Chapter 5
Self-regulatory Hardware: Evolutionary Design for Mechanical Passivity on a Pseudo Passive Dynamic Walker

Hiroshi Yokoi and Kojiro Matsushita

5.1 Introduction

The functioning of our body is the resultant of the lifelong survival competition. The body possesses the special physical characteristic shape, size, and material, and has been living throughout using this characteristic by achieving the function of the movement and the sense. Lot of functions have been added to the simple reflective system that emerged in the first generation. After the competition, the basic function of the reflective system of sense and action has been changed to be integrated and over wrapped by the new reflective system. The basic function necessary for survival has been achieved. The performance of this simple reflective system gives the chance for surviving, and we have the simple way to design an individual with good performance who can adapt to the environment.

We focused on the process to acquire the structure and the material characteristics of the leg as an example of a simple reflective system. Moreover, the result of examining how the function of walking develops is described. We discuss evolution design system by using simple genetic algorithm (GA) that allow to achieve the function of the leg. We also demonstrate how to optimize a set of parameters in the competition between various designs of hardware.

Various experiments were conducted on the relation of the change in the biped structure and the walking functions. The experimental result shows that the phenomenon of absorption of the kinetic energy with active rhythm generation is the main mechanism of a passive pendulum movement, and the viscoelasticity of the body and the discharges confirmed to stabilized walking generations are the central characteristics. Particularly, the self regulatory function as an autonomous adjustment of motion by the passive element was developed by using Pseudo Passive Dynamic Walker of various types by arranging the viscoelasticity of the body in the main joint of the leg (waist, knee, and ankle).

A. Adamatzky and M. Komosinski (eds.), *Artificial Life Models in Hardware*,

5.2 Background

Conventional robots are designed for multiple purposes. So they implicitly tend to have high specifications (i.e., multiple degrees of freedom, fast information processing, and high energy consumption), and their movements are precisely manipulated by their control for the purpose of achieving all required tasks. Meanwhile, biomimic robots are mimics of biological system. So, their control and physical structure implicitly indicate their high adaptability to their tasks and environments and, therefore, tend to require smaller energy consumption and lower control complexity than the conventional robots. The representative instance is the passive dynamic walker [3, 6]. The robot does not have any motors and sensors, but has a well-designed structure based on the human characteristics during walking: passive hip joints, latch knee joints, and semi-circular feet. Then, the robot maintains balance and walks down a slope by exploiting gravity as the driving force. The physical structure itself self-regulates its locomotion.

Thus, we believe that it is necessary to implement self-regulatory physical structures in a design process, and such concept is referred to as embodiment [2,4] in the field of embodied artificial intelligence and robotics [7].

Embodiment is basically defined as special features in the body, causing high adaptability to its tasks and environments in robotics. There is increasing evidence that the exploitation of a robot's embodiment can increase its energy efficiency and reduce the complexity of its control architecture. However, embodiment has only been investigated using conventional robots and its implications have not been systematically quantified. Then, the current agreement in embodied cognitive science indicates that embodiment can emerge in robots by the biologically inspired reproductive process. One of the most successful of these applications was the work of Sims [8,9], in which artificial creatures were automatically designed within a three-dimensional physics simulation. The simulation generated a variety of locomotive creatures with unique morphologies and gaits, some of which have little analogy in the biological world. This suggested that the interdependence between morphology and control plays an important role in the evolution of locomotion. However, the Sims' work did not achieve "legged" locomotion by the design system.

Thus, evolutionary design has not yet overcome these technical difficulties and the use of simulation. Therefore, as the best solutions at present, biologically inspired knowledge should be appropriately applied to unknown parts of the system. For example, legged locomotion has not yet been emerged spontaneously in coupled evolution – only crawling. It seems that more detail of the morphological composition is required in its design process and, then, the evolution leads to more locomotion than crawling. So to make further progress, we need to gain a better understanding of how to synthesize complex yet functional morphologies, and biologically inspired knowledge will be useful for improving our designs: Alexander [1] has shown a variety of locomotion types using different structures such as curved surfaces, universal joints, and parallel links (structure); Vogel [11] stressed the importance of material properties such as muscle, ligament, tendon, and bone (material properties). We believe that such biologically inspired knowledge contributes to generating more concrete design of locomotive robots and provide variety of self-regulatory mechanisms.

5.3 Evolutionary Design System of Legged Robots

In Fig. 5.1, a conceptual figure of the proposed evolutionary design system is shown. The system has three main features: coupled evolution, interactive interface, and evaluation. The coupled evolution architecture is an automatic design system of the morphology and controller of a legged robot. The design process is based on a biologically similar reproductive process, so that we assume that the design system provides a developmental environment to emerge embodiment of legged robots. The reproductive process is basically computed with a GA so that its meta-heuristic characteristic helps designers to interact with evolutionary processes. Thus, the designers conduct trial-and-error activities by observing acquired behavior and physical structures through the interactive interface architecture. Then, evaluation criteria (i.e., fitness function and energy efficiency) are used to specify their physical features. Through the repetition of the two architectures, the evolutionary design system facilitates concrete design solutions involving legged locomotion and the emergence of embodiment (i.e., self-regulatory hardware).

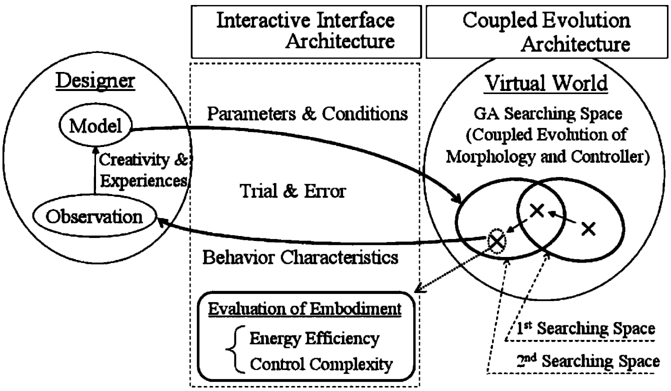


Fig. 5.1 Conceptual figure of evolutionary design system

5.3.1 Three-dimensional Physics World

The design system is implemented using Open Dynamics Engine (ODE) [10], which is an open-source physics engine library for the three-dimensional simulation of rigid body dynamics. The environmental configuration of the design system is given as sampling time 0.01 s, gravity 9.8 m s^{-2}, friction 1.0, ground spring coefficient 5,000 N m^{-1}, ground damper coefficient 3,000 N s m^{-1}.

5.3.2 Coupled Evolution Part

The coupled evolution part is characterized by a general GA process, a gene structure representing morphology and controller, and evaluation methods. The general GA process starts with random genes and conducts 100–300 generations using a population size of 100 for each run. After all generations, an evolutionary process ends, and the next evolutionary process starts with new random genes. Table 5.1 lists setting values for the GA.

Table 5.1 Values for GA parameters

Parameter	Value
Seed	30–100
Generation	300
Population	100–200
Num. of gene locus	50–100%
Crossover	5–10%
Mutation	5–10%

The GA process uses an elite strategy that preserves constant numbers of higher fitness in the selection/elimination process due to its local convergence. Here, fitness is defined as the distance traveled forward for a constant period (i.e., 10 s). At the end of each generation, the genes are sorted from highest to lowest fitness value. The genes in the top half of the fitness order are preserved, while the others are deleted. The preserved genes are duplicated, and the copies are placed in the slots of the deleted genes. The copied genes are crossed at 5–10% and mutated at 5–10%.

The gene structure is a fixed-length gene and presents morphological and control parameters. Each locus contains a value ranging from −1.00 to +1.00 at an interval of 0.01. Figure 5.2 shows locus IDs corresponding to design parameters: L, W, H, M0, M1, M2, M3, M4, k, c, amp, and cycle. Morphology of a legged robot in the design system consists of five basic kinds of design components in Table 5.2: joint type (compliant/actuated), joint axis vector, link size, link angle, and link mass. These physical components are viewed as basic components of a biological system.

Based on the physiological knowledge of gait control, the controller of a legged robot consists of simple rhythmic oscillators. The characteristics are mainly determined with two types of parameters: amplitude and frequency (Table 5.3). Pre-conditional, all the oscillators have the same wavelength, and the contra-lateral oscillators are in anti-phase. Here, we assume that a simple controller leads to forming special physical features on evolved legged robots (embodiment).

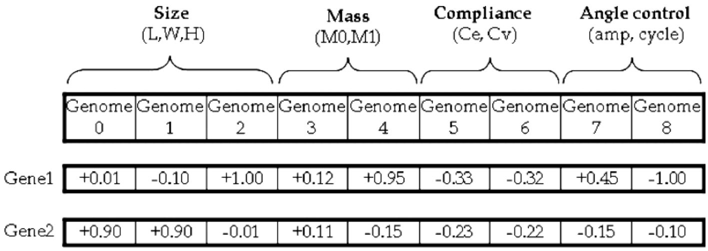


Fig. 5.2 Concept figure of gene structure

Table 5.2 Basic morphological configuration

		Link 1	Link 2
Size	Length [m]	0.1	0.1
	Width [m]	0.1	0.1
	Height [m]	0.1 to 0.5	0.1 to 0.5
Absolute Angle at Pitch (y axis) [rad]		$-\pi/3$ to $\pi/3$	$-\pi/3$ to $\pi/3$
Mass [kg] (Total Mass X [kg])		X * 10-90%	X * 10-90%

Table 5.3 Basic joint configuration

			Joint 1	Joint 2
Type	Compliance	Elasticity [N/m]	10^{-2} to 10^{+4}	10^{-2} to 10^{+4}
		Viscosity [Ns/m]	10^{-2} to 10^{+4}	10^{-2} to 10^{+4}
	Angle Control	Amplitude [rad]	0 to $\pi/2$	0 to $\pi/2$
		Cycle [sec]	0.5 to 1.5	
Axis Vector		X	-1.0 to +1.0	-1.0 to +1.0
		Y	-1.0 to +1.0	-1.0 to +1.0
		Z	-1.0 to +1.0	-1.0 to +1.0

5.3.3 Evaluation Methods

Energy consumption and energy efficiency are applied as evaluation methods. It contributes to qualifying evolved legged robots. In physics, mechanical work is equivalent to the amount of energy transferred by a force, and is calculated by multiplying the force by the distance or by multiplying the power (in Watt) by the time (in seconds). Then in the case of a motor, time and rotational distance are related with its angular speed and the torque, which causes angular speed to increase, is regarded as mechanical work. So, power W in rotational actuation is calculated with the following equation:

$$W = \text{torque (N m)} \times 2\pi \times \text{angular velocity (rad s}^{-1}\text{)}. \tag{5.1}$$

Energy consumption for a walking cycle is represented as follows:

$$J = T \sum_{i=0}^{N} \int_{0}^{T} |2\pi Tr_i(t)\dot{\theta}_i| \, \mathrm{d}t, \tag{5.2}$$

and energy efficiency is computed as energy consumption per meter (in this equation, total mass is ignored because it is set as a common characteristic among all robots):

$$J/m = J/Dis. \tag{5.3}$$

In (5.1)–(5.3), t is time in seconds, N is a number of actuated points, Tr_i is a torque in point i, Dis is a distanced traveled for a walking cycle (in meters), dt is a sampling time (in seconds), $\dot{\theta}_i$ is an angular velocity (rad s^{-1}), T is a walking cycle (in seconds).

5.4 Evolutionary Design of Biped Robots

Evolutionary design of biped robots is conducted in this section: the first evolutionary design aims at verifying emergence of embodiment; the second evolutionary design aims at specifying self regulatory mechanisms.

5.4.1 Morphological and Control Configuration for Biped Robots

Biped robots are constructed using nine rigid links (Fig. 5.3): an upper torso, a lower torso, a hip, two upper legs, two lower legs, and two feet. These body parts are, respectively, connected at torso, upper hip, lower hip, knee, and ankle joints, and the robots have eight degrees of freedom.

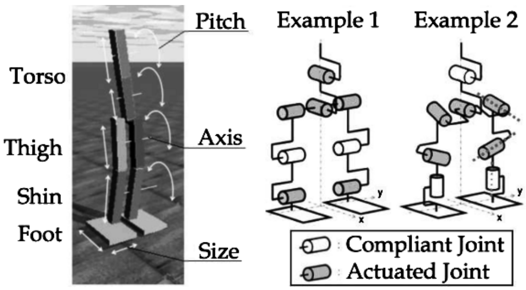


Fig. 5.3 Morphological configuration

Table 5.4 lists control parameters (i.e., amplitude and frequency) and Table 5.5 lists morphological parameters (i.e., size, weight, absolute angle of each link and selection of whether it is oscillatory or compliant, as well as its elasticity coefficient and viscosity coefficient if the joint is compliance or amplitude and frequency if the joint is a oscillator, and axis vector of each joint). In addition to this setting, joint settings are constrained to be contra-laterally symmetric around the xz plane (Fig. 5.4).

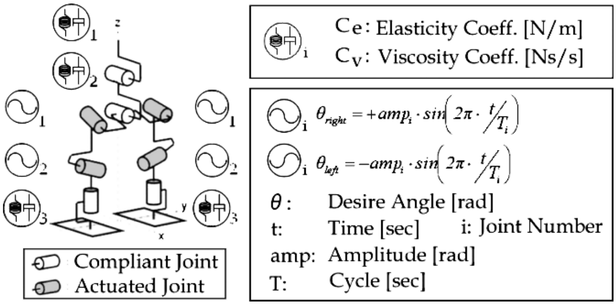


Fig. 5.4 Control configuration

Table 5.4 Characteristic of joints (searching parameters colored in blue)

	Torso	Hip	Knee	Ankle
Type				
Compliance				
Elasticity coeff. [N m^{-1}]	$10^{-2} - 10^{+4}$	$10^{-2} - 10^{+4}$	$10^{-2} - 10^{+4}$	$10^{-2} - 10^{+4}$
Viscosity coeff. [N s m^{-1}]	$10^{-2} - 10^{+4}$	$10^{-2} - 10^{+4}$	$10^{-2} - 10^{+4}$	$10^{-2} - 10^{+4}$
Actuation (angle control)				
Amplitude [rad]	0 to $\pi/2$	0 to $\pi/2$	0 to $\pi/2$	0 to $\pi/2$
Cycle [s]	0.5 to 1.5	0.5 to 1.5	0.5 to 1.5	0.5 to 1.5
Axis vector				
X	1	−1.0 to +1.0	−1.0 to +1.0	−1.0 to +1.0
Y	0	−1.0 to +1.0	−1.0 to +1.0	−1.0 to +1.0
Z	0	−1.0 to +1.0	−1.0 to +1.0	−1.0 to +1.0

Table 5.5 Characteristic of links (searching parameters colored in gray)

		Upper/ lower Torso	Hip	Thigh	Shin	Foot
Size	Length [m] (X axis)	0.1	-	0.1	0.1	0.1 to 0.5
	Width [m] (Y axis)	0.1	-	0.1	0.1	0.1 to 0.5
	Height [m] (Z axis)	0.1 to 0.5	-	0.1 to 0.5	0.1 to 0.5	0.05
	Radium [m]	-	0.05	-	-	-
Absolute angle at pitch (y) axis [rad]		-π/3 to π/3	-	-π/3 to π/3	-π/3 to π/3	-π/3 to π/3
Parallel displacement on y axis[m]		-	-	-	-	0 to 0.2
Total Mass 20 [kg] (a+2b+2c+2d+e=100%)		e	a	b	c	d

5.4.2 *Results of First Evolutionary Design*

We focus on the most successful nine seeds: that is, those are the biped robots that traveled forward more than 7 m for 10 s (Fig. 5.5). Table 5.6 lists the performance of

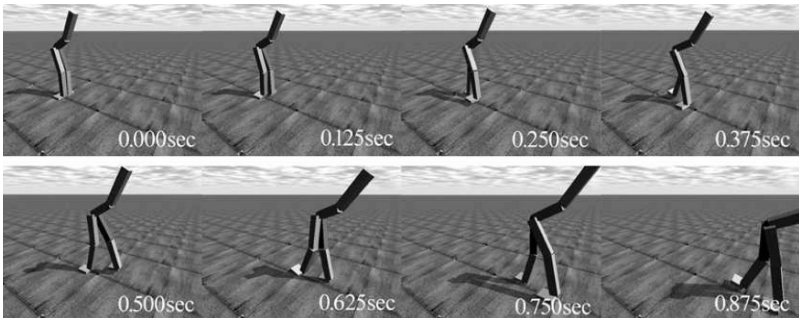


Fig. 5.5 A walking scene

the best nine biped robots: the second column reports their distance traveled forward for 10 s; the third column, their walking cycle; the fourth column, their angular velocity of oscillators; the fifth column, their energy efficiency; the six column, their numbers of contralateral set of actuated joints (i.e., four types – torso hip, knee, ankle joints).

The biped robots with less number of actuated joints indicate high energy efficiency. As shown in Table 5.7, the further analysis indicates that hip joints tend to become actuated joints, and knee joints tend to be compliant joints. Especially, the characteristics of the compliant joints are categorized into three types: free joint, suspension joint, and fixed joint corresponding to the degree of elasticity and viscosity.

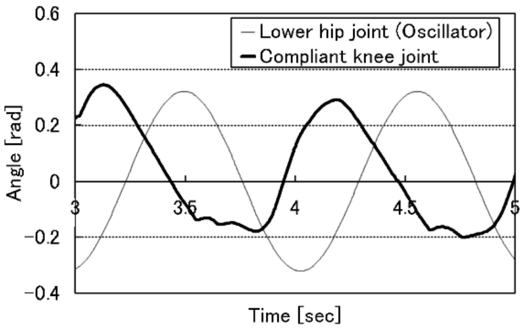
Table 5.6 Performance of best nine biped robots in order of energy efficiency. Energy efficiency is computed with average torque 25 N m, and lower values indicate better performance

Seed	Distance [m]	Cycle [s]	Angular velocity [rad/s]	Energy efficiency [J/m]	Number of actuated DOFs
09	13.0	1.02	0.50	6.0	2
11	7.3	1.05	0.32	7.0	1
02	7.7	1.17	0.38	7.7	2
00	10.6	1.05	0.55	8.2	3
14	7.0	1.01	0.45	10.0	2
22	11.9	1.06	0.99	13.1	3
08	9.2	1.04	0.81	13.8	3
21	7.1	1.08	0.69	15.2	3
17	7.2	1.04	0.88	19.1	3

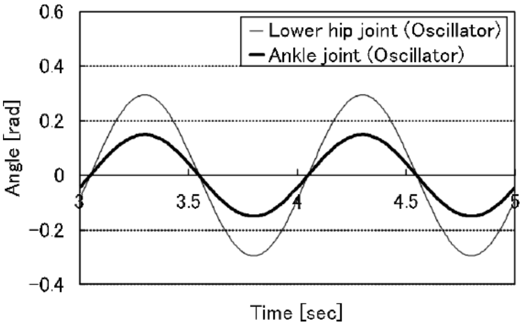
According to the effects of the compliance, the best nine biped robots can be categorized into two types of walks: the biped robot walks without using any compliance (i.e., actively controlled walker) and the biped robot walks with using some effects of compliance (i.e., compliant walker). The differences are shown in Figs. 5.6 and 5.7. Figure 5.6 shows joint angle trajectories of both walkers, and Fig. 5.7 presents results of frequency analysis on the transitions. It reveals that the knee oscillation of the compliant walker is induced by oscillators at other joints, 1 Hz frequency. This can be considered as self-regulation. The amplitude of 2 Hz

Table 5.7 Characteristics of compliant joints among best nine biped robots, where C_e is an elasticity coefficient, in $N\,m^{-1}$, C_v is a viscosity coefficient, in $N\,s\,m^{-1}$

Types	Condition	Num. of compliant joints				
		Torso	Hip	Knee	Ankle	Total
Free joint	0<=Ce<10 && 0<=Cv<10	1	0	1	1	3
Suspension joint	10<Ce<=100 && 0<=Cv<10	0	0	5	0	5
Fixed joint	Ce>100 || Cv>=10	3	1	1	1	6
Total num.		4	1	7	2	14



(a)



(b)

Fig. 5.6 Joint angle trajectories of hip and knee joints: (**a**) Compliant walker and (**b**) Actively controlled walker

oscillations in Fig. 5.7a realizes ground impact absorption (self-stabilization) with high compliance. That is, these two appropriate states of compliant joints indicate passive and dynamical functions during locomotion. Therefore, such type of the robots can be called pseudo-passive dynamic walkers. Moreover, these two functions serve as examples of the computational trade-off possible between morphology

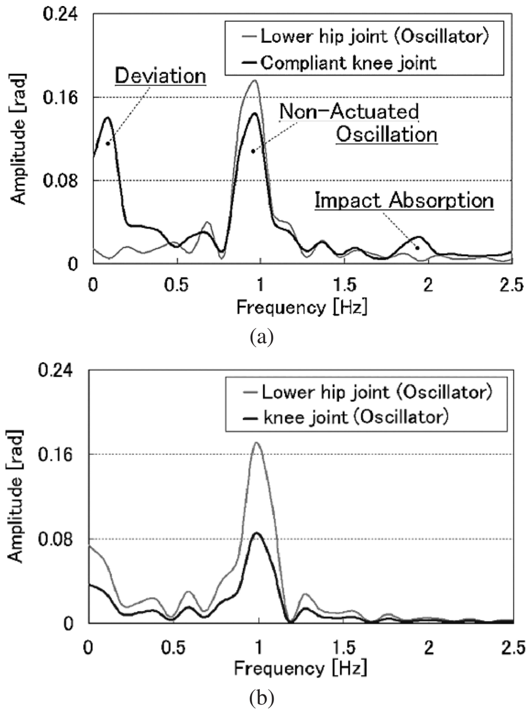


Fig. 5.7 Frequency analysis (i.e., discrete Fourier transform) of joint angle trajectories of hip and knee joints: (**a**) Compliant walker and (**b**) Actively controlled walker

and controller, because compliant joints can be moved by energy input channels other than controlled motors and filter noise without computational power. It suggests that the embodiment, which reduces control complexity and energy consumption, is emerged in the design system.

5.4.3 Additional Setup Condition for the Second Evolutionary Design

The second evolutionary design is conducted for clarifying the embodiment: compliance. Basically, for the purpose of narrowing its solution space to specify physical structures exploiting compliance, an additional condition (i.e., restriction of the numbers of actuated joints) is added to the design system. Table 5.8 indicates joint configurations for the second evolutionary design, and a scheme for joint-type selection is as follows: one of four types of joint structures (i.e., either set of torso, hip, knee, and ankle becomes an actuated joint and other sets of the joints are compliant)

Table 5.8 Joint configuration (searching parameters colored in gray)

	Torso	Hip	Knee	Ankle
Type				
Compliance				
Elasticity Coeff. [N/m]	$10^{-2} - 10^{+4}$	$10^{-2} - 10^{+4}$	$10^{-2} - 10^{+4}$	$10^{-2} - 10^{+4}$
Viscosity Coeff. [Ns/m]	$10^{-2} - 10^{+4}$	$10^{-2} - 10^{+4}$	$10^{-2} - 10^{+4}$	$10^{-2} - 10^{+4}$
Actuation (angle control)				
Amplitude [rad]	0 to $\pi/2$	0 to $\pi/2$	0 to $\pi/2$	0 to $\pi/2$
Cycle [sec]	0.5–1.5	0.5–1.5	0.5–1.5	0.5–1.5
Selection of Joint Type				
0–3				
0	Act.	Comp.	Comp.	Comp.
1	Comp.	Act.	Comp.	Comp.
2	Comp.	Comp.	Act.	Comp.
3	Comp.	Comp.	Comp.	Act.

is selected for a walker. The evolutionary design is conducted using 100 different random seeds, is run for 100 generations, and the population is comprised of 100 individuals.

5.4.4 Results of the Second Evolutionary Design

The evolutionary design generated six notable walks. In this section, their walking characteristics are described according to their joint structures.

Hip actuated walkers arose the most (i.e., 55 out of 100 seeds). The gaits can be characterized into three notable types: statically stable, dynamically unstable, and dynamically stable walks. The statically stable walk (Fig. 5.8a) is achieved most often among the hip actuated walkers: they increase their mechanical stability and keep a narrow amplitude range in their oscillation so that their COG-X always remains within their supporting polygon while walking. Figure 5.8b shows a dynamically unstable walk. It walks with a tottering gait because the edges of its feet randomly contact the ground. So, its performance is unstable even on the flat plane. Meanwhile, Fig. 5.8c shows a dynamically stable walk. The main feature is the axis vector of its hip joint: the oscillations at the hip axis synchronously move not only the legs in the sagittal plane but also the torso in the lateral plane. So, the hip actuation mechanism keeps its balance and forward locomotion (i.e., self-regulatory mechanism). Overall, the hip actuated walkers tend to exploit compliance only a little, and achieve their walks mainly by their actuation.

Knee actuated walkers are rarely generated (i.e., three out of 100 seeds). Basically, the walker rotates the knee at the x axis, and does not fall over for 6 s.

Ankle actuated walkers are also hardly generated (i.e., 12 out of 100 seeds). Its walk exploits compliance: the ankle is actuated and, then, the compliance in the walker synchronously moves the hip, knee, and torso joints by the actuation.

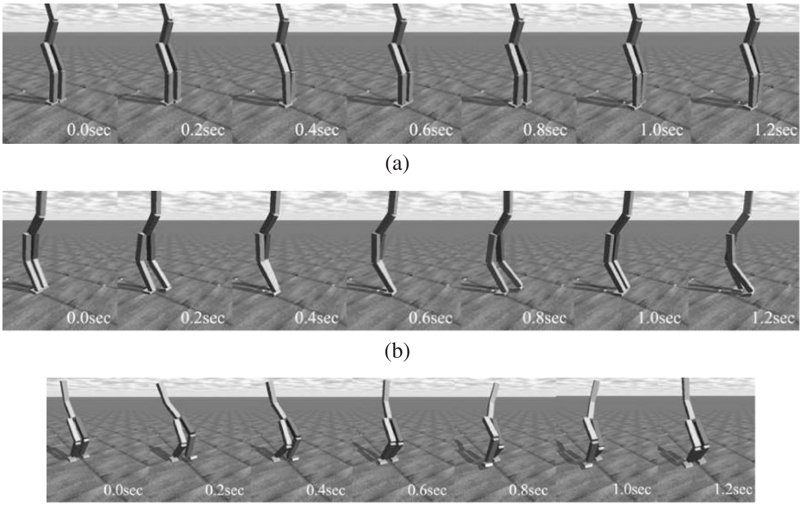


Fig. 5.8 Representative hip actuated walkers: (**a**) statically stable walk, (**b**) dynamically unstable walk, (**c**) dynamically stable walk

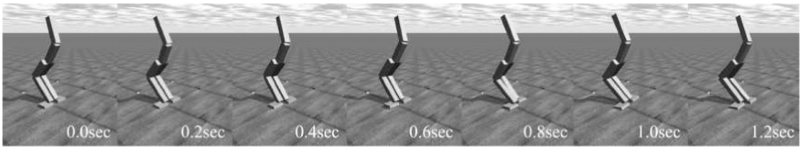


Fig. 5.9 Representative ankle actuated walker

Figure 5.9 shows the walking scene. It is observed that the physical structure of the walker is regarded as a laterally oscillating spring while walking. Thus, it indicates that compliance contributes to its stable walk.

Torso actuated walkers are produced as the second most common solutions (i.e., 29 out of 100 seeds). Figure 5.10 shows the representative walking scene. The walker transfers a torso oscillation (actuation) in the lateral plane to hip oscillations (compliance) in the sagittal plane by exploiting its joint structure and material properties and achieves stable walking.

Overall, we illustrated the relations between physical structures, distances traveled, and energy consumption; the best fitness from 100 independent evolutionary runs is plotted on a two-dimensional graph, see Fig. 5.11, where energy consumption is vertical axis, distance traveled is horizontal axis, and markers represent joint structures. It is characteristic that each type of walkers is distributed around a certain

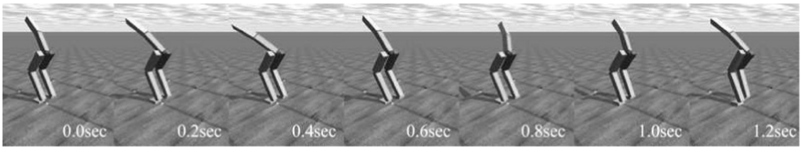


Fig. 5.10 Representative torso actuated walker

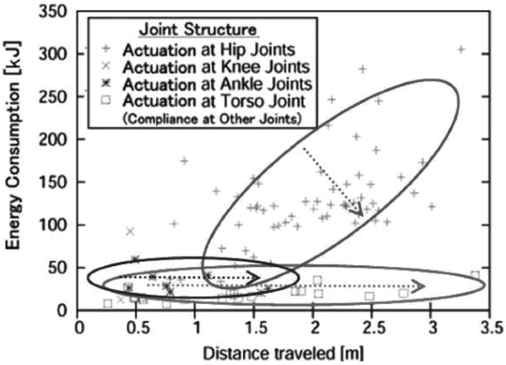


Fig. 5.11 A physical representation of embodiment. It illustrates the relations between joint structure, energy consumption, and distance traveled. *Circles* indicate distribution of four types of walkers, and *arrows* indicate the tendency of specific physical characteristics

area on the graph: the hip actuated walkers around the center; the knee actuated walkers around zero; the ankle actuated walkers around the left bottom; the torso actuated walkers around the bottom.

Table 5.9 Best performance of four types of walkers

Actuated Joint	Hip	Knee	Ankle	Torso
Number of best fitness (Total 100 seeds)	56	3	12	29
Max distance traveled [m] (For 6 s)	3.04	0.48 (fall)	1.62	3.42
Energy consumption [kJ] (For 6 s)	120.	–	25.	45.
Energy efficiency [kJ/m^{-1}]	39.4	–	15.4	13.1

Table 5.9 shows parameters of the best performance, that is, their distances traveled, energy consumption, and energy efficiencies, in each type. In terms of the rate of solutions generated, the evolutionary design generated hip actuated walkers the most. However, the torso and ankle actuated walkers achieved higher energy efficiencies (energy consumption divided by distance traveled), so the generating rate does not relate to the emergence of embodiment.

For physical features, higher fitness (i.e., distance traveled) of each walker tends to have a more specific physical feature:

1. The ankle actuated walkers have high compliance at hip for the sagittal rotation, knee and torso for the lateral rotation;
2. The hip actuated walkers have low compliance at knee, ankle, and torso (i.e., only the hip is joints with mobility);
3. The torso actuated walkers have high compliance at hip for the sagittal rotation, low compliance at knee and ankle (i.e., the thigh and shin are regarded as one link).

Figure 5.11 demonstrate the joint structures and material properties (special physical features) and distance traveled and energy consumption energy efficiency (evaluation of embodiment). We see that the walkers with the special physical features perform better in distance traveled and energy efficiency. That is, it indicates a physical representation of the embodiment, a mechanism for self-regulation.

5.4.5 Development of a Novel Pseudo Passive Dynamic Walker

The best embodiment in the representation (Fig. 5.11) illustrates a structure, which is high compliance at the hip, low compliance at the knee and ankle, and actuation at the torso, and which achieves stable locomotion by transferring actuation power from lateral oscillation at the actuated torso to sagittal oscillations at the compliant hip. Then, such biped robots are simplified, and a novel PPDW is designed as shown in Fig. 5.12 (left). Figure 5.12 (right) shows walking mechanism of the PPDW: it exploits its own physical features (i.e., actuation, gravitational, and inertial forces) for taking steps.

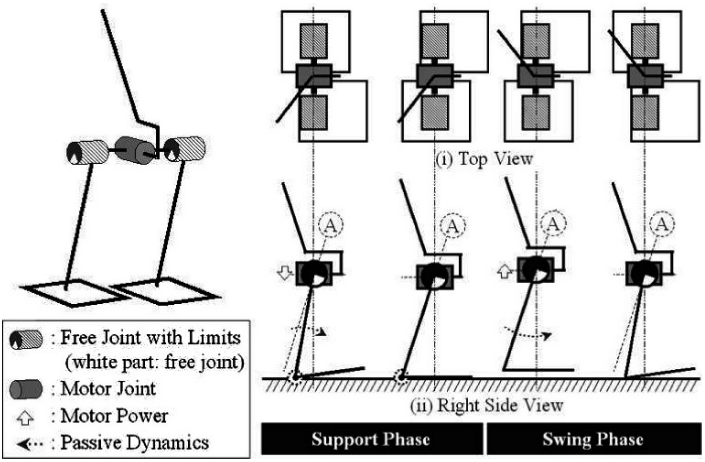


Fig. 5.12 A novel pseudo passive dynamic walker (PPDW)

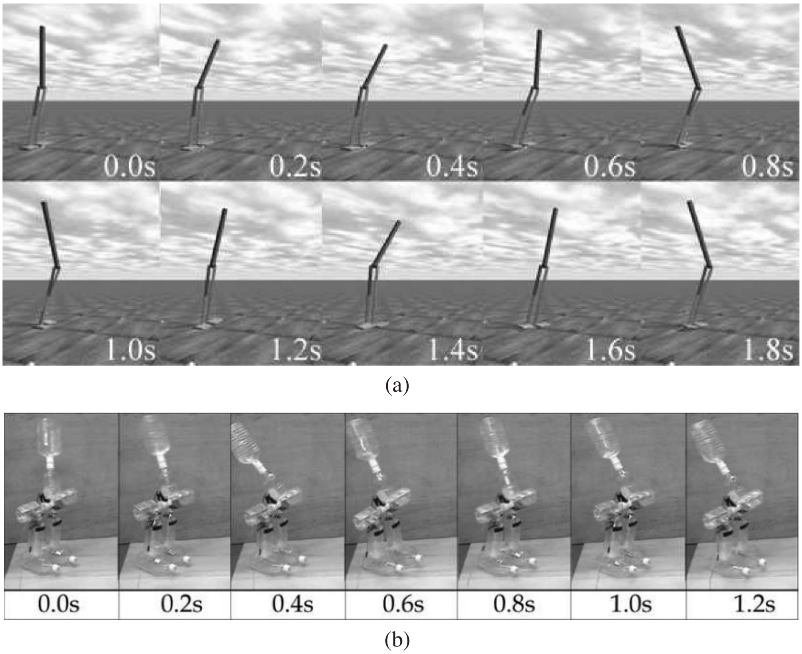


Fig. 5.13 Walk scenes of the PPDW: (**a**) virtual world, (**b**) real world

The PPDW is developed for the verification of the embodiment in both virtual and real world. The ODE is used for the implementation of virtual PPDW. A robotic development kit is applied for the development of real PPDW. The robotic development kit characterizes using plastic bottles as frames of robot structure, RC servomotors as actuated joints, and hot glues for connecting them [5]. This unique approach has advantages of shorting machining and building time and enabling easy assembly and modification for everyone. It is not for developing precisely operated robots but the kit is durable enough to realize the desired behavior.

As a result, the PPDW was developed in both virtual and real world, the PPDW achieved the desired stable locomotion (Fig. 5.13). It is significant that the real PPDW developed with the developmental kit that characterizes rough design, but it performed the desired locomotion. Therefore, the embodiment indicates high robustness, and low-cost stable locomotion on flat plane.

5.5 Conclusion

In this paper, we focused on self-regulatory functions of legged robots. We proposed a design process for emerging embodiment – an evolutionary design system – in the three-dimensional virtual world and it characterized the following:

1. A biologically reproductive process (i.e., coupled evolution of morphology and controller),
2. An interactive interface for designers to tune parameters, and
3. Evaluation methods of their embodiments for specifying their functions.

Then, we explored self-regulatory functions in various solution spaces representing morphological and control parameters. Eventually, the design system clearly illustrated a physical representation, and automatic motion adjustments (i.e., passive mechanism) were specified among the evolved robots: a torso oscillation in the lateral plane actuated passive hip joints. Such biped robots were regarded as novel pseudo passive dynamic walkers, and their self regulatory locomotion was investigated in both virtual and real world.

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