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2DOF link mechanism mimicking cheetah's spine and leg movement*

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***Abstract*— A spine of a quadruped animal has compliantly connected several segments. This structure enables the animal to realize bending/stretching motion during running along with the motion of the legs. In this paper, we describe a link mechanism for mimicking such bending/stretching motion of the spine and the leg with few degrees of freedom. By designing a linkage mechanism, we try to realize a similar motion of the spine and the hind leg as that of a cheetah. We developed a prototype with such a structure and demonstrate that it can realize the similar movement of the spine and the leg as that of a cheetah with a simple control strategy.**

***Index Terms*— Biomimetics, Quadruped animal, Spine**

I. Introduction

The spine of a quadruped animal consists of many segments (bones) with compliant joints. It is driven by muscles and realizes bending/stretching motion[1][2][3]. The range of motion of the legs is subject to the spine curvature; by stretching the spine, the pelvis moves slightly backward and it also rotates backward (Fig.1). As a result, the range of motion of the hind leg will be wider concernig the center of gravity. The animal is supposed to increase the stride by stretching the spine. Whereas, by bending the spine, the animal can dexterously avoid obstacles and land on the rough terrain. Some robotic researchers focus on the function of the flexible spine and tried to mimic it for realizing adaptive quadrupedal locomotion.

There are mainly two way to realize the spine function. The first way is to use a soft, multi-articulated structure as a spine that can be bent by actuators[4][5][6][7][8]. This structure consist of many blocks and soft materials connect these each other. Therefore, this way can realize curving of spine like a real quadruped animal because of its a lot of joints. However, this spine has many degrees of freedom. It is very complex and difficult to control the shape of spine during not only running but also walking. The second way is to use single-joint spine[4][9][10][11]. This structure has only one degree of freedom and spine can be bent in the middle by a actuator. The structure is very simple and it is relatively easy to control its shape. However, this structure has difficulty realizing curvature like the spine of animal because this has only one joint. Therefore, we need a new mechanism that satisfies both of the advanteges described above. The literature has many studies about cheetah movement and the available data for the animal is correspondingly rich. The purpose of this research is to realize the structure shown below.

- The structure can realize the bending or stretching movement of the spine.
- The spine consists of a lot of joints.
- The structure can have only a few degrees of freedom.

Moreover, we propose a new spine-leg mechanism based on the spine mechanism. We built a robot that had the spine-leg mechanism and confirmed whether the movement of the mechanism is enough for applying to a quadruped robot.

Therefore, we choose to mimic the cheetah's movement.

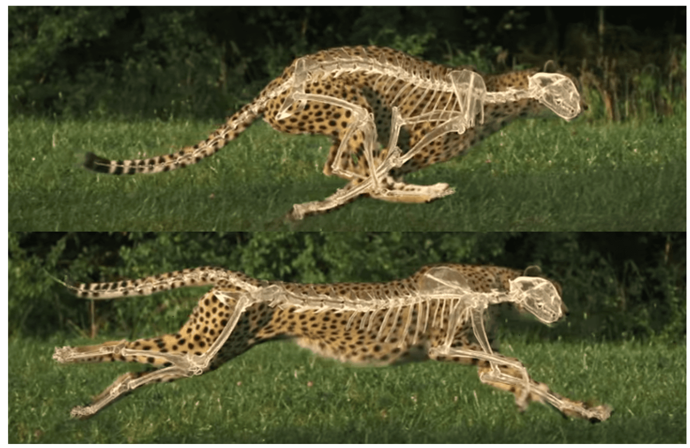

Fig. 1: The movement of the running cheetah[1]. The cheetah repeats bending or stretching movement of the spine actively during running. They achieve optimal running by changing its shape at the appropriate timing according to the movement of legs.

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II. Mechanism Design

This chapter introduces the mechanism design of the robot step by step. The first is the fundamental structure of the spine. The second is the spine-leg structure based on the spine structure.

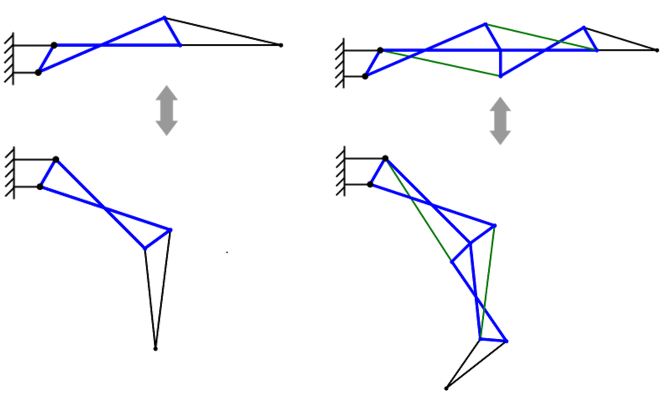
A. Spine structure

To simplify the spine structure, we focus on the three objectives which are shown below.

- Realizing cheetah-like curve and stretch movement with one degree of freedom.
- Utilizing a simple linkage that can bend with one degree of freedom as the parts of the spine structure.
- Reproducing the interlocking movements of the bending and stretch without adding any degree of freedom.

Fig.2 shows the one degree of freedom linkage mechanism. The blue lines compose a four-joint linkage. Its movement is shown in Fig.2a. This mechanism has four joints. Moreover, this four-joint linkage mechanism can connect with another linkages following the same rule. Fig.2b shows the linkages that consists of the two four-joint linkages. The two green lines connect the two four-joints linkages with one degree of freedom mechanism. The size or the curvature of this mechanism can be changed by modifying the length of linkages.

We followed the design rule mentioned above to develop the spine mechanism. Fig.3 shows the designed spine movement. This mechanism realized bending and stretch movement by changing the length of the red linkage. The black triangle represents the pelvic of robot. This simulation confirmed bending motion of the designed spine mechanism. We determined the length of the all linkage empirically in reference to the movement of the running cheetah (Fig.1).



(a) One four-joint linkage **(b)** Two four-joint linkages

Fig. 2: The four-joints one degree of freedom linkage mechanism.

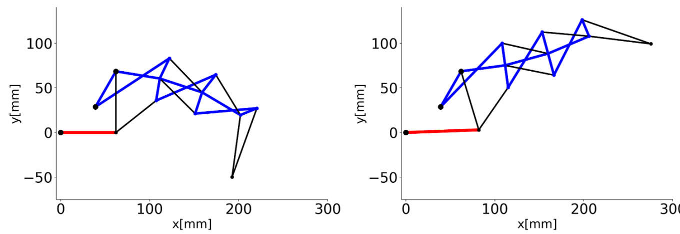


Fig. 3: The movement of the designed spine mechanism.

B. Spine-Leg structure

Continually, we combine the hind leg and above spine mechanism. The mechanism of the hind leg is designed by following the parallel linkage mechanism. Fig.4 shows the developed spine-leg mechanism. The two green parallel linkage mechanisms correspond to the femur bone and tibia bone of cheetah. The blue four-joints linkage mechanism connects the parallel linkage mechanism with the spine structure. This mechanism has one degree of freedom and moves following the change of length of the red linkage. The parameters of this structure was also determined empirically.

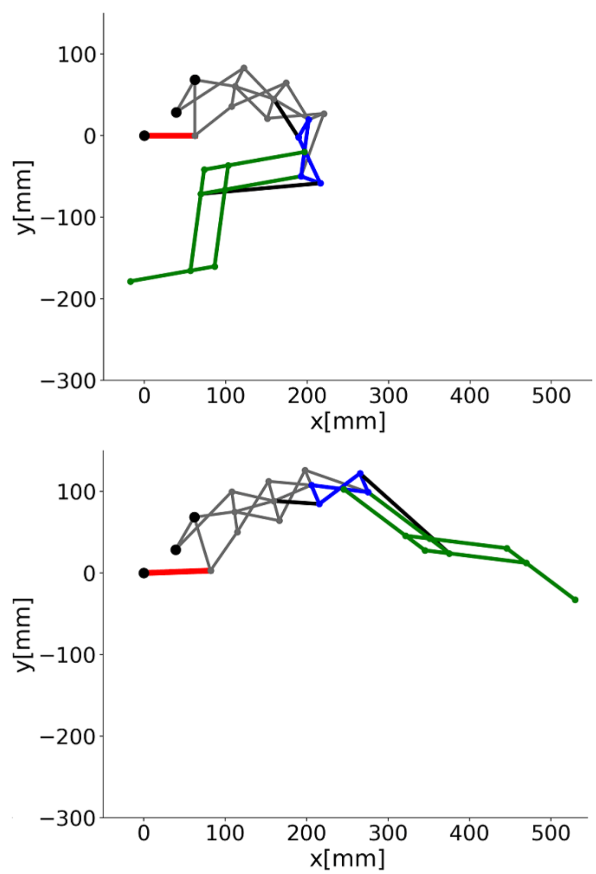


Fig. 4: The movement of the spine-leg mechanism.

Fig.5 is the comparison of the cheetah movement during running and the movement of the designed spine-leg mechanism. The mechanism geometrically realized the cheetah-like movement.

To install this spine-leg structure in a quadruped robot, the mechanism needs additional structure to retract the robot's foot during running or walking. It is difficult to achieve the spine-leg structure and that with only one degree of freedom. Therefore, we add a degree of freedom to achieve the above design requirement. Then the designed robot has two degrees of freedom. Fig.6 shows the mechanism designed movement of the robot. The black lines represent the tibia. The structure bends its knee and retracts the foot by the length change of the red linkage.

We define the length of red linkages of Fig.3, and Fig.4, and Fig.5 as $L1$, and the length of red line of Fig.6 as $L2$. When $L1$ and $L2$ move on clockwise from the red point of Fig.7a, the position of foot change on counterclockwise from the red point of Fig.7b. The running path was confirmed by these generated paths.

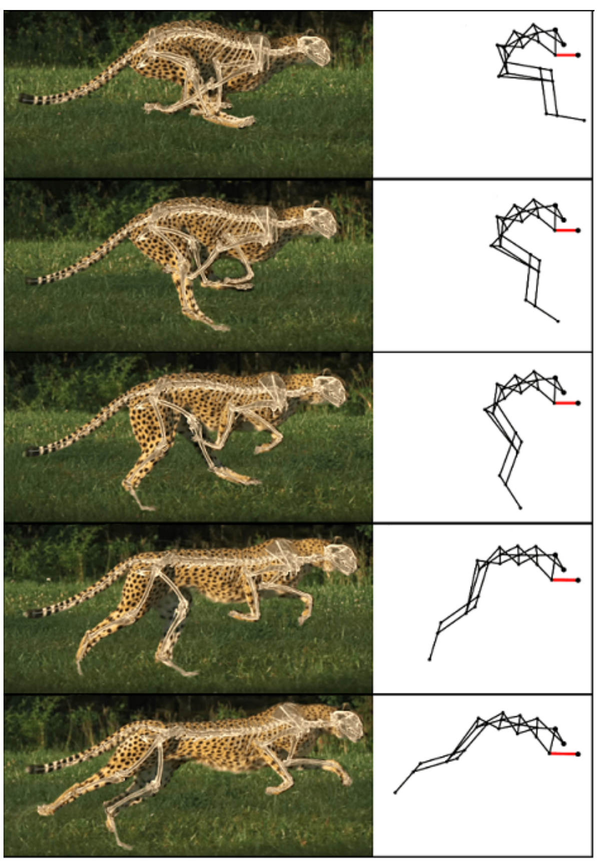


Fig. 5: The movement comparison of the cheetah and the spine-leg mechanism. The link structure realizes the same movement of running cheetah.

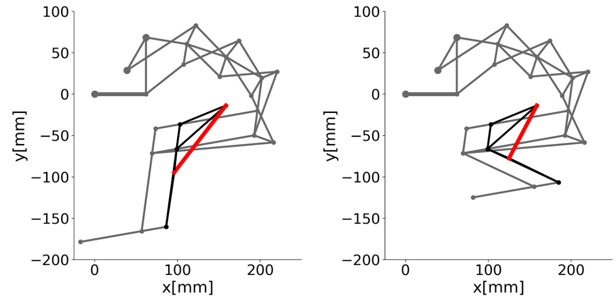
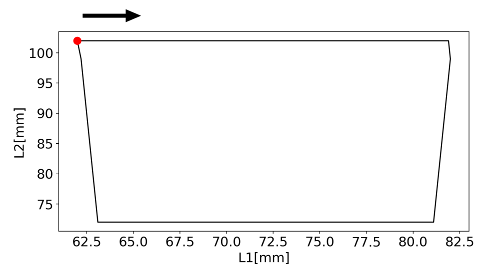
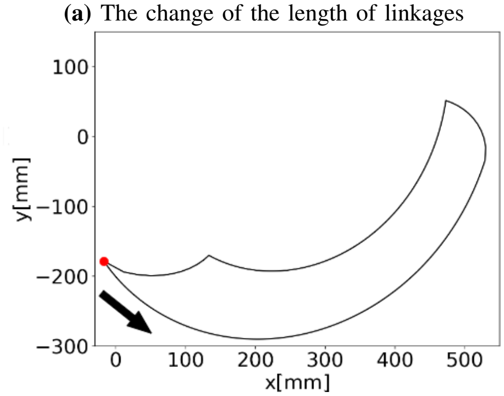


Fig. 6: The movement of the robot's foot.



(a) The change of the length of linkages



(b) The generated path of the foot

Fig. 7: The paths of foot generations.

III. Experiment

We developed a robot based on the mechanism we introduced in the previous chapter. This chapter describes the detail of the robot and the experiments.

A. Experimental robot

The designed robot is shown in Fig.8. This robot is composed of pneumatic cylinders, solenoid valves, a circuit plate, and a Lipo battery. The pneumatic cylinders are controlled by an Arduino Uno with a valve control circuit.

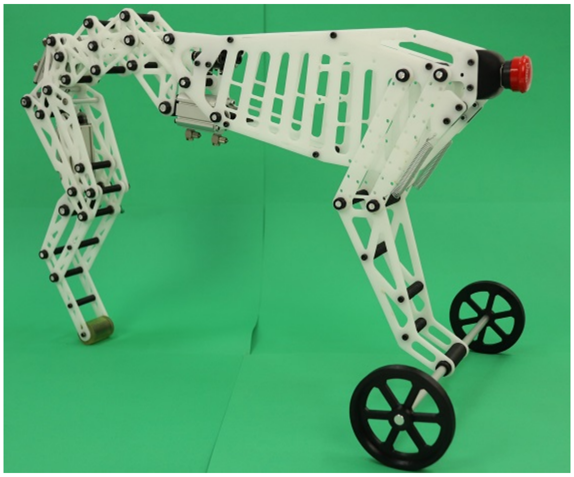


Fig. 8: The experimental robot. The length, width, and height of the robot are approximately 900, 300, 400[mm] and the total weight including actuators, control devices and battery is 1.8[kg].

1) Actuator and Control system: Fig.9 shows the overview of the system of the robot and Table.I shows the characteristics of the components. The robot moves by actuating the pneumatic cylinders. The pneumatic cylinders are easy to install into the designed mechanism. Furthermore, when the robot receives the shock of the ground reaction force, the pneumatic cylinder can absorb the shock force passively. The spine-leg structure is actuated by two cylinders (Cylinkder1, 2) in order to increase the output force and make the width of the robot smaller. However, we operate them by one solenoid valve (Valve1) to realize the interlocking movement, so that the spine-leg structure is still one degree of freedom. Fig.10 shows that Cylinder1 and Cylinder2 are actuated in an antagonistic manner with one degree of freedom. The structure that enables the robot to retract its foot upward is actuated by one cylinder (Cylinder3) and one solenoid valve (Valve2).

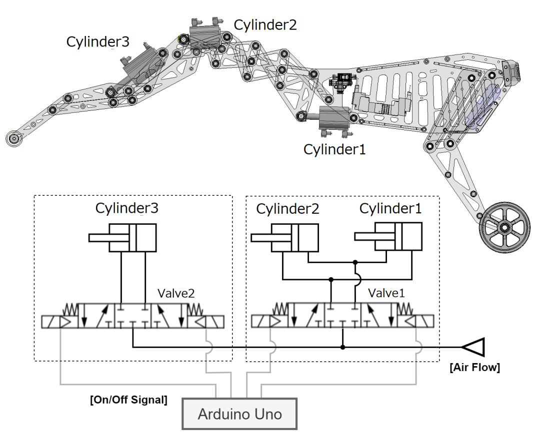


Fig. 9: The overview of the system of the robot.

TABLE I: Characteristics of the robot, in control system.

Characteristic	Component name
Pneumatic Cylinder 1, 2	SMC JCDQ25-20
Pneumatic Cylinder 3	SMC JCDQ25-30
5-port on/off Solenoid Valve	SMC SYJ3320-6MZ-M3

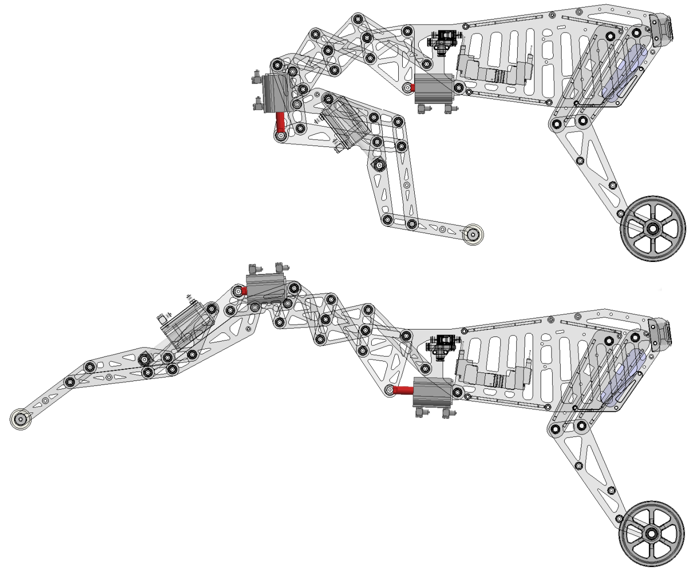


Fig. 10: The movement of the spine-leg structure and the change of its actuators. Each rod of the cylinder is showen in red. By actuating two cylinders in an antagonistic manner at the same timing by one solenoid valve, the spine-leg structure keeps its degree of freedom still one.

2) Materials: The structure of the robot was composed of Polyoxymethylene(POM) plates, aluminum shafts and 3D printing set collars. They are light materials compared to the metal plates. POM is a very useful and robust material for designing a robot. POM plates can easily be cut using a laser cutter. Therefore, it is suitable for the rapid prototyping of robots. Moreover, POM has low friction. Even if both ends of the shaft of joint are stopped with set collars and the plates of the links are pressed against each other, the link joints move smoothly. By using the low friction of POM, we can realize simple linkage mechanisms more easily compared to the aluminum, the surface of which is easily damaged by friction.

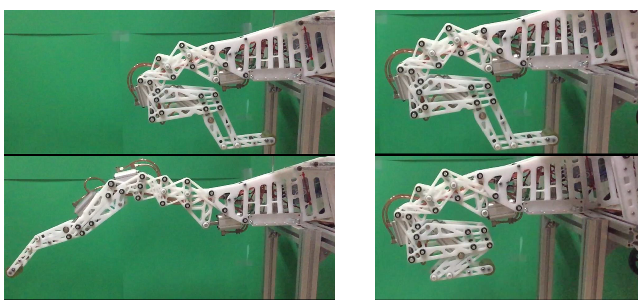
3) Front leg structure: The robot has a simple linkage structure that has springs and wheels to support its body. In quadruped animals, the body and head can be kept as horizontal as possible by the front leg moving. Considering the four legs animal, its body and head can keep as horizontally as possible by moving the front leg.

B. The movement of actuation

To confirm that the robot can move as per our design, we conducted the examinations of operating each solenoid valves individually. Fig.11 shows that the robot achieves the designed movement. The movement of each structure are shown in Fig.11a and Fig.11b. We found that it took about over 200[ms] for deformation of the spine-leg structure, and 100[ms] of the deformation of the foot retraction.

C. Running experiment

We conducted a running experiment with the robot on a treadmill. We operated solenoid valves by using a very simple control. Two valves were actuated by a designed timing and we adjusted the parameters empirically. Fig.12 shows the operation cycle of the valves mentioned at Fig.9. Each state changes from left to right. Solenoid valve 1 operates the structure of the spine and hind legs, and solenoid valve 2 operates the structure that retracts the foot. The green labels show the operation of the valves. The pressure of the air we supplied to the robot is 0.6[MPa]. Fig.13 shows the sequential snapshot of the running robot. At this time, we set T1 = 300[ms], T2 = 330[ms], T3 = 0[ms], T4 = 470[ms]. The robot realized the running movement like cheetah when the robot kicked the ground and stretched its spine and leg (Fig.13.1-3,7-10). The robot retracted its foot too quickly (Fig.13.3-5) duaring the swing phase. Also, the stance phase (Fig.13.6-9)was a little long. The robot was able to run for about 10 seconds at about 4[km/h].



(a) The movement of spine **(b)** The retraction of the foot

Fig. 11: Individual examination of the design movement.

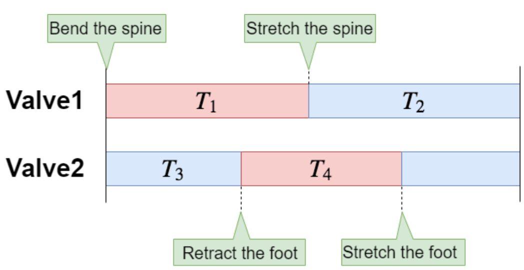


Fig. 12: Control pattern of the valves.

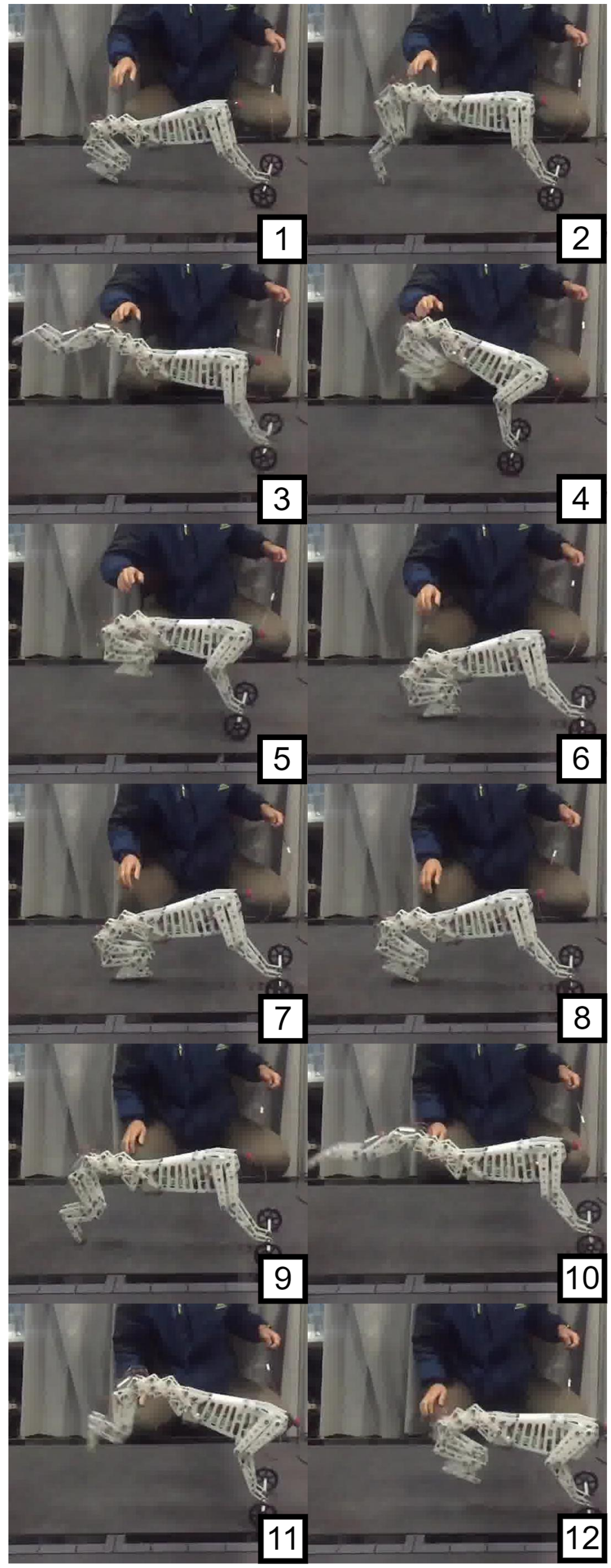


Fig. 13: The sequential snapshot of the running experiment. The period between the image is about 100[ms].

IV. Conclusion and future work

We developed a one degree of freedom cheetah inspired spine structure that consists of simple linkages. Moreover, we proposed the spine-leg structure that realizes the movement of running cheetah with only two degrees of freedom. To test the performance of the proposed structure, we built a robot that had the spine-leg structure and conducted a running experiment of the robot by simple on/off control. The robot realized the running movement like cheetah when the robot kicked the ground and stretched its spine and leg. On the other hand, the foot retraction was too quickly during the swing phase and the stance phase was a little long. We think that the quick foot retraction may be improved by changing parameters. It was difficult to control the movement of the robot more responsively during stance phase because of the delay of the pneumatic cylinders. It seems that the delay was caused by two main factors. Firstly, the inertia of the foot is relatively large concerning the output of the cylinders. Secondly, the air in the cylinders was easily compressed by the outside force or the inertia of the outside structure. We have to resolve the problems to improve the performance of the proposed mechanism.

In the future, we will work on the following topics.

- To establish how to decide the parameters of the linkage structure by calculation.
- To improve the delay of the control by changing the actuators or reducing the size and weight of the structure.

Acknowledgment

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