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The Effect of Robot Morphology on Locomotion from the Perspective of Spinal Engine in a Quadruped Robot

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***Abstract*— Although the conventional hypothesis which states the coordination of the legs contributes much to locomotion has been widely accepted over the past decades, an alternative one has been proposed with an emphasis on the spine as an engine. In this paper, based on the biological hypothesis of spinal engine, we investigate how morphology of the robot e.g., the choice of actuated joint, the position of rotational joint and the shape and stiffness of the leg, can be adequately exploited to achieve stable and dynamic locomotion. The preliminary experimental results in the real world reveal that the position of rotational joint and shape of the legs are key elements for stable and dynamic locomotion. Based on the results, we discuss the effect of morphology of rear legs, aiming to design a new leg to improve the stability on the spine-driven locomotion.**

***Keywords*—morphology, spinal engine, quadruped robot**

I. INTRODUCTION

Over the past decades, it has been widely accepted that locomotion is generally achieved by the coordination of the legs, and the spine is only considered to be carried along in a more or less passive way [1]. This popular hypothesis has been accepted by most of robotics researchers as well as biologists. A considerable amount of research has been conducted on legged robots with little consideration on their spines [2]. However, an alternative hypothesis has been proposed with an emphasis on the spinal engine, i.e., locomotion is firstly achieved by the motion of the spine; the limbs came after, as an improvement but not a substitute [3]. Then, he extended this hypothesis to quadruped animals featuring flexion-extension spinal movement [4]. This implies that the spine is the key structure in locomotion. Although some robotics researchers came to realize the importance of the spine [5], [6], most of them still consider the spine as an assistant element to enhance the capability of locomotion.

We aim at investigating how a robot driven by spinal engine is able to achieve dynamic locomotion mostly by making use of body morphology. Since the morphologies and coordination between the movements of the spine and the legs affect the behavior of the whole robotic system, they must be appropriately designed to introduce the concept of the spinal engine to a quadruped robot. However, it still remains unclear how the morphology of the spine and the leg interacts with each other to achieve stable and dynamic locomotion.

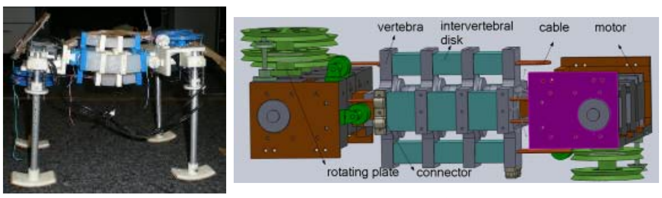
In this paper, inspired by this biological hypothesis of spinal engine, we explore the morphology of a spine and legs to study their effect on locomotion with a real quadruped robot, which has an articulated, multiple degree-of-freedom spine and passive legs. The effect of spine morphology is investigated on the position of the virtual spine rotational joint, which is defined as a softer part on the spine. The different shapes of the passive legs are studied for their role and effect on the locomotion. The preliminary experimental results in the real world reveal that the virtual joint on rear side of the body benefits rapid locomotion in the case of the passive legs without a knee joint where robot behaves more stably but less dynamically. In the case of the passive legs with a knee joint, a robot shows more dynamic but less stable movement due to the effect of dynamic property of the passive legs. Based on our results, the morphology of rear legs is discussed to better understand its effect and prepare for a new leg design aiming to increase the stability on the spine-driven locomotion.

II. DESIGN OF A QUADRUPTED ROBOT

A. *Robot design with biologically inspired spine*

We developed a quadruped robot (29 cm wide, 23 or 25 cm long, 20 cm high and 1.1 kg) , with an articulated artificial spine, to investigate the effect of morphology of a spine and legs on locomotion (Fig.1 (a)). It is designed in a modular architecture. The bottom of foot is glued with asymmetrical friction material to control the walking direction.

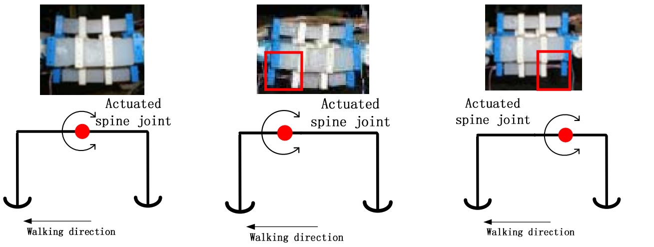
Fig.1 (b) shows this artificial spine endowed with biological characteristics. It consists of cross-shaped rigid vertebrae made of ABS plastic, silicon blocks and cables driven by motors. The vertebrae are separated by the silicon blocks, which work as intervertebral discs. They are connected by a cable through the vertebrae and the silicon blocks. The four driven cables are pulled respectively by the four RC motors located at the front and rear part, which can control the stiffness and movement of the spine. In this design, multiple socket-ball joints formed by vertebrae are adopted to produce more versatile posture.



(a) (b)

Fig. 1: The robot structure (a) and its spinal structure (b).

Fig.2 shows three spine morphologies which differ in the position of virtual joint where the spine is possible to achieve wider bending movement. We define the position of virtual joint in the Fig.2 (a) in the middle, since the silicon blocks fill in all the gaps between vertebrae.

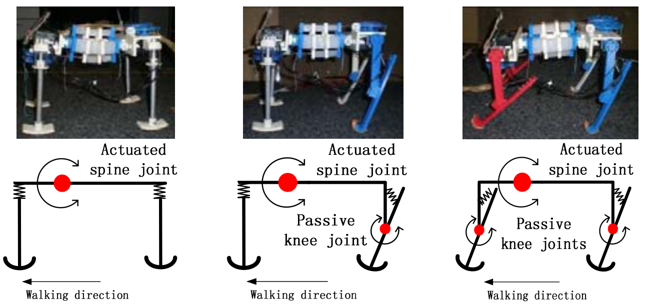


(a) SM1 (b) SM2 (c) SM3

Fig. 2: Robot equipped with spine whose virtual joint is in the middle (a), front (b) and the rear (c) part of the body. The red square highlights the area where the silicon block is taken out.

B. *Leg morphology*

We used three types of passive legs which have no hip joints, and are fixed to the robot body. They mainly differ in the existence of passive knee joint (Fig.3). In LM1, linear springs (N=0.48N/mm) are introduced in each stick-shaped leg to cushion shock from the ground (Fig.3 (a)). In LM2, the rear legs are changed by the ones with springy passive joint (N=1.25N/mm) to generate more upward and forward force (Fig.3 (b)). In LM3, two fore legs with springy passive joint (N=0.44N/mm) are applied to further investigate the body morphology (Fig.3 (c)).



(a) LM1 (b) LM2 (c) LM3

Fig.3: Leg configuration: LM1 with all stick-shaped legs (a); LM2 with stick-shaped fore legs and rear legs with springy passive joint (b); LM3 with all springy-passive-joint legs.

III. EFFECT OF SPINE AND LEG MORPHOLOGY

To better understand the correlation between the morphological property and the locomotion behavior, a series of experiments were conducted in the real world based on the combinations of the legs and spine morphologies (Table 1).

TABLE 1. Morphological combination

Leg morphology (LM)	Spine morphology (SM)
All legs: stick-shaped (LM1)	Virtual joint in the middle (SM1)
Fore legs: stick-shaped; Rear legs: springy passive knee Joint (LM2)	Virtual joint in the front (SM2)
All legs: springy passive knee joint (LM3)	Virtual joint in the rear (SM3)

During the experiments, Sine waves with tunable amplitude are taken as control signals for two motors in order to generate the up-down movement of the spine. The rest control parameters (Phase lag = 180°, frequency=2) are kept the same. Three trials were performed for each experiment. The performance for each morphology was evaluated in terms of the speed.

First, we compared the speeds of locomotion on the leg morphology 1 (LM1) with three different spine morphologies. Fig.4 shows that the overall performance of the robot is the best with spine morphology 3 (SM3) where the virtual spinal rotational joint is in the rear part of body. The position of the virtual joint decides the height of fore legs or rear legs' ground clearance. In SM3, it is easier to get fore legs' ground clearance, which increases the forward speed only when this ground clearance is not high enough to flip the robot. Spine morphology 2 (SM2) where the virtual joint is in the front is slightly better than spine morphology 1 (SM1) when the control parameter amplitude is less than 105°. However, when it exceeds this point, SM2 has the lowest speed. This is because the rear legs show ground clearance as the amplitude increases (see Table 2), and then the rear legs move slightly backward. Therefore, the robot shows lower speed.

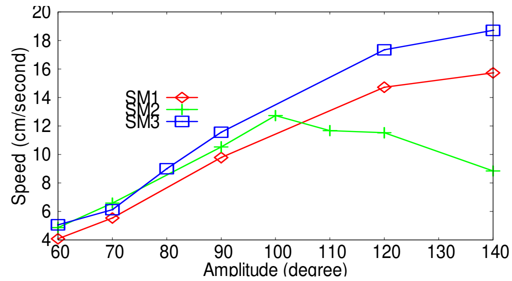


Fig.4: The effect of LM1 together with three spine morphologies on locomotion

TABLE 2. The states of ground clearance in LM1

	60°	70°	80°	90°	100°	110°	120°	130°	140°
SM1	00L	00L	00L	00L	00L	00L	10L	10L	10L
SM2	00L	00L	00L	00L	10L	11L	11L	11L	11L
SM3	00L	00L	00L	00L	00L	10L	10L	10L	10L

(Digit 1: ground clearance in the fore legs, 0: no; 1: exist
Digit 2: ground clearance in the rear legs, 0, no; 1: exist
Digit 3: L: robot moves forward, F: robot falls, S: robot doesn't move.)

Next, the stick-shaped fore legs and the springy passive rear legs were taken to speed up the locomotion by increasing the fore leg's ground clearance under the same given amplitude, inspired by the analysis of LM1.

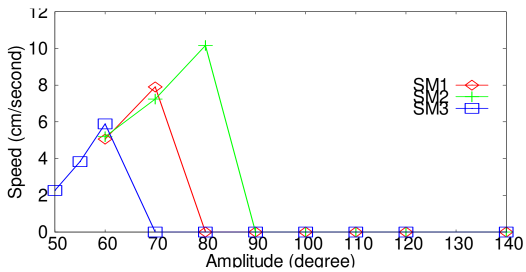


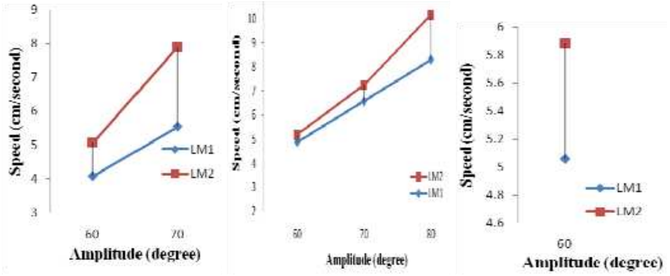
Fig.5: The effect of LM2 together with three spine morphologies on locomotion

Fig.5 shows that in the case of spine morphology 3 (SM3), where the ground clearance can be increased by the rear position of virtual joint, in addition to the other one generated by the springs in the rear legs, the ground clearance is so high as to turn over the robot above 70^o. The flip happened to SM1 above 80^o and SM2 above 90^o respectively (see Table 3) because of high fore leg's ground clearance produced by the rear. Fig.6 indicates that before the robot's falling, the speed of the robot with LM2 is higher than the robot with LM1 which has 4 stick-shaped legs.

TABLE 3. The states of ground clearance in LM2

	50^o	55^o	60^o	70^o	80^o	90^o	100^o	110^o	120^o
SM1	00L	00L	00L	01L	10F	10F	10F	10F	10F
SM2	10L	10L	10L	10L	10L	10F	10F	11F	11F
SM3	00L	00L	01L	10F	10F	10F	10F	10F	10F

(The meaning of symbols is the same as Table 2.)



(a) (b) (c)

Fig.6: Comparision of the robot's speed with LM1, LM2 under the condition of SM1 (a), SM2 (b) and SM3 (c) before the robot with LM2 falls.

We observed the range of tunable amplitude is limited and the robot's performance is more sensitive to the spine dynamics compared to the leg morphology 1 (LM1), due to the dynamic properties of its legs. To extend this limited range, leg morphology 3 (LM3) was adopted where each leg has passive knee joint, but varies in the stiffness and direction of the spring.

Fig.7 suggests that the energy transferred from the spine and spring in the rear legs is partially absorbed by the springs in the fore legs, leading to a relatively stable state. The upward force applying in the fore legs is reduced by applying this leg morphology, and then the range of spine bending angle is extended accordingly. We observed that because of the energy absorption in the fore springs, the robot stops moving at 60^o (see Table 4), which is much lower than the case of LM1 and LM2. We found that LM3 has two effects: it absorbs partial energy to stabilize the system, while it also consumes some energy, leading to a lower speed.

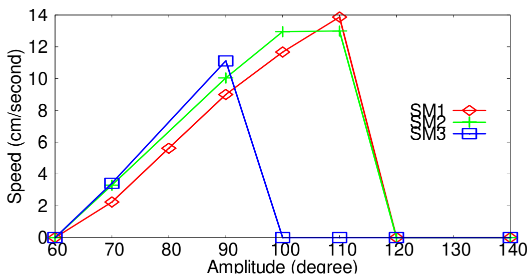


Fig.7: The effect of LM3 together with three spine morphologies on locomotion

TABLE 4. The states of ground clearance in LM3

	60^o	70^o	80^o	90^o	100^o	110^o	120^o	130^o	140^o
SM1	00S	00L	00L	00L	00L	10L	10F	10F	10F
SM2	00S	00L	00L	10L	10L	10L	10F	10F	10F
SM3	00S	10L	10L	10L	10F	10F	10F	10F	10F

(The meaning of symbols is the same as Table 2.)

IV. Discussion

The experimental results showed the position of spine virtual rotational joint determines the fore or rear legs' ground clearance which plays an important role in the stability and speed. In the case of SM2, the rear leg's ground clearance is easily achieved, which might lead to hind legs' slight backward movement. This behavior can be improved by adding an actuated hip joint to guide the movement of the hind leg. In the case of SM3, on one hand, the ground clearance is increased to speed up the locomotion by appropriately exploit the body dynamics caused by the virtual spine joint; on the other hand, if it is too high, the robot will lose its balance and turn over. This flip behavior can be avoided by a well-designed leg, e.g., LM3.

V. Conclusion

In this paper, we conducted a series of experiments in the real world to demonstrate how morphology of the robot, e.g., the choice of actuated joint, the position of rotational joint, the shape and stiffness of the legs can be exploited to achieve stable and dynamic locomotion. The preliminary experimental results in the real world revealed that under the same control parameters, the robot's performance mainly depends on the ground clearance mostly caused by the position of virtual joint and the shape and stiffness of the springs which could absorb the energy transferred from the movement of the spine. Based on our results, we will design new legs with hip joint, aiming to increase the stability and dynamic behavior on the spine-driven locomotion. Although the biological underlying mechanism is not well known, this study offers a basis to further investigation of how the morphology of the spine and the leg interacts with each other to achieve stable and dynamic locomotion.

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