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Autonomously clearing obstacles using the biological flexor reflex in a quadrupedal robot

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SUMMARY

This paper suggests one possible mechanism for the biological flexor reflex by emulating a cat's behavior with its robotic counterpart, making it capable of walking around and clearing obstacles autonomously in various environments. A central pattern generator and a hip-to-knee mapping function are employed to realize basic rhythmic motion for a quadrupedal robot. When an input from a contact sensor on the robot's toe is detected, a patterned motion generated by the flexor reflex emerges depending on the location of the bumping phase, and replaces the ongoing rhythmic motion of that leg, causing it to be raised high enough to clear the obstacle. By restricting this reflex to within one cycle time of the walk and only to the bumping leg, rhythm and stability of motion are ensured. Numerical simulations and experimental implementation on a physical quadrupedal robot demonstrate the effectiveness of the proposed method.

KEYWORDS: Quadrupedal robot; Rhythmic motion; Clearing obstacle; Central pattern generator (CPG); Flexor reflex.

1. Introduction

Clearing obstacles is a basic requirement for a legged robot that is expected to perform in a real world where low-lying obstacles are very common. Various approaches have been developed to acquire such capability. A traditional artificial intelligence (AI) approach constructs a world model representing the environment with detailed parameters, and modularizes perception, modeling, planning, and execution to make adaptive responses emerge as a result of preprogrammed behavioral procedures. For example, the famous Honda humanoid robot walks upstairs. But the disadvantage of the AI approach is that it is largely unable to handle an unpredictable and changing environment due to slow reasoning and the complexity of representing a dynamic real world. Brooks proposed a behavior-based approach in which emergent behaviors of a robot are generated by many individual functional modules interacting with the environment based on sensory information. He designed a subsumption architecture consisting of eight augmented finite state machines (AFSMs) for a six-legged walking machine. When the robot met an obstacle, a leg-lifting AFSM was triggered to cause the leg to be raised high enough to clear the obstacle, based on the force change on its forward swing motor.[1] A behavior-based approach is more like the way living organisms interact with the world, but as Brooks noted as criticism in ref. [2], it is unprincipled and will not scale well. Kimura *et al*. achieved dynamic walking with obstructions to swinging legs, in a quadrupedal robot prototype, which when assisted by two track beams, was able to walk in a line, by employing the flexor reflex and the crossed extension reflex. These involved reflex torque change of joints and the modification of a few parameters in a neural oscillator network heuristically through experiments.[3] In further research, however, they addressed the challenge of clearing obstacles mechanically for a quadrupedal robot walking at a higher speed, by designing passive ankle joints that were relatively high off the ground, and which were capable of swinging back when bumping up against obstacles.[4] This kind of mechanical approach is not flexible enough to cope with obstacles that vary widely in height.

To summarize, the research described above dealt with the obstacle-clearing issue by employing either a carefully designed model of the world, or some rules derived from a living system. Since animals have long served as inspiration to robot design and control—their adaptability, flexibility of motion, and great variety of behaviors have made them the benchmarks for robot performance—we try to approach the problem by concentrating on the animal's behavior, and then building a link between the robot and its counterpart by emulating the animal's motion on it. It has been accepted by many scientists and engineers that an animal achieves its locomotive ability by employing a basic rhythmic motion controlled by a central pattern generator (CPG), and by using a variety of reflex activities, ranging from lower level unconditioned reflexes to higher level conscious responses.[5,6,7,8] When bumping into an obstacle, a stimulus from a tactile sensor in the foot triggers a flexor reflex, which makes the leg retract immediately and be raised high enough to clear the obstacle. In this paper, the biological flexor reflex behavior of a cat is investigated, modeled mathematically, and emulated on a quadrupedal robot. In response to an input from contact sensors attached to each toe, the carefully designed animal-like flexor reflex motion pattern replaces the ongoing CPG-generated rhythmic motion, as an emergent activity in the leg that encounters the obstacle, allowing the robot to clear obstacles autonomously in an uncertain environment.

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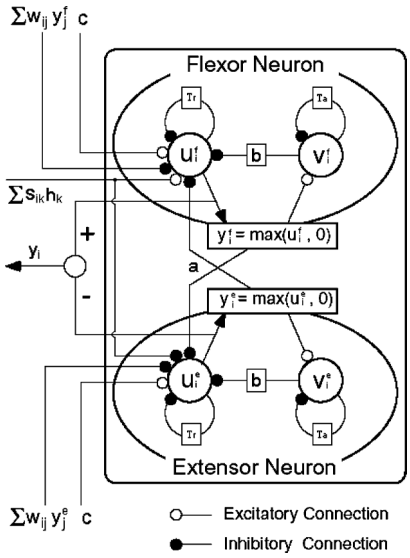


Fig. 1. Matsuoka's oscillator (revised from [3]).

2. Control of Rhythmic Motion

2.1. CPG model

Animals have rhythmic motion as a basic pattern for locomotion. It is believed that this rhythmic motion is controlled by CPGs, which are networks of neurons in vertebrate spinal cords and invertebrate thoracic ganglia, networks that are capable of generating rhythmic muscular activity in the absence of sensory feedback. A similar rhythmic motion and accompanying neural mechanism are employed simply, yet robustly, in some legged robots. We use a CPG model in Eq. (1), proposed by Matsuoka[9,10] and applied to bipedal simulation by Taga,[11] and a quadrupedal robot by Kimura *et al.*,[12] to control a quadrupedal robot. Matsuoka's oscillator consists of two reciprocally inhibited neurons, which correspond to a flexor neuron and an extensor neuron in animals, respectively (Fig. 1).

$$\begin{cases} T_r \dot{\mathbf{U}}^{f,e} + \mathbf{U}^{f,e} = b\mathbf{V}^{f,e} + a\mathbf{Y}^{e,f} + \mathbf{W}\mathbf{Y}^{f,e} + \mathbf{S}\mathbf{G}^{f,e} + c\mathbf{E} \\ T_a \dot{\mathbf{V}}^{f,e} + \mathbf{V}^{f,e} = \mathbf{Y}^{f,e} \\ y_i^{f,e} = \max\left(u_i^{f,e}, 0\right) \\ \mathbf{Y} = p(\mathbf{U}^f - \mathbf{U}^e) \\ \mathbf{U}^{f,e}, \mathbf{V}^{f,e}, \mathbf{Y}^{f,e}, \mathbf{Y} \in R^n, \quad \mathbf{W} \in R^{n\times n}, \quad \mathbf{S} \in R^{n\times m}, \quad \mathbf{G} \in R^m \\ \mathbf{E} = [\underbrace{1, 1, \ldots, 1}_{n}]^{\mathrm{T}}, \qquad i = 1, 2, \ldots, n. \end{cases} \tag{1}$$

where the subscripts and superscripts and the variables i, n, m, f, and e denote the ith oscillator, the number of oscillators, the number of sensing inputs, the flexor neuron, and the extensor neuron, respectively,

- **U** are the neuronal states,
- **V** represent the internal adaptability,
- b represent an adaptive coefficient,
- T_r is a rising time constant that determines the oscillation period,
- T_a is an adaptability time constant that characterizes the delay of the adaptability effect,
- c is the constant tonic input from higher levels that linearly determines the output amplitude,
- p functions as a regulating gain that makes the output amplitude equal c,
- $\mathbf{Y}^{f,e}$ and a are the neuronal output and an inhibition coefficient of the neuron–neuron coupling term, respectively,
- **W** is a gait matrix of the oscillator–oscillator coupling term, which represents the walking pattern of a legged robot,[13]
- **S** are sensing inputs of the feedback term,
- **G** are the reflex gains of the feedback term,
- **Y** are a set of stably oscillating outputs of the CPG, which are used as angular position control signals for a quadrupedal robot.

2.2. Knee function

For rhythmic movement, it is crucial to ensure a uniform and steady rhythm over the course of the whole motion. We meet this challenge by designing a knee control function that imitates a cat's well-evolved motion. In cat locomotion, it is observed that the hips move in a fixed relationship to the knees of the same legs. Put simply, the hip and the knee move synchronously during the swing phase, with the knee flexing to its limit position during the first half of the swing, and then extending back to its original position during the second half of the swing. During the stance phase, the hip swings backward and the knee is kept motionless. This relationship is formulated as a hip-to-knee mapping function as:

$$\begin{cases} \theta_k(t) = \begin{cases} \mathrm{sgn}(\psi)(A_h - |\theta_h(t)|)\mathrm{d}(t) & (\dot{\theta}_h \geq 0, \quad \text{swing phase}) \\ 0. & (\dot{\theta}_h < 0, \quad \text{stance phase}) \end{cases} \\ \mathrm{d}(t) = d_0\left(1 + \frac{|\theta_h(t)|}{A_h}\right) \\ \mathrm{d}_0 = A_k / A_h \\ \text{flag of joint style}: \psi = \begin{cases} -1, & (\text{knee}) \\ 1. & (\text{elbow}) \end{cases} \end{cases} \tag{2}$$

where θ_h and θ_k are the angular positions of the hip and the knee, respectively; A_h and A_k are the angular amplitudes of the hip and the knee, respectively; and d is the variable gain.

The sign function, $\mathrm{sgn}(\psi)$, is used to indicate the two types of joints found in quadrupeds and also in some legged robots, knee-style and elbow-style, which rotate in opposite directions at their hips and knees.

Through the mapping specified by Eq. (2), the hip control signals are turned into the knee control signals over time, so that a uniform rhythm is entrained in the whole system, and simplicity in multi-degree of freedom (DOF) control is guaranteed.

3. Clearing Obstacles Using the Flexor Reflex

Evolution has shaped the marvelous abilities of animals, allowing them to adapt remarkably well to their environments. To simplify the design of motion and to acquire a natural reflex pattern, we investigated a cat's flexor reflex behaviors, and emulated them in a quadrupedal robot, to make the robot clear obstacles autonomously in its environment.

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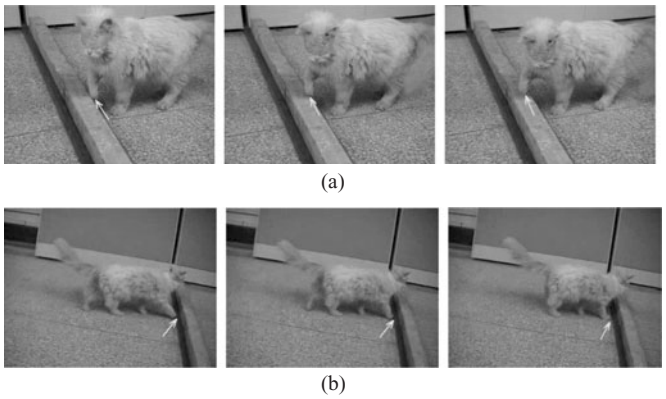


Fig. 2. A cat's flexor reflex. (a) bumping into a board during anterior swing. (b) bumping into a board during posterior swing.

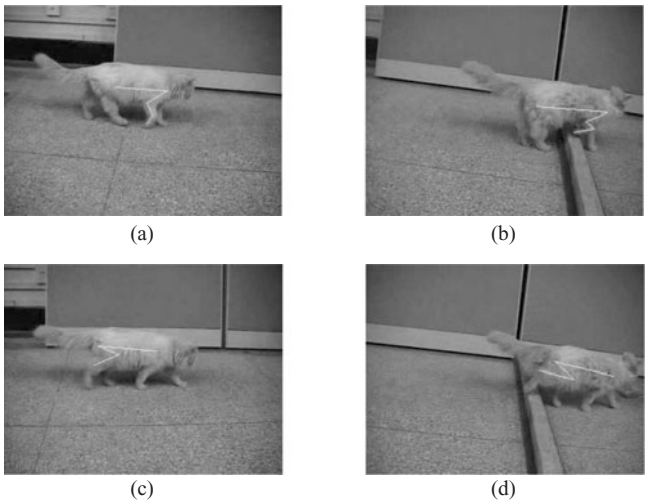


Fig. 3. A cat walking normally and clearing an obstacle. The lines in the pictures show the positions of its trunk and main segments of the leg being lifted. (a) Front leg in normal stride. (b) Front leg clearing obstacle. (c) Hind leg in normal stride. (d) Hind leg clearing obstacle.

3.1. Flexor reflex behavior of a cat

To quantify the flexor reflex behavior of cats, we conducted the following experiment[1]: covering the cat's eyes to prevent it from adapting using visual input, we recorded the cat's response to a wooden board that was placed before it as an obstacle. We found that the cat responded quite differently depending on when its leg bumped the board. When bumping the board during the anterior swing (AS), with enough time to respond, the bumping leg retracted slightly, then was raised up higher to clear the board (Fig. 2a). On the other hand, after bumping the board during the posterior swing (PS), the leg retracted a little more and touched down on the ground because the remaining swing time was too short to allow a complete stepover (Fig. 2b). Such different responses, relating to phase locations, can ensure a stable rhythm in motion by avoiding a reflexive response that conflicts with the basic movement.

The videos also showed that a cat stepped over an obstacle by flexing its leg like a scissor much more than normal, to achieve a higher foot clearance (Fig. 3). Such a finding gives clues for the design of the quadrupedal robot's motion.

3.2. Modeling the flexor reflex

Inspired by the cat's behavior, we developed three rules to design the robot's flexor reflex:

(a) Addressing the flexor reflex differently depending on the bumping phase location.
(b) Flexing the leg much more to clear the obstacle.
(c) Only the bumping leg should respond, and the other legs should continue their normal motion, to keep the whole rhythm unchanged in the robot.

Based on these rules, the quadrupedal robot's flexor reflex is designed to have two patterned motions responding dependently on the bumping phase location.

3.2.1. Determining the bumping phase location. Provided a bump happens to a swinging leg at t_0, i.e., Point I in Fig. 4, y_0, the output of the leg at the very time, is recorded and is looked up in a prestored list of the swing-phase data of the CPG, that is, the increasing segment of the curve, to determine whether the bump occurs in anterior swing (AS) or posterior swing (PS), which are segmented by zero, and calculate the reflex time, T_{ref}, as the rest of the swing time.

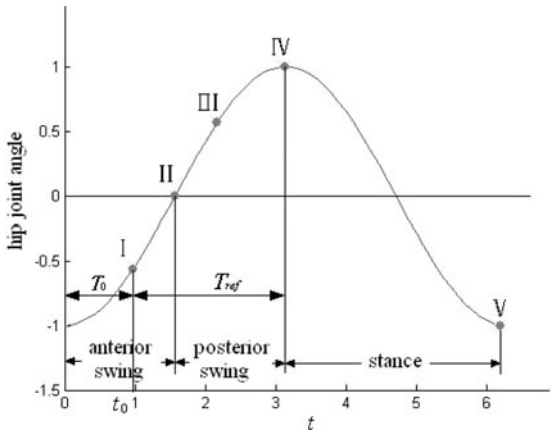


Fig. 4. Phase definition of a one-period CPG output.

3.2.2. Bumping during anterior swing. According to Section 3.2 Rule (c), the flexor reflex acts only on the bumping leg. When a leg bumps into an obstacle during AS, the reflex time is divided into three stages: retracting, stepping over, and touching down, namely, the AS-pattern:

1. *Retracting:* The hip output decreases linearly to make the leg retract, while the knee output increases for the elbow-style joint or decreases for the knee-style joint, to ensure that the hip and the knee flex like a scissor to lift the foot.
2. *Stepping over:* The hip output increases linearly to make the leg swing forward, while the knee remains stationary, to step over the obstacle.

[1] The use of the cat in the experiments was done in accordance with *the U.S. Government Principles for the Utilization and Care of Vertebrate Animals Used in Testing, Research, and Training.*

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3. *Touching down:* The hip keeps swinging, and the knee returns to its normal peak phase-switch position, i.e., the phase location of Point IV in Fig. 4.

The AS-pattern is represented discretely as:

$$
\begin{aligned}
&y_h(x+1)\\
&=\begin{cases} y_h(x)+\dfrac{Q_h}{T_1}\Delta t, & (t_0<t\le t_0+T_1)\\ y_h(x)+\dfrac{A_h-(y_0+Q_h)}{T_{ref}-T_1}\Delta t, & (t_0+T_1<t\le t_0+T_{ref}) \end{cases}\\
&y_k(x+1)\\
&=\begin{cases} y_k(x)+\dfrac{Q_k}{T_1}\Delta t, & (t_0<t\le t_0+T_1)\\ y_k(x), & (t_0+T_1<t\le t_0+T_1+T_2)\\ y_k(x)+\dfrac{0-(y_0+Q_k)}{T_3}\Delta t & (t_0+T_1+T_2<t\le t_0+T_{ref}) \end{cases}.
\end{aligned}
\tag{3}
$$

$$
\begin{aligned}
&Q_h=-\gamma_h A_h,\quad Q_k=\mathrm{sgn}(\psi)\gamma_k A_k,\quad t=x\Delta t,\\
&T=T_{sw}+T_{st},\quad T_{sw}=(1-\beta)T,\\
&T_{ref}=T_{sw}-T_0=T_1+T_2+T_3,\quad T_1=\lambda_1 T_{ref},\\
&T_2=\lambda_2 T_{ref}.
\end{aligned}
$$

where

h	hip,
t_0	bumping time,
k	knee,
y_0	the output of the bumping hip at t_0,
sw	swing,
T	the cycle time of the walk, i.e., the period of the CPG,
st	stance,
T_{ref}	the period of the reflex time,
x	sequence number,
T_0	the period of time from the stance-to-swing phase-switch point to t_0 as shown in Fig. 4,
y	joint output,
T_1	the period of time of retracting,
Q	retracting change,
T_2	the period of time of stepping over,
γ	retracting change gain,
T_3	the period of time of touching down,
β	duty factor,
λ_1	the proportion of the retraction stage to the reflex time,
Δt	calculating step,
λ_2	the proportion of the stepping-over stage to the reflex time,
t	current time.

Provided the quadrupedal robot has elbow-style joints in its front legs and knee-style joints in its hind legs, and is moving in trot gait,[13] using the parameters values listed in Table AI, an AS-pattern flexor reflex numerical simulation is shown in Fig. 5. Bumping an obstacle at $t = 1.48$ s, Leg LF (left front) reflexes immediately with its hip output decreasing and its knee output increasing (Fig. 5b), to lift the leg with the foot clearance from the original 0.011 to 0.039 m (Fig. 5c). Other legs, including the two supporting legs and the opposite swinging leg, move as usual (Fig. 5a), to keep the whole motion rhythm unchanged and the body center of the robot barely swaying.

Table AI. Parameters values used in the paper [si: simulation, ex: experiment]

Parameter	Value	Parameter	Value	
W	$\begin{bmatrix} 0 & -1 & 1 & -1\\ -1 & 0 & -1 & 1\\ 1 & -1 & 0 & -1\\ -1 & 1 & -1 & 0 \end{bmatrix}$	β	0.5	
		λ_1	1/3	
		λ_2	1/3	
			si	ex
a	-1.0	γ_h	1.5	5.0
b	-2.0	γ_k	1.0	6.0
c	A_h (rad)	A_k	13°	5°
p	0.18	T	0.8 (s)	1.6 (s)
A_h	13.4°	T_r	0.04	0.08
Δt	0.012 (s)	T_a	0.38	0.80

3.2.3. Bumping during posterior swing. According to the motion investigation of the cat in Section 3.1,when bumping an obstacle during PS, the leg retracts and touches down directly on the ground instead of stepping over the obstacle, namely, PS-pattern. The motion pattern occurs as follows: the hip of the bumping leg decreases linearly to the valley phase-switch point, i.e., the point V in Fig. 4, during the reflex time, then remains stationary until the beginning of the next swing. The knee does not reflex. PS-pattern is represented discretely as:

$$
\begin{aligned}
&y_h(x+1)\\
&=\begin{cases} y_h(x)+\dfrac{-y_0-A_h}{T_{ref}}\Delta t, & (t_0<t\le t_0+T_{ref})\\ y_h(x), & (t_0+T_{ref}<t\le t_0+T_{ref}+T_{st}) \end{cases}.
\end{aligned}
\tag{4}
$$

where T_{st} is stance time, which equals swing time as for the trot gait with duty factor of 0.5.

A PS-pattern flexor reflex numerical simulation is shown in Fig. 6. Bumping an obstacle at $t = 1.65$ s, Leg LF (left front) retracts immediately with its hip output decreasing and its knee output remaining unchanged, and then touches down to be in stance. Other legs move as usual.

4. Experiment

4.1. Quadrupedal robot

We constructed a quadrupedal robot, Biosbot (Biologically Inspired Robot), to perform in the real world. Each leg of the robot has three joints: hip, knee, and ankle, with one pitching DOF. Hips and knees are active joints driven by DC motors.

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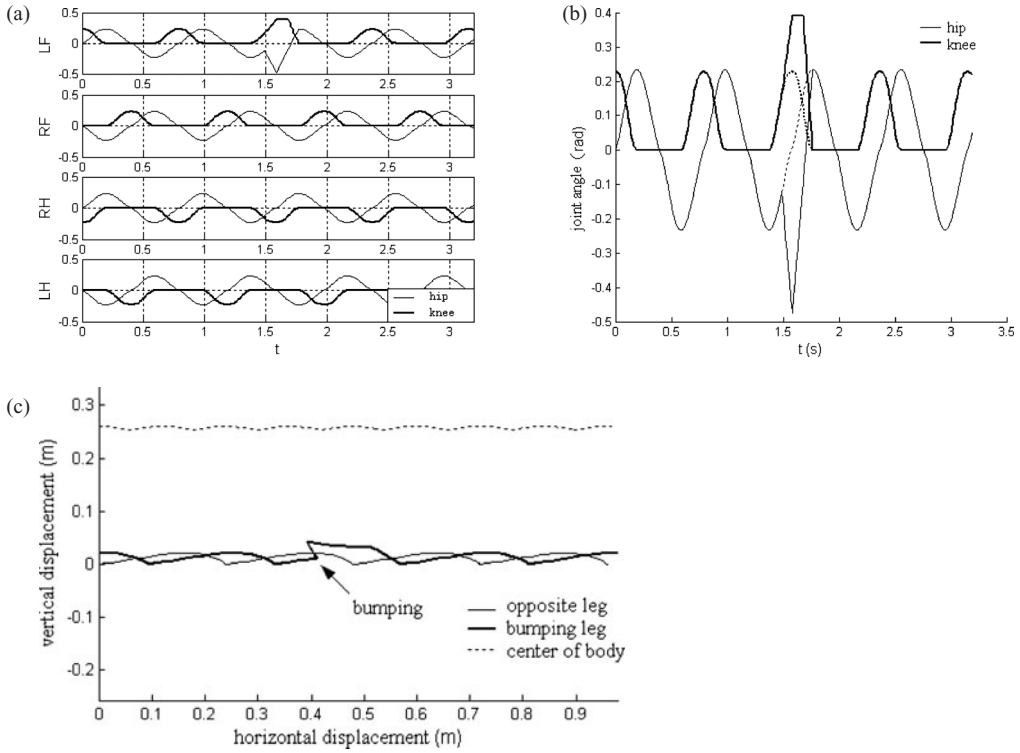


Fig. 5. AS-pattern flexor reflex simulation. (a) CPG outputs of the quadrupedal robot. L, R, F, H is left, right, front, hind leg separately. (b) Outputs change of the bumping leg. Dotted lines are the original outputs and solid lines are the reflexing outputs. (c) Trajectories of the body and the feet of the robot. The opposite leg is the one out of phase with the bumping one.

Ankles are spring damper passive joints. All joints can rotate up to 180°. The robot is equipped with these sensors: a photo encoder on each joint; contact switches on the toe of each leg to detect obstacles; and pitch and roll inclinometers on the trunk to acquire inclination of the terrain and sense the smoothness of the performance. The robot has dimensions of 400 mm × 320 mm × 300 mm, and a mass of 5.7 kg, as shown in Fig. 7.

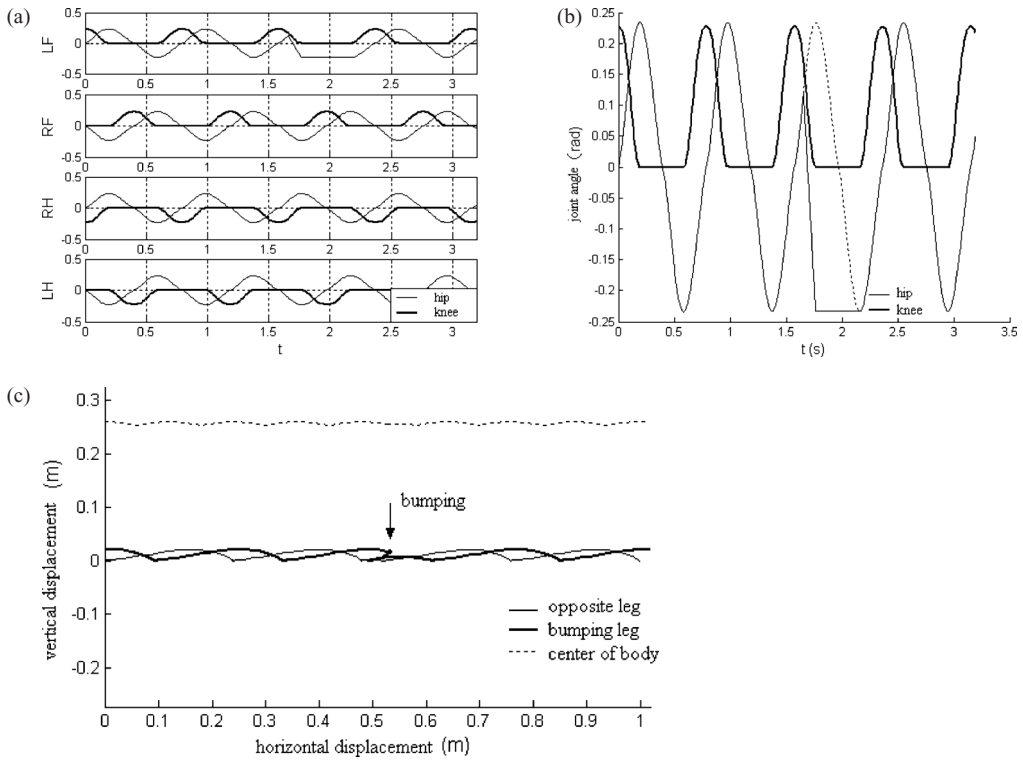


Fig. 6. PS-pattern flexor reflex simulation. (a) CPG outputs of the quadrupedal robot. (b) Outputs change of the bumping leg. (c) Trajectories of the body and the feet of the robot.

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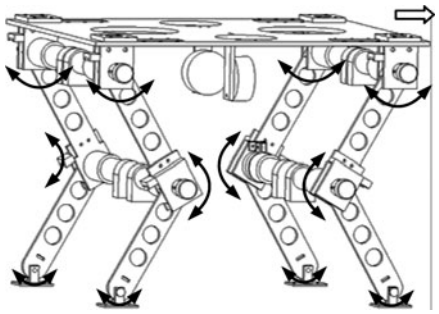


Fig. 7. Mechanical draft of the quadrupedal robot, Biosbot.

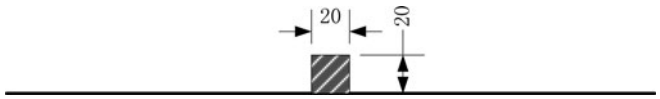


Fig. 8. The obstacle used in experiments.

4.2. Experimental implementation

A long bar with cross section of 20 mm × 20 mm, is placed in the experimental environment as an obstacle (Fig. 8). The location of the bar is unknown to the robot, so that the swinging leg can bump on it at any phase location.

We controlled Biosbot by combining the flexor reflex models in Eqs. (3) and (4) with the basic rhythmic generator in Eq. (1) and the hip-to-knee mapping function in Eq. (2). Biosbot walked around in the environment with the obstacle of uncertain location. Seen from Figs. 9a and 10 Frame 1–9, Biosbot executed proper flexor reflex when its right front leg bumped the bar under two different situations. At $t = 35.2$ s, Leg RF bumped the obstacle during PS (Fig. 10, Frame 2), and a PS-pattern was triggered. With its hip output decreasing and its knee output unchanged, Leg RF retracted and touched down on the ground (Fig. 10, Frames 2 and 3). At $t = 36.0$ s, Leg RF bumped the obstacle again, but during AS (Fig. 10, Frame 4), an AS-pattern was triggered. With its hip output decreasing and its knee output increasing, Leg RF retracted and lifted its foot to step over the obstacle (Fig. 10, Frames 4–9). With other legs moving as usual, the robot kept its normal motion rhythm during the stepover and did not topple over, due to the swift response. From Fig. 10 Frame 6, we can also see that the foot clearance of the bumping leg is much higher than the bar. That implies Biosbot can clear a bar higher than 20 mm, whereas control experiments without such flexor reflex employed showed that it failed to clear an obstacle 20 mm high. A similar flexor reflex and obstacle clearance on the right hind leg under the two situations are shown in Figs. 9b and 10 Frames 10–18.

5. Conclusion

In this paper, we modeled the flexor reflex for a quadrupedal robot to autonomously clear obstacles blocking its path, by designing two kinds of reflex patterns through imitating a cat's flexor reflex behavior. Control simplicity and swift response are achieved because the flexor reflex motion patterns are designed linearly and discretely. By restricting the flexor reflex influence to only the bumping leg, and to within one cycle time of the walk, rhythm and stability of motion are ensured. The experiments have proved, with the flexor reflex, that the quadrupedal robot can successfully clear obstacles whose locations have not been communicated to the robot, whereas without the reflex the robot fails to clear the obstacles. The flexor reflex designed here is similar to a lower level reflex in animals, which emerges inherently as a rapid and fixed activity, while not interfering with the basic rhythmic motion. The ability of the biological flexor reflex to allow a quadrupedal robot to clear obstacles has implications toward both the fundamental understanding of the control of adaptive motion in animals and practical realizations of legged robots for use in real world applications.

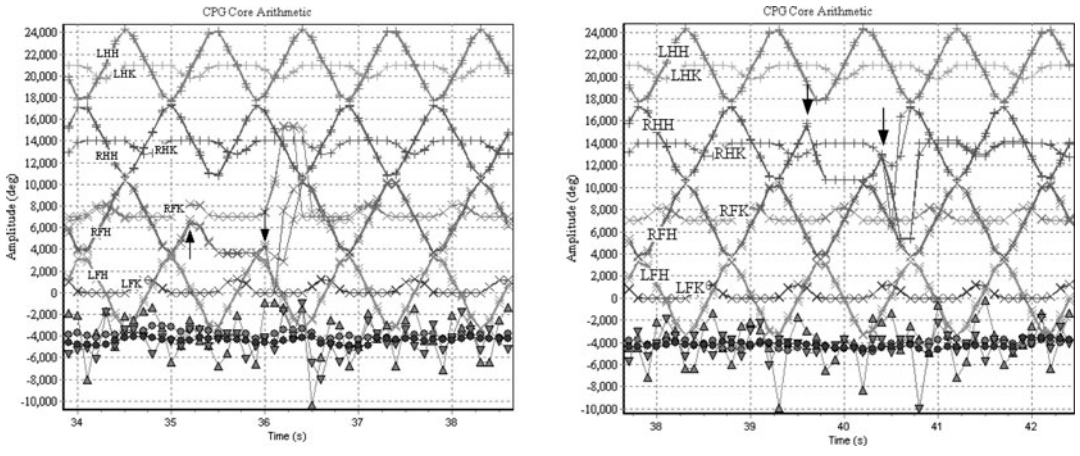


Fig. 9. Actual flexor reflex output curves of Biosbot clearing an obstacle. (a) Right front leg. (b) Right hind leg.

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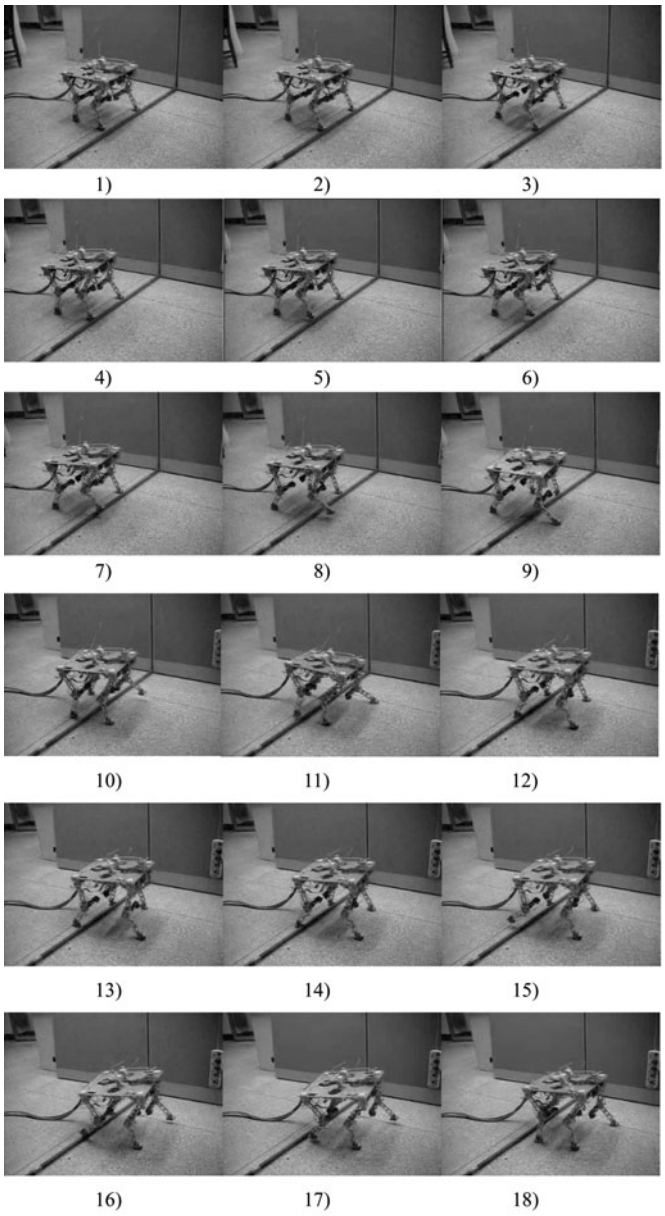


Fig. 10 Videos of Biosbot clearing an obstacle. Frames 1–9: right front leg. Frames 10–18: right hind leg.

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