The 2010 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 18-22, 2010, Taipei, Taiwan

Facilitating Multi-modal Locomotion in a Quadruped Robot utilizing Passive Oscillation of the Spine Structure

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Abstract— **An important topic in robotics is the design of a robot body using passive mechanical properties, such as viscoelasticity, to obtain energy-efficient locomotion at low computational costs. To achieve this aim, this study examines adopting a spinal structure with variable viscoelasticity and multiple joints. In order to investigate the effect of this spinal structure, a physical model of the spinal structure and a quadruped robot incorporating this design were developed, and the relationship between the gait pattern of the legs of the robot and viscoelasticity as a source of passive oscillation of the spinal structure was observed. The experimental results indicate that there are several interactions between the gait pattern and the viscoelasticity that can achieve one of various types of successful locomotion. These results suggest that the proposed spinal structure is a suitable body design for facilitating multi-modal locomotion at low computational costs.**

I. INTRODUCTION

One of the problems with developing legged locomotors is achieving animal-like locomotion that is energy-efficient and has low computational costs. Although there has been much discussion about designing controllers that provide stable locomotion for bipedal robots [1] or adaptive gaits utilizing camera images or motion capture data [2], [3], these methods generally entail high computational and energy costs. In contrast, there has been little discussion regarding the design of the robot body. *Passive mechanisms*, such as viscoelastic or free joints driven passively by external forces, are important candidates for providing successful, energy-efficient locomotion at low computational costs. Generally, it is difficult to control systems that include passive mechanisms, and these systems have high energy and computational costs. However, we have achieved an example of a passive mechanism that contributes successfully to locomotion at low costs. The passive dynamic walker, a bipedal walker with passive joints [4], does not require any computational cost to plan the trajectories of the joints or energy cost to follow planned trajectories due to well-designed physical characteristics, such as the placement of its center of mass and inertia of the links . Some other studies have achieved energy-efficient walking using bipedal walkers based on the passive dynamic walker [5], [6]. These studies suggest that a consideration of the robot body design will provide more energy-efficient locomotion at lower computational costs. In particular, the appropriate design and arrangement of the passive mechanism may be the key issue to achieving a proper design.

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In the research field of multi-legged locomotion, quadruped locomotion in this study, it is assumed that body designs taking into consideration passive mechanisms will play an important role. One of the challenging issues for quadruped robots is achieving multi-modal locomotion, which includes walking, trotting, and crawling. As Hoyt et al. described, a living horse switches between types of locomotion, such as walking, trotting, and galloping, according to the velocity of its movement in order to minimize the amount of the energy consumption over the distance traveled [7]. There have been many studies conducted with the goal of realizing multi-modal locomotion. Almost all of these have focused on the design of the controllers to drive the leg joints. Many studies adopted the central pattern generator (CPG) model [8], [9], which uses a controller that imitates a living nerve system to plan leg joint trajectories [10], [11], [12]. Although these approaches obtain lower computational costs due to the small set of parameters, almost all of them do not obtain animal-like dexterous multi-modal locomotion.

In this study, we discuss the body design of a quadruped robot with a focus on the design of the torso. The torso of the quadruped acts as a beam between the forelegs and hind legs. The behavior of the torso, along with leg motion, affects the feasibility of any locomotion. A necessary condition for the leg motion to realize multi-modal locomotion is that the footfall pattern depends on the type of locomotion. The function of torso motion is to achieve the appropriate posture for the footfalls. Therefore, individual legs should swing periodically with certain phase differences to each other, and the torso should oscillate according to the gait pattern of the four legs. It is expected that many types of locomotion can be obtained by appropriate pairings of the gait pattern of the four legs and the torso oscillation. There have been some studies on torsos with the multiple joints necessary to obtain such oscillation, and, as in the cases of planning leg joint trajectories, these focus on the design of the controller driving the individual joints of the torso. For example, CPG can also be used to plan the trajectories of the torso joints [13], [14].

We then propose a novel design that uses the characteristics of passive mechanisms to obtain multi-modal locomotion with lower energy and computational costs than present quadruped robots that have the multi-joint torsos. As seen in animal torsos, spinal structures that have multiple rigid vertebrae and elastic intervertebral discs are supported by viscoelastic muscles. It is not natural to see that torso is actively oscillated by the activation of individual muscles; rather, it is passively oscillated by landing impact by means of a variety of viscoelastic elements tuned by the degree of muscle co-contraction. It has been reported that passive joint oscillation can be controlled by changing the viscoelasticity [15], and it is effective to adopt such a variable viscoelasticity to realize torso oscillation that depends on the type of the locomotion, without any additional energy or computational cost. Therefore, in this study, we adopted a spinal structure whose viscoelasticity can be mechanically varied and built a quadruped robot with its four legs driven by servo motors. The purpose of this paper is to explain how it is possible to achieve successful locomotion by selecting appropriate pairings of gait pattern and spinal viscoelasticity. The spine can be oscillated passively without any actuation on the spinal joints. Although some prior studies have adopted animal-like spinal structures [16], the spines in these studies are driven by actuators, and, to our knowledge, there has been no prior research in the effect of using a spinal structure with a passive mechanism. In particular, the aim in our study is to show the effect of a passive mechanism, and we expect that effective quadruped locomotion can be achieved by combining an appropriate actuation of the leg joints with a well-designed body. In the next section, the specifications of the developed spinal structure and quadruped robot are introduced, and then the experiment is explained in the section that follows.

II. Design of the quadruped robot

The developed quadruped robot is shown in Figure 1. It is 340 mm long, 96 mm high, 285 mm wide, and weighs 550 g. The robot has a spinal structure made of chemical wood and silicone, and it has four servo motors to swing its legs. This section introduces the details of the spine and actuation.

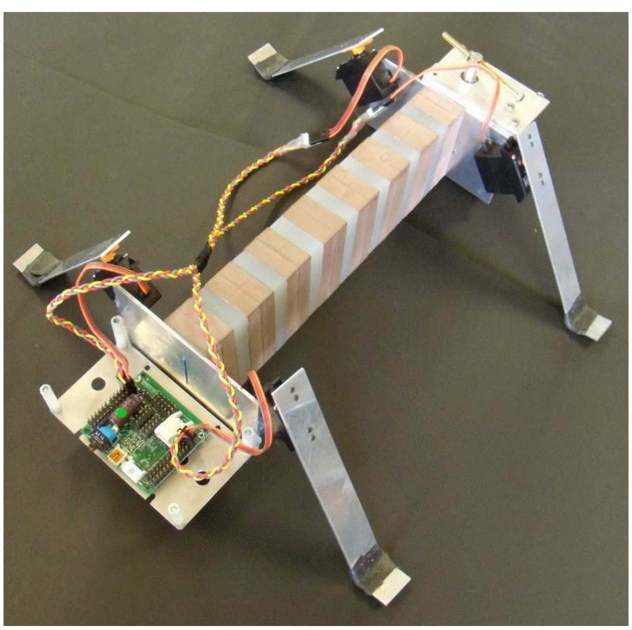

Fig. 1. Developed quadruped robot

A. *Spine structure*

One of the key types of mechanisms to discuss in robot body design for locomotion is the use of passive mechanisms that are affected by external forces, such as landing impact and kicking force against the ground by the legs. It is important to clarify the passive elements embedded in the body design, and to tune the physical properties of the body to use these elements for energy-efficient locomotion with low computation costs. In this paper, we focus on 2D passive oscillation of the spinal structure to achieve such efficient locomotion. Figure 2 shows the developed spinal structure. The spine has rigid blocks as vertebra and elastic discs as the intervertebral discs. The blocks are made of chemical wood. They are each 30 mm wide, 60 mm high, and 20 mm thick. The centers of both sides are recessed by 5 mm. The discs are made of silicone. They are 30 mm wide, 60 mm high, and 10 mm thick. The Young's modulus of these intervertebral discs is about 55 KPa. In order to prevent them from falling off, each disc has a boss at the center to insert in the recessed portion of a block. The aim of this study is to observe the behavior of locomotion utilizing 2D passive oscillation. The height of the blocks and discs of the spine was chosen longer than their width to minimize bending in the direction of the gravitational force. Eight blocks and seven discs form a spine a total of 231 mm in length. The spine is so simple that it does not have any mechanical joint structures but has flextion by deforming the intervertebral discs. It is easy to add additional vertebrae and intervertebral discs.

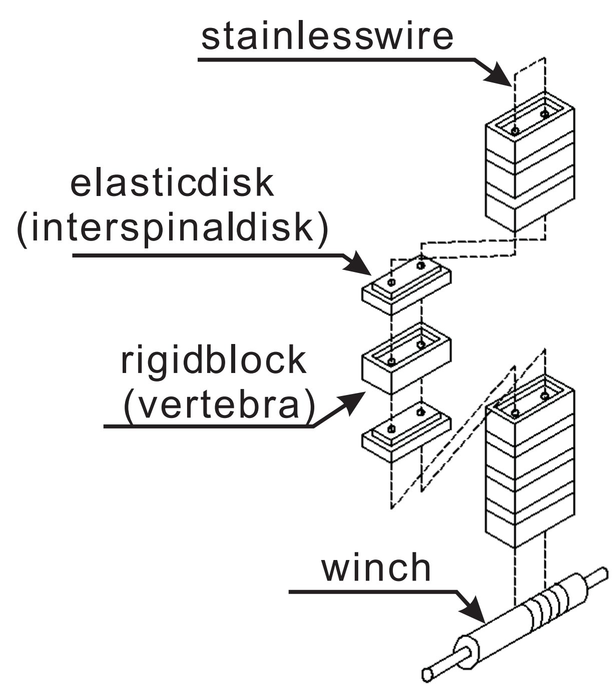

Fig. 2. Schematic design of the spinal structure

When the discs are compressed by the tensile force of a winch and stainless wire, the viscoelasticity is changed, changing the physical properties of the spinal structure according to the compressive force applied along the longitudinal direction of the spine. Figure 3 shows the relationship between the compressive force and the spine length. This study treats this correlation as a linear relationship, and, using the least squares method, expresses it as a linear equation, for example:

$$L = -0.06F + 230.4, \quad (1)$$

where L is the spine length, and F is the reductive force. The units of L and F are millimeters (mm) and newtons (N), respectively. We can see various oscillations according to the amount of compressive force (see the attached video).

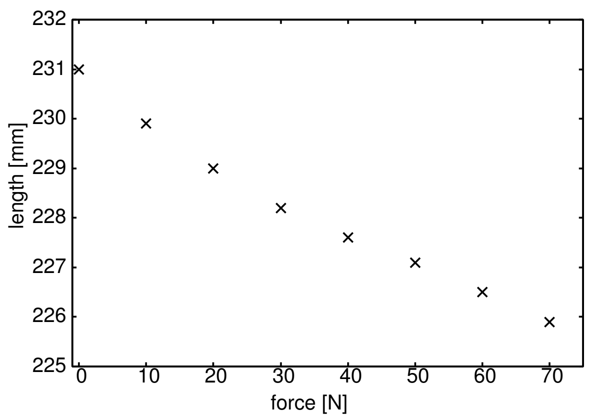

Fig. 3. Relationship between the reductive force and the spine length

As shown in Figure 2, the rigid blocks and elastic disks have holes, and a stainless wire is passed through these holes. The end of the wire is rolled up by a winch, and the tensile force, which corresponds to the compressive force on the spine, can be changed according to the rotational angle of the winch. The tensile force is determined by the relationship between the force and the spine length, as described in Equation (1). In the rest of this paper, we will refer to the blocks and discs using only the terms "vertebra" and "intervertebral discs", respectively.

B. Actuation

Four servo motors (GWM, Micro2BBMG) are attached at the bases of the limbs, at what correspond to the shoulders and hip joints in an animal body. The robot does not have knee or elbow joints. The motors are controlled by the controller (VStone, VS-RC003HV), which has an external power supply, to follow planned trajectories. In order to generate swaying force for the passive oscillation of the spine, the rotational joints are not horizontal relative to the ground but have some slant. Figure 4 shows the angle between the horizontal axis and the motor joint. The absolute value of the angle ξ in the figure is approximately 0.7 rad.

Figure 5 shows a schematic mechanism to generate the swaying force for the spine oscillation. In the figure, the anti-clockwise direction is designated as positive. Angle θ is the joint angle of the servo motor. The origin of the angle ξ is parallel to the ground, and the origin of θ is relative to the intersection of the frontal plane of the robot and the

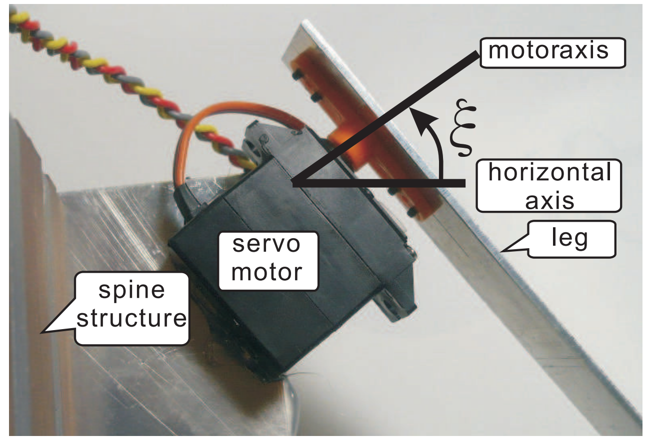

Fig. 4. Angle between horizontal axis and motor joint

plane in which the attached foot swings, plane A-A' in the figure. For the case $\xi > 0$, from the coodinate system fixed on the shoulder shown in the Figure 5, the foot position $(x_f, y_f, z_f)^T$ is calculated as

$$\begin{pmatrix} x_f \\ y_f \\ z_f \end{pmatrix} = \begin{pmatrix} l \sin\xi \cos\theta \\ l \sin\theta \\ -l \cos\xi \cos\theta \end{pmatrix}, \quad (2)$$

where l is the length of the foot. Utilizing pseudo-inverse Jacobian matrix from Equation (2), swaying force F_{sqay} is calculated as

$$F_{sway} = \begin{cases} -\frac{\tau}{l} \sin\xi \sin\theta \ (\text{if } (\theta < 0, \tau > 0)\text{or}(\theta > 0, \tau < 0)) \\ 0 \quad (\text{else}) \end{cases}, \quad (3)$$

where τ is the torque of the servo motor. This equation indicates that the swaying force is determined by the angle of the servo motor (ξ) and the angle of the swing leg (θ).

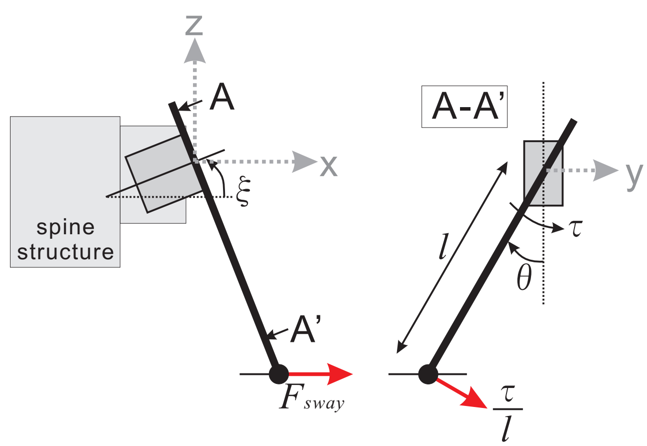

Fig. 5. Mechanism to generate the swaying force F_{sway} necessary to oscillate the spine

III. Experiment

A. Experimental setup

In order to observe the pairings of the physical properties of the spinal structure and the gait pattern of the four legs, we observed the correlation between the compressive force (F) mentioned in the previous section and the planned trajectories of the four legs discussed below. The trajectories are indicated by triangular waves with phase differences between a foreleg and hind leg. In order to walk forward, the trajectory has an offset. Figure 6 shows trajectories for the same side of the foreleg and hind leg. The offset, the amplitude, and swinging cycle for each leg are 1/18π rad, 1/18π rad and 0.33 sec $\simeq$ 3 Hz, respectively. A parameter ϕ expresses the phase difference between the hind leg and the foreleg. For example, the right or left foreleg swings earlier than that of the hind leg when $\phi > 0$. There are some types of combinations of phase differences that include not only that between a foreleg and hind leg (ϕ) but also that between the left and right legs; such combinations determine different types of locomotion, for example, crawling, trotting, and running [17]. In this study, as a first step to observe pairings of the physical properties of the spinal structure and the gait pattern of the four legs, the phase difference between the right and left forelegs and hind legs is fixed at π rad. By changing the compressive force (F) that controls the physical properties of the spinal structure and the phase difference between the foreleg and hind leg (ϕ), the gait pattern can be determined and the resulting locomotion observed. The schematic arrangement of the parameters is shown in Figure 7.

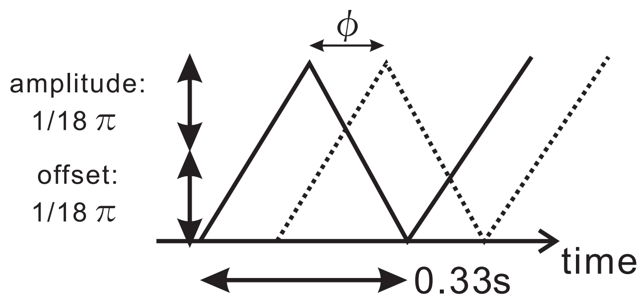

Fig. 6. Leg trajectories for same-side foreleg and hind leg

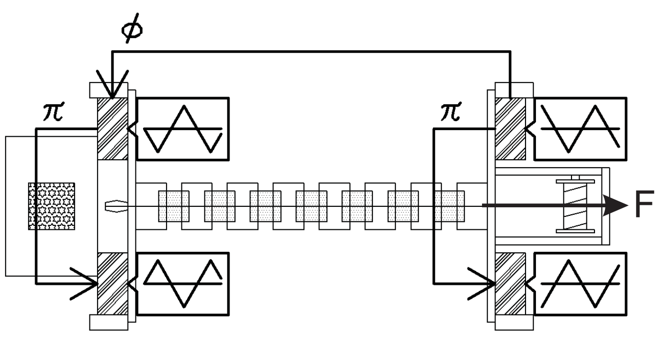

Fig. 7. Schematic arrangement of the parameters F and ϕ in the experimental setup

Figure 8 shows sequential pictures of locomotion in one trial. The robot successfully walked when F = 40 N and ϕ = -0.4π rad, walking 0.2 m in 18.86 s. This period was measured as an average in 10 trials. The velocity is then calculated by dividing the distance, 0.2 m, by the average walking period. The velocity in this set of trial was 0.0106 m/s. In the figure, the left side of each picture is the walking direction. The frame rate of the pictures is 15 frames per second, and so one cycle of the triangular wave pattern of the leg movements corresponds to just under 5 frames. The numbers in the upper left of the pictures are the frame numbers. The symbols ◯, △, and □ shown in frames 4 to 9 indicate the positions of the centers of the first, fourth, and last vertebrae. Note that these marks are set subsequently by hand based on the pictures in order to show the passive oscillation of the spine, and so these marks do not indicate the exact positions of the centers of the vertebrae. These pictures show that the spine passively oscillates according to the motion of the four legs. For example, the spine is almost straight in frame 4, and then the spine is bent to left with respect to the direction of locomotion in frame 5, straight again in frame number 6, and then bent right in frames 7 and 8. The most remarkable aspect of this locomotion is that the vertebras are not driven by any actuators but passively oscillated determined by the swaying force expressed in Equation (3) and the timing of the landing impacts.

In the experiment, the velocities of sets of 10 trials, each covering 0.2 m of walking, were recorded and the average calculated. The compressive force (F) was varied from 10 N to 70 N in steps of 10 N, and the phase difference (ϕ) was changed from -0.8π to 1.0π in steps of 0.2π.

B. Result

Table I shows the average velocities of walking 0.2 m by compressive force (F) and phase difference (ϕ), where the units are meters per second (m/s) and "-" indicates that the robot could not complete the walking goal within 180 s. When ϕ is zero (i.e., the foreleg and hind leg on the same side swing together), the spine does not oscillate much. On the other hand, when ϕ is more or less than zero, the spine oscillates. At every trial with the same fixed F and ϕ, the velocity was almost same, and so the gait is reproducible; that is, the locomotion always either succeeds or fails, according to F and ϕ. Figure 9 shows a 2D map based on Table I. Grid cells are brighter for higher walking velocities and darker for lower velocities. The settings for which the robot could not walk are indicated by black. Overall, the velocities were quite low because the legs drag on the ground while swinging. The velocities with different leg structures that avoid dragging will be measured in future studies. Setting aside the low velocities, this map shows some interesting phenomena important for developing quadruped robots. When $\phi < 0$ (i.e., the foreleg swings later than the same-side hind leg), the compressive force on the spine should be less to achieve successful locomotion. When ϕ is close to zero, the robot can walk faster for any amount of compressive force on the spine. When $\phi > 0$, the force should be greater. This result shows that the appropriate pairings of F and ϕ facilitates locomotion, and, considering that the type of the locomotion is determined by

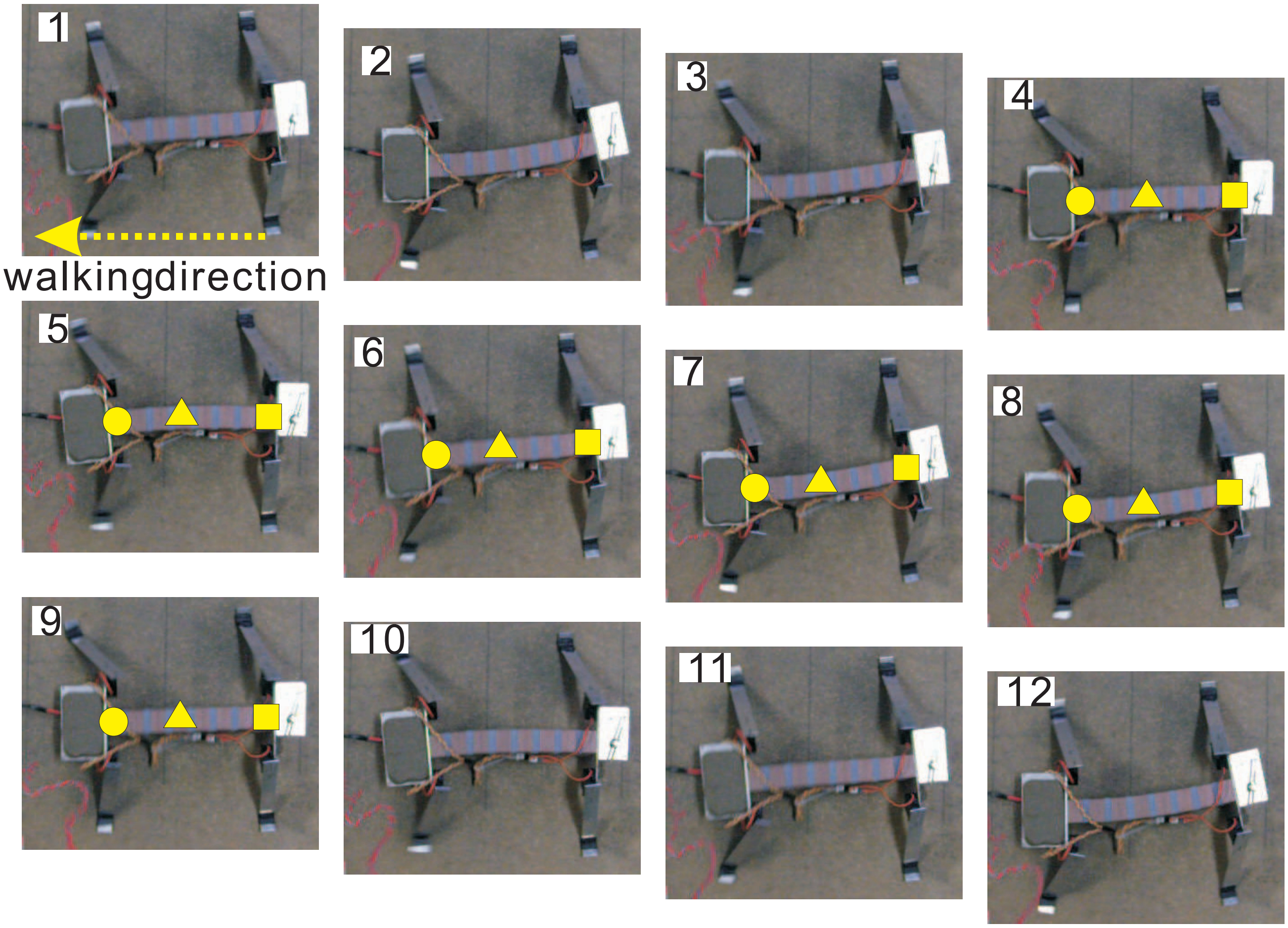

Fig. 8. Sequential pictures of the locomotion when F = 40 N and ϕ = -0.4π rad. The symbols ◯, △, and □ in frames 4 to 9 indicate the positions of the center of the first, fourth, and the last vertebra.

the gait pattern, multi-modal locomotion can be achieved by selecting the pairing of the physical properties of the spinal structure and the gait pattern of the four legs. The mechanism to facilitate the locomotion will be investigated in future studies. Note that phase difference ϕ is the only motor controller parameter: the other parameters, frequency and amplitude of the leg joint trajectories, were not changed. Therefore, the gait pattern can be obtained with a very simple electric circuit, such as an RC multivibrator, and therefore it can be concluded that appropriate viscoelasticity of the spine structure facilitates successful locomotion at low computational costs.

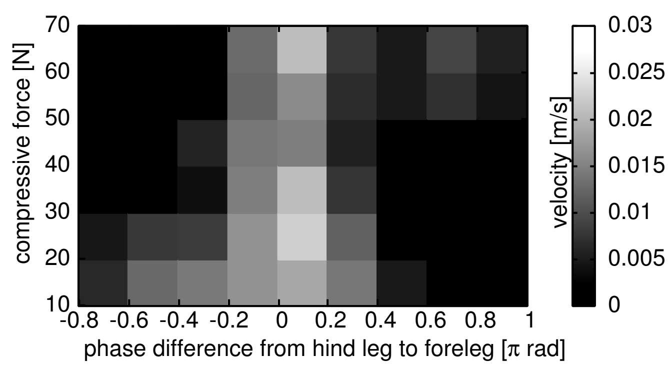

Fig. 9. 2D mapped average velocity with different ϕ and F

IV. Conclusion

The biped robot based on the passive dynamic walker suggests that an appropriate body design, including the proper arrangement of passive mechanisms, can provide energy-efficient locomotion at low computational costs. In considering the body design of a quadruped robot, we focused on the passive mechanisms of an animal-like musculoskeletal structures. We then adopted the spinal structure design that has multiple joints with tunable viscoelasticity. This paper has as its hypothesis that there are some appropriate pairings of gait pattern and the viscoelasticity that facilitate locomotion, and therefore we should be able to achieve multi-modal locomotion by selecting the pairing corresponding to the desired type of locomotion. In order to investigate the effect of passive mechanisms on locomotion, the relationship between the gait pattern of a quadruped robot and the viscoelasticity of the spinal structure were observed.

A spinal structure with sheathed rigid vertebrae and elastic

TABLE I

AVERAGE WALKING VELOCITIES OVER A DISTANCE OF 0.2 M BY COMPRESSIVE FORCE (F), WHICH DETERMINES PHYSICAL PROPERTY OF THE SPINAL STRUCTURE, AND PHASE DIFFERENCE (ϕ), WHICH DETERMINES THE GAIT PATTERN OF THE FOUR LEGS (VELOCITY UNITS: M/S)

Compressive force F [N]	Phase difference from hind leg to foreleg ϕ [$\times\pi$ rad]									
	-0.8	-0.6	-0.4	-0.2	0.0	0.2	0.4	0.6	0.8	1.0
10	-	0.0066	0.0126	0.0118	0.0174	0.0204	0.0109	-	-	-
20	0.0052	0.0144	0.0180	0.0157	0.0218	0.0162	0.0095	-	-	-
30	-	-	-	-	0.0291	0.0230	-	-	-	-
40	-	-	0.0106	0.0056	0.0245	0.0077	-	-	-	0.0030
50	-	-	-	0.0077	0.0188	0.0084	0.0064	-	0.0038	0.0039
60	-	-	-	-	0.0235	0.0131	-	0.0136	0.0109	-
70	-	-	-	-	0.0286	0.0187	-	0.0068	0.0054	0.0063

intervertebral discs acting as a beam between the forelegs and the hind legs was adopted; this structure has a unique oscillation according to the degree of viscoelasticity. We then adopted a mechanism to change the properties of the spinal structure, and, by tuning one of these properties, an appropriate spine oscillation, also depending on the gait pattern of the four legs, was achieved. Because passive oscillation does not require the actuation at each spinal joint, the locomotion consumes less energy and computational resources than current multi-joint robots with joint trajectories planned and joints actuated to follow these trajectories. Please note that the passive mechanism used in the present study is only one factor to facilitate locomotion, and more effective locomotion can be obtained by adding actuation on a well-designed robot, such as a passive walker, to walk on level ground.

ACKNOWLEDGE

This work has been partially supported by a Grant-in-Aid for Scientific Research on Priority Areas “Emergence of Adaptive Motor Function through Interaction among Body, Brain and Environment” from the Japanese Ministry of Education, Culture, Sports, Science and Technology.

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