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Biological System Models Reproducing Snakes' Musculoskeletal System

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Abstract— **Snakes are very unique animals that have distinguished motor function adaptable to the most diverse environments in terrestrial animals regardless of their simple cord-shaped body. Revealing the mechanism underlying this distinct locomotion pattern, which is fundamentally different from walking, is signifficant not only in biolgical field but also for applications in engineering firld. However, it has been difficult to clarify this adaptive function, emerging from dynamic interaction between body, brain and environment, by previous scientific methodologies based on reductionism, where understanding of the total system is approached by analyzing specific individual elements. In this research, we aim at revealing the mechanisms underlying this adaptability by the use of the constructive methodology, in which biological system models reflecting biological knowledge is used as a tool for analysis of the total system. In this report, we present development of system models, i.e. a dynamics simulator and a robot, constructed based on biological data obtained from dissection, CT-imaging, kinematics measurements and EMG measurements. By constructing mechanical models based on anatomical studies and applying control input designed according to EMG and kinematics measurements into the models, locomotion similar to living snakes was achieved and remaining problems in the models were clarified.**
Keywords: Snake, Constructive approach, Mobiligence

I. INTRODUCTION

A. *Adaptive motor function in snakes*

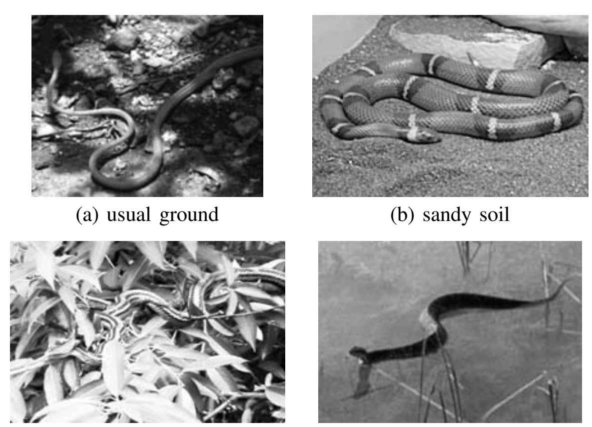
Snakes can adapt to the most diverse environments in the terrestrial animals regardless of their very simple cord-shaped body. They can locomote on rough ground, grass field, rocky area, mud, water surface and tree branches (Fig. 1). In order to achieve this adaptability, they adopt unique locomotion pattern by curving their body. Besides, in accordance with spiecies, surrounding environment and internal/external situations, they can change the locomotion mode: lateral undulation or rectilinear locomotion on normal ground, concertina locomotion on slippy surface or in narrow space, or sidewinding on sandy soil.

Revealing the mechanism underlying this adaptive motor function is significant not only as a biological finding on animals' locomotion, but also for application in engineering field. Because the adaptability emerges from dynamic interaction between the neural systems, the body and the situated environment, we have to holistically analyze the total system including the interaction in order to elucidate the mechanism of emerging animals' adaptive motor functions.

B. *Previous works on snakes' locomotion mechanisms*

The researches on snakes in biology have been conducted mainly on taxonomy, anatomy and snake poison and there are few researches on snake locomotion until now. In locomotion studies [1]-[15], analytical discussions have been carried out based on kinematics recording with respect to specific locomotion modes or EMG recording with a few muscles that are said to be dominant for locomotion. For example, Jayne [10] records EMG with the three dominant muscles with lateral undulation locomotion in terrestrial and aquatic environments in relation to curvature and moving velocity of a specific part of the snake trunk. Based on the results, he made a detailed discussion on the relationship between curvature and timing of muscle activity and on phase difference between muscles in both environments. In the recent study by Astrey [15], kinematics of snake locomotion on many cylinders with different diameter and inclination and in tunnels is recorded and qualitatieve and quantitative adaptation of locomotion with regard to environmental conditions is precisely investigated. Thus, locomotion studies based on the biological methodologies mainly focuses on description of phenomena based on reductionism. In order to synthetically understand the mehcanism of the adaptive function, a methodology to integrate these individual findings into a total system is needed.

The constructive approach is recently attracting attention as an methodology effective to synthetically reveal the mechanism of animals' adaptive motor function involving the dynamic interaction between body, brain and environment.



(a) usual ground (b) sandy soil (c) tree branch (d) water surface

Fig. 1. Adaptation to various environments in snakes

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In this approach, elemental findings obtained in biological way is integrated and total system models, i.e. simulators or robots, are "constructed". Then, by activating these system models, the holistic mechanisms are analyzed. By adopting this methodology, we can achieve the synthetic understanding of the mechanisms, which is impossible only by analysis of elemental components.

Thus, for understanding of the mechanisms of snakes' adaptive motor functions by the constructive methodology, we need a system model of snakes that include biological knowledge. Until now, many snake-like robots have been developed aiming at engineering application of snakes' adaptability (e.g. [16], [17], [18]). Are these robots available as system models for the constructive methodology? Unfortunately, the answer is "No". Previous snake-like robots only imitates superficial phenomena (e.g. body shape during locomotion) and the mechanism to reproduce the phenomena is developed based on engineering thinking. For example, animals' body motion is generated by antagonistic arrangement of flexible muscles along with the skeletal system. However, most of the previous robots are actuated by geared electrical motors and its physical and control characteristics are fundamentally different from animals. Hence, for constructive study on snakes, system models with more biological considerations are needed.

C. Objective

Based on the above discussion, the objective of this research is on development of biological system models for constructive understanding of snakes' adaptive motor functions. Though the system models should imitate the living snakes in both mechanical and neural aspects, as a first step, we mainly focus on development of mechanical models in this report. The derived results are expected to contribute to understanding of real snakes and this leads to development of snake-like robots with greater adaptivity.

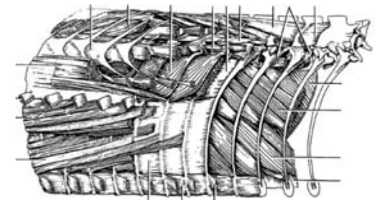
D. Composition of the paper

In what follows, we present our biological analysis for construction of the system models in section II. Next, in section III, we describe development of a simulation model involving biological knowledge and some results. In section IV, our snake-like robot PAS-2 designed according to the biological knowledge are introduced and results of some preliminary experiments are shown. Finally, in section V, we conclude the paper and some future works are shown.

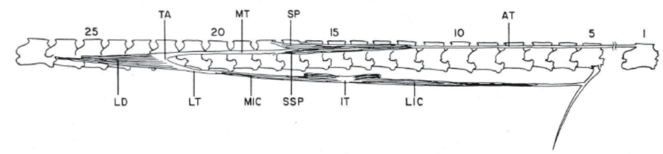
II. ANALYTICAL STUDIES ON SNAKES

As mentioned in I-C, at the first stage of this research, we focus on development of mechanical models of snakes. In order to develop the model, precise numerical data about musculoskeletal structure of snake body is needed. Because such detailed data cannot be found on literature in biology, we conducted some necessary experiments to obtain data. In what follows, dessection and CT-imaging is described in II-A and kinematics recording is explained in II-B.

We used corn snakes (*Elaphe g. guttata*) as experimental animals.



(a) musculoskeletal system of desert horned viper (*Cerastes cerastes*) [9]



(b) arrangements of dominant three muscles in yellow rat snake (*Elaphe obsoleta quadrivittata*) [10]

Fig. 2. Previous anatomical studies on snakes

A. Dessection and CT-imaging

Fig.2 (a) shows an anatomical drawing of snake musculoskeletal system [9]. The figure shows a very intricate structure of dozens of muscles and tendons. However, past biological researches pointed out that three muscles, i.e. longissimus dorsi (LD), semispinalis-spinalis (SSP-SP) and illiocostal (IC) muscles, are dominantly correlated with locomotion. Fig.2 (b) shows the arrangement of the three muscles shown by Jayne [10]. SSP-SP starts with spinous process (top of vertebra) and spans to LD via tendon. IC attached to rib bone and the other end is attached to LD also. The opposite end of LD is on diapophysis (side of vertebra).

The following points are important:

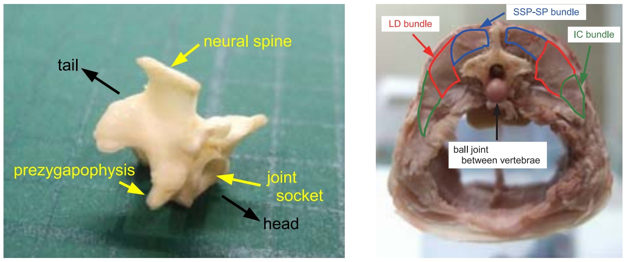
- Muscles related to locomotion are hyper-articulated spanning over 20 vertebrae.
- SSP-SP go through dorsal to vertebrae and is expected to be mainly related to motion in pitch axis.
- IC go through a lateral side of trunk and is expected to be mainly related to motion in yaw axis.
- Each muscle is arranged at a tilt and the balance of tensions of these muscles is expected to be related to motion in roll axis.

In order to obtain detailed numerical data of this structure, we conducted dessection and CT-imaging of the experimental animal.

First, we confirmed that each of the three muscles is covered with fascia forming a thick bundle and vertebrae are mutually connected with ball joints (Fig.3 (a)). Then we measured the attachment positions of tendons coming out from the bundles. Besides, as shown in Fig.3 (b), we made a sample of cross-section of trunk and measured cross-sectional area and position of centroid of each bundle using image-processing method. In addition, we derived three dimensional precise positions of attachment points of tendons or muscles by comparing the results of the dessection with a polygon model obtained from CT-image (Fig.4).

B. Kinematics measurement

We measured kinematics of locomotion in order to obtain precise data of snake motion. Fig.5 (a) shows the setting of



(a) vertebra (b) three muscle bundles

Fig. 3. Dessection of snake

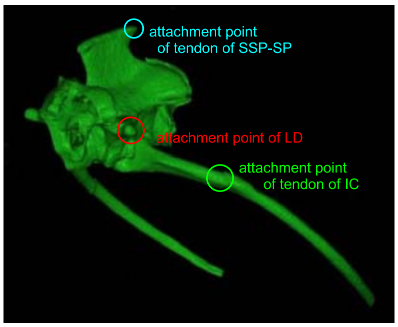
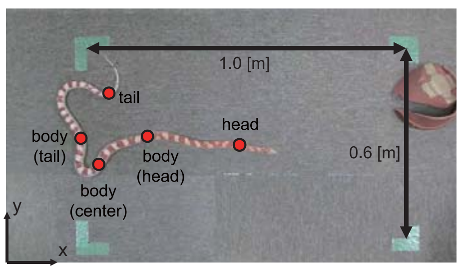
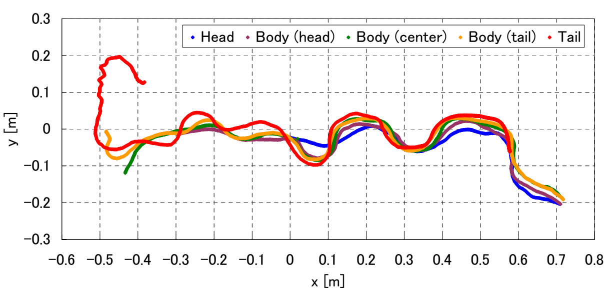


Fig. 4. CT-image of snake skeleton



(a) arrangement of markers



(b) trajectory of all markers

Fig. 5. Markers for motion capture

measurement. We attached small marks right above the snake spine and captured the motion of the marks using ceiling camera with HD resolution. Fig.5 (b) shows the result. We obtained data of motion cycle and phase difference between vertebrae from the result.

III. DYNAMICS SIMULATOR

Based on the obtained biological data, we developed a dynamics simulator reproducing snakes' musculoskeletal structure (Fig.6). We use Open Dynamics Engine (ODE) as a library for dynamics simulator.

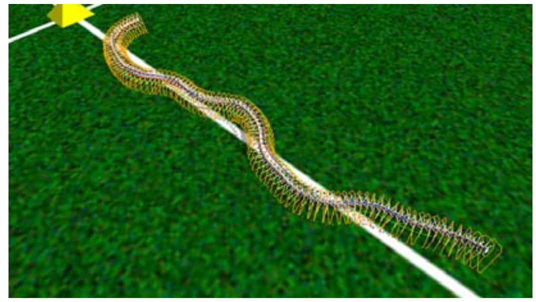


Fig. 6. Appearance of virtual snake simulator

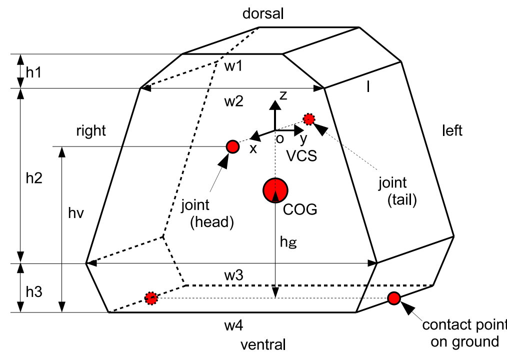


Fig. 7. Body segment

A. Design of mechanical model

1) Body segment: The modeled body trunk is composed of serially connected segments modeled as rigid bodies (Fig.7). One segment corresponds to one vertebra. The shape of the segment is octangular prism approximating shape of real cross-section (Fig.3 (b)). The mass and the inertia tensor of a segment is calculated based on the experimental animal. Conflict between segments and between a segment and the ground is ignored and the forces that each segment receives are given as follows:

- A force applied by adjacent segments at the ball joints (ODE automatically calculates)
- Reaction forces from the ground received at two points on the bottom of the segment (applied as external forces calculated by a contact model described bellow)
- Forces received at attachment points and via points of muscles and tendons (applied as external forces calculated by a mucle model described bellow)

2) Contact to ground: In the model of physical interaction between the body segment and the ground, vertical reaction force and horizontal frictional force are applied to the two contact points on the bottom (Fig.7) as external forces.

As for the vertical reaction force, we assume that the contact points sink into the ground at a very small amount. Using a spring-damper model with the amount of sinking depth, we modeled the abdomen surface with a certain amount of softness. As for frictional force, we used Coulomb's model of kinematic friction. Here, it is known that abdomen surface of snake has anisotropic frictional characteristics: slippy in axial direction and not in lateral direction. Here, we set axial

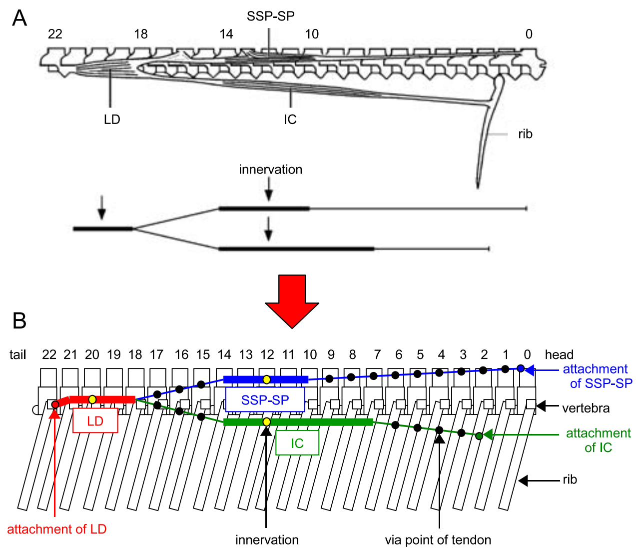


Fig. 8. Arrangement of muscles (A: biological data [14], B: our setting)

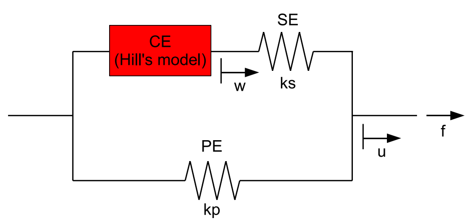


Fig. 9. Muscle contraction model

and lateral frictional coefficients as $\mu_t = 0.46$, $\mu_n = 0.83$, respectively refering previous reports.

3) Muscle model: Fig.8 A shows the arrangement of the three muscles dominant for locomotion and relating tendons [14]. Our designed arrangement based on this is shown in the figure B. Via points of muscle bundles on the segments are set to the positions of centroids obtained in II-A and tendons are arranged between the muscles and the attachment points as shown in the figure.

The forces that the body segment received from muscles and tensons are as follows:

- **Force at attachment point of muscles/tendons** At an attachment point, tension of the muscle/tendon is applied to the segment as an external force.
- **Force at via point of muscles** At a via point, total force of muscle tensions in two directions (craniad and caudal) is applied to the segment as an external force.

Fig.9 shows the muscle contraction model we applied. Each muscle is composed of Hill's contractile element (CE) [20], serial elastic element (SE) and parallel elastic element (PE). CE and SE are serially connected and PE is parallelly arranged to them. The model parameters is given by trial-and-error by reference to actually measured values of muscle bundles and previous studies.

B. Control system

At the present stage, the model of cenral neural systems driving muscles, i.e. brain and spinal cord, is out of our consideration. Instead, we gave driving inputs to muscles by setting time-line of muscular activity predesigned for each of three musles and propageting the signal to caudal direction. Concretely, We set phase of body segment i ($i = 0$ at the head segment) as $\theta_i(\omega t - \Delta\theta i)$ and set the activity of specific muscle as follows:

$$\alpha_{im}(t) = \begin{cases} c_m & \left(\begin{array}{c} 2n\pi + \theta_m^{\circ} \leq \theta_i(t) \\ < 2n\pi + \theta_m^{\circ} + 2\pi\delta_m \end{array} \right) \\ 0 & (\text{otherwise}) \end{cases} \quad (1)$$

Here, t is time, ω is angular frequency, $\Delta\theta$ is phase difference between adjacent segments, suffix m is type of muscle (SSP-SP, IC or LD), $\alpha_{im}(t)$ is activity level of the muscle, θ_m° is on-set phase and $\delta_m \in [0, 1]$ is duty ratio. And contralateral muscles are set anti-phasic.

Parameters dependent on the type of muscles, θ_m° and δ_m, are set according to Moon's data in [14]. ω and $\Delta\theta$ is derived from the result of the kinematics measurement described in II-B. c_m is set by trial-and-error.

C. Lateral undulation locomotion on horizontal plane

To verify validity of the developed system model, we simulated lateral undulation locomotion on a horizontal plane with the model. Fig.10 shows the resultant movement. The result shows that phasic travelling wave similar to living snakes was successfully generated. However, compared with motion of real snakes, significant side-slip was observed and consequently propellant speed was only 21% of the experimental animal. Besides, we observed small rotation in pitch and roll axis that is not observed in real snakes.

D. Discussion

From the simulation result, body curvature similar to living snakes is reappeared by implementing three muscles, SSP-SP, IC and LD, which verifies the biological forecast that these muscles are dominant for locomotion.

On the other hand, propulsion efficiency severely degraded by large side-slip. Major possible cause of this is inadequacy of the model of physical interaction between the body and the ground, i.e. frictional model. In this simulation, we used Coulomb's kinematic frictional model according to previously reported frictional coefficients. However, as for the physical interaction, it is also said that snakes actively forms a sharp structure, named "edge", on the side of abdomen surface and press it on small swell on the ground. By concentrating pressure on the edge, reaction force in lateral direction becomes larger and axial friction becomes smaller because the ground contact area becomes small.

Hence, we conducted another simulation in consideration of edge effect. In this simulation, we set axial frictional coefficient μ_t as 0.046 (tenth part of original μ_t). Resultant motion is shown in Fig.11. In this case, side-slip becomes much smaller and moving trajectory becomes similar to biological experiment in II-B.

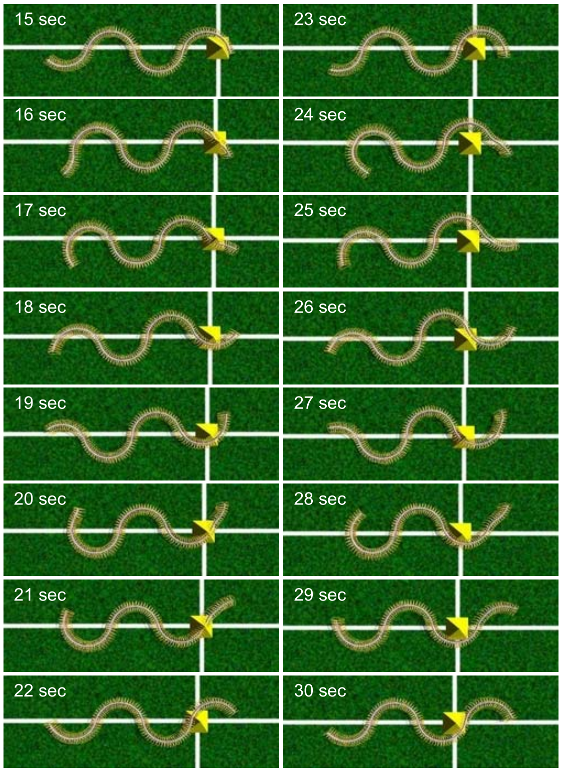


Fig. 10. Serial pictures of simulation

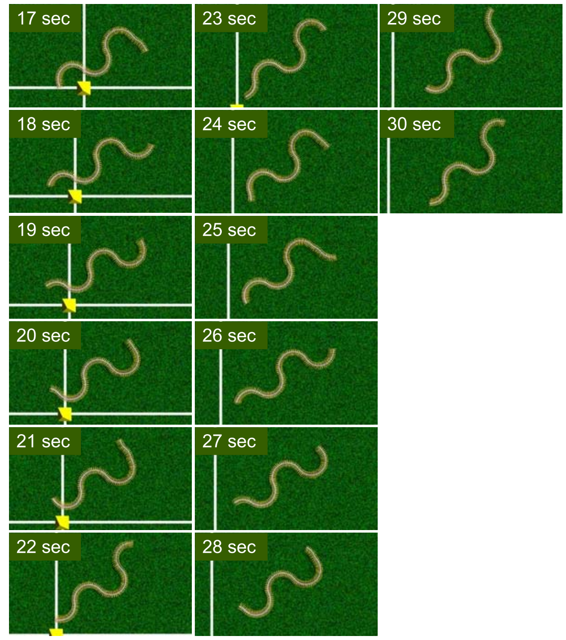


Fig. 11. Serial pictures of simulation with ideal frictional condition

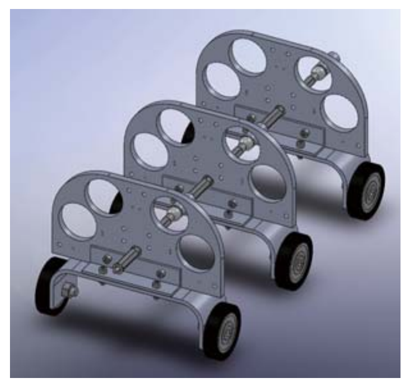


Fig. 12. Overview of PAS-2 link structure

IV. SNAKE-LIKE ROBOT: PAS-2

In order to verify validity and utility of applying knowledge obtained from biological analysis and simulations into the real world, we are now developing a snake-like robot, PAS-2, designed based on the simulation model. Here, we show design of PAS-2 and some results of preliminary experiments.

A. *Design of PAS-2*

In order to realize a snake-like robot with bundles of hyper-articulated muscles same as the simulation model, we use long McKibben-type pneumatic actuators as artificial muscles. This is a direct acting actuators that contracts when high-pressure air is injected. Because it has viscoelastic characteristics similar to actual muscles, it is widely used in biomimetic robots to mimick biologically natural dynamics (e.g. [19]).

Here, because it is difficult to implement the model completely the same as the simulation model, we assigned one robot link to three body segments (vertebrae) in the simulation. Besides, by dividing the function of LD, the robot has only two kinds of muscles: muscle A (corresponds to SSP-SP+LD/2) and muscle B (corresponds to IC+LD/2).

Fig.12 shows schematic view of the link structure. A body chasis is composed of an upstanding plate and abdomen structure. Two passive wheels are equiped with the abdomen structure to yield anisotropy of frictional coefficient. Links are serially connected with ball joints. On the plate, there are small holes to attach metal wires connected to the actuators and positions of the holes corresponds to real muscle/tendon attachment positions obtained from biological analysis. And there are four large holed on the plate in which the muscle bundles go through. The position of the center of the large holes are also corresponding to the anatomical data. As the result of setting one link for three vertebrae, the actuaters span 7 links and therefore 6 actuators are passing in the hole.

B. *Motion by PAS-2*

As preliminary experiments, two kinds of motion are tested by driving 6 links at the head of 24 links.

Fig.13 shows resultant motion of lateral undulation locomotion using only muscle B. The result shows achievement of the locomotion and only 6 links can trail total 24 links. We are now revising the robot mechanism to make it possible to compare simulation and experiment results.

Fig.14 shows resultant motion of neck-lifting motion by contracting muscle A. By the use of bundle structure of

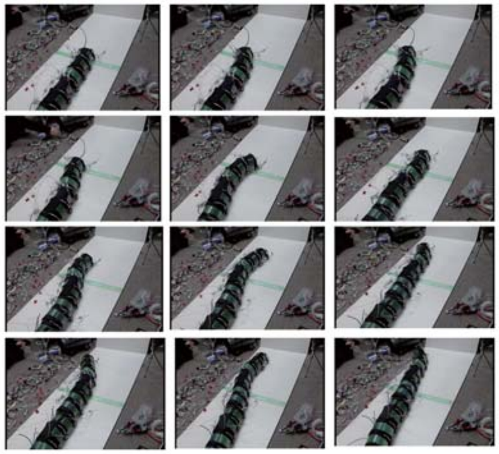


Fig. 13. Lateral undulation by PAS-2

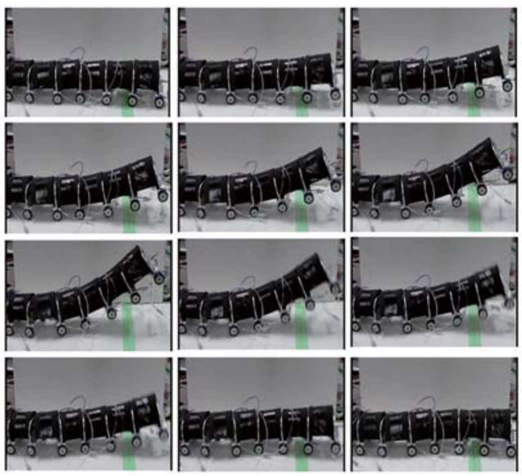


Fig. 14. Neck-lifting by PAS-2

actuators, the robot can generate torque in pitch axis large enough to lift 5 links.

V. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

In this papre, we indicate significance of constructive research on snakes' locomotion and developed biological system models as tools of it based on biological analysis. In order to synthetically understand the mechanism of adaptive motor function of snakes, we first analyzed snakes' musculoskeleta system numerically and we developed a simulation model and a snake-like robot as the system models using the obtained data. The simulation results partly reproduced characteristics of motion of living snakes, but several problems remained.

B. Future Works

In this paper, we mainly focus on the mechanical model. In this aspect, main remaining problems are as follow: correction of physical interaction model between the snake body and the ground, consideration of physical effect of other muscles and skin, and development of a new ground contact mechanism for PAS-2 different from wheels.

And the next challenge will be consideration of neural systems related to motor control.

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