoM, red dot) inside the polygon. Stability is maintained as long as the CoM remains within the support polygon

Each leg is powered by motors or hydraulic actuators at the joints. Many quadruped robots use compliant actuators or series elastic actuators, which allow for small, spring-like give in the joints. This helps the robot absorb shocks, handle rough terrain, and produce smoother movement.

Figure 7, on the left, shows the details of the Unitree go2 [7] robot during trot motion, where two legs are in the stance phase (on the ground) and two are in the swing phase (moving forward). On the right, a rendering of the internal actuation mechanism of the robot's leg is shown.

Figure 7
Trot motion of the Unitree go2 robot (on the left) and internal structure of its legs[1] (on the right)

Regarding perception, quadruped robots utilize a variety of sensors to navigate and interact with their environment. Cameras, LIDAR, force sensors, and IMUs (inertial measurement units) allow the robot to understand the environment and adjust its gait in real time. Feedback from foot sensors tells the robot when and where each leg has made contact with the ground, allowing it to correct its movements continuously.

[1] https://sketchfab.com/3d-models/unitree-go2-leg-animation-d8f72b659e6c4659a5760da4366feafa

4. Conclusion

The journey from animal locomotion to robotic walking is a testament to both the ingenuity of nature and the creativity of human engineering. While evolution shaped bipedalism and quadrupedalism through millions of years of adaptation, robotics has rapidly advanced by learning from, and sometimes diverging from, these biological templates. Bipedal robots embody the ambition to replicate the complexity and versatility of human movement, yet they continue to face formidable challenges in stability, control, and energy efficiency. Quadrupedal robots, inspired by the inherent stability and adaptability of four-legged animals, have become the workhorses of real-world robotic applications, excelling in robustness and versatility across diverse environments.

The interplay between hardware and software, reminiscent of philosophical debates about body and mind, now defines the frontier of robotics. As reliable mechanical platforms become ubiquitous, the focus shifts to intelligent control, perception, and learning, domains where AI is beginning to close the gap between engineered and biological systems. The integration of advanced AI, sensor fusion, and adaptive control is enabling robots not only to walk but also to perceive, reason, and respond to the world with increasing autonomy.

Ultimately, the evolution of legged robots is not a simple race to mimic nature but a dynamic process of innovation, adaptation, and synthesis. By blending biological inspiration with engineering pragmatism, robotics is forging new forms of locomotion and intelligence that extend beyond the limits of either domain alone. As research continues, the boundary between the natural and the artificial will blur further, opening up unprecedented possibilities for mobility, exploration, and interaction in both human and machine worlds.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

Paolo Tripicchio is an Editorial Board Member for *Journal of Climbing and Walking Robots*, and was not involved in the editorial review or the decision to publish this article.

Keywords: walking robots, bipeds, quadrupeds

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How to Cite: Tripicchio, P. (2026). A Commentary on the Evolution of Legged Robots. *Journal of Climbing and Walking Robots*. https://doi.org/10.47852/bonviewJCWR62029537