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Engineering observation of lateral undulation in colubrid snakes for wheel-less locomotion

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SUMMARY
Nature has always inspired engineers. This research tries to understand the contribution of snake anatomy in its locomotion from engineering point of view to be adopted in the design of snake robots. Rib design and muscular structure of snake robots will have a great impact on snake robot flexibility, weight, and actuators' torque. It will help to eliminate wheels in snake robots during serpentine locomotion. The result of this research shows that snakes can establish the required peg points on smooth surfaces by deflecting the body and ribs. The results are verified by both field observations and simulation.

KEYWORDS: Design enhancement; Lateral undulation; Snake anatomy; Snake robot; Simulation; Vertebra design; Snake movement; Wheel-less locomotion.

1. Introduction

New achievements in different areas of science have increased demand of mobile robots with capability to function in various environments. Wheeled robots have serious problems to function over rough terrains. Legged robots function better over irregularities; however, they have stability problem as well as a limited capability to pass. Observing natural phenomena, humans have been motivated to mimic the underlying principles to achieve more efficient systems. Snake locomotion is unique since it enables the animal to move in trenches, over trees, inside water, or into a hole. A snake robot with such capabilities will be useful for many tasks such as rescue application, surgery, and inspection of dangerous or hard to reach places such as inside oil pipes.

In the last three decades various designs have been offered for snake robots' joints and body. Hirose[1] did the most extensive study based on biological studies of snake. He built several snake robots. His robots were using wheels for gliding. DC motors were used as robots actuators (Fig. 1(a)). Locomotion of wheeled snake robots is limited to flat environment with sufficient friction.

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Some works focused on the design of snake-arm robots. These robots were basically fixed base articulated arms for handling applications. NASA's jet propulsion laboratory (JPL) adapted the design of NEC Corporation[2] and made the first version of this kind of robot (Fig. 1(b)).

Carnegie Mellon in 2005 (http://www.cs.cmu.edu/~biorobotics/projects/prj_bridgeinspection.html) demonstrated a highly efficient and flexible robot using conical gears and electrical motor as actuators. The joints rotation angle was limited to 120° (http://www.cs.cmu.edu/~biorobotics/serpentine/serpentine.html). To expunge gears and motor from joints, EMMA robot was made by Piligram.[3] Cables passing through the links activated the robot links. These links were connected by flexible coupling to be able to change their orientations[3] (Fig. 1(c)). Snake-arm robots are flexible in more ways than one and their versatility allows them to be useful in a wide range of situations (http://www.azorobotics.com/equipment-details.aspx?EquipID=129)

Attempts to build wheel-less snake robots have increased recently. Bayraktaroglu *et al.*[4,5] made a wheel-less snake robot that was able to use some peg points and move forward. The peg points were pre-located on a panel by the designer. This robot uses pre-located natural peg points (Fig. 1(d)). Extra touch sensors along with an intelligent algorithm will enable the robot to find random peg points. Liljebäck[6,7] designed a snake robot with ability to traverse cluttered and irregular environments by using irregularities around its body as push points to aid propulsion. He proposed a control strategy employing measured contact forces to maintain propulsion while simultaneously preventing the snake robot from being jammed between obstacles in its path.[6,7] In some attempts to make wheel-less snake robots, the designer has adapted the worm motion system to solve this problem. GMD snakebots[8,9] and ANAΠ[10] are the results of these efforts. The robot is usually composed of several blades. Each blade can rotate along a horizontal axis, perpendicular to motion direction. The blade is activated by means of servomotors. By controlling the sequence of blade rotation, a worm-inch wave appears along the body, resulting in forward motion (Fig. 1(e)). Slimbot is another robot made in 2006, utilizing friction of surface as a fulcrum. All modules of robot consist of friction plate with ragged surface.[11]

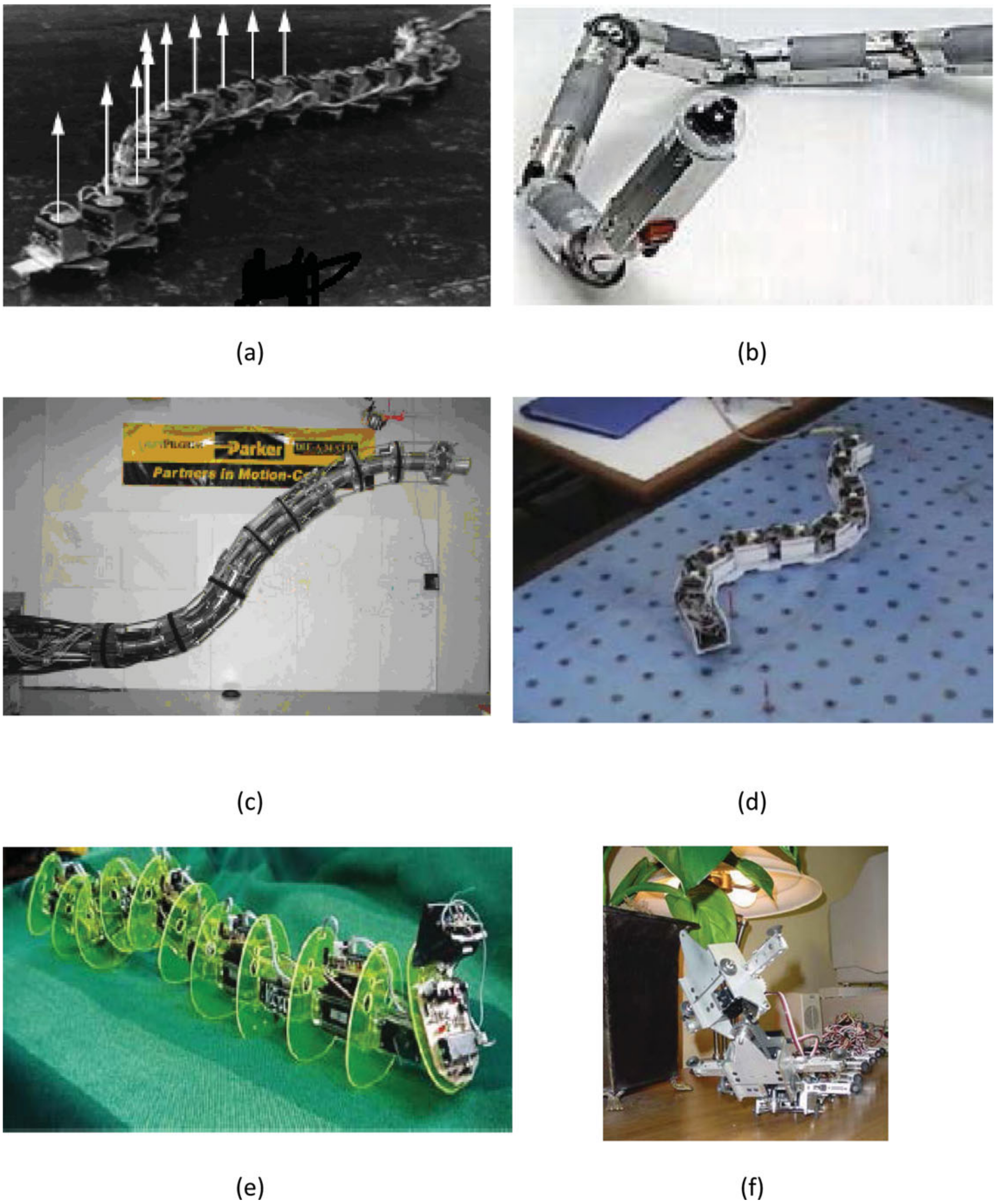

Fig. 1. (Colour online) (a) ACMIII robot made by Hirose.[1] (b) JPL.[2] (c) EMMA robot with cable motivation system (http://www.cs.cmu.edu/∼biorobotics/serpentine/serpentine.html). (d) Wheel-less snake robot.[11] (e) ANAΠ snake robot.[10] (f) King Snake.[15]

In most of the designs explained earlier, servomotors were the main source of motion. Servomotor energy consumption is considerable. Also, their behavior is very different from muscle manners. Some researchers have worked to implement new actuators in their robot. Bently and Mahdavi[12] in UCL University of England used Shape Memory Alloy (SMA) as actuator in their design, but SMAs are not energy-efficient.

Barazandeh[13,14] has built several snake robots with different actuators since 1999 (pneumatic muscle, SMA wires, servo motors, etc.). Figure 1(f) shows one of the King Snakes, which is a mobile robot with capability to move in three-dimensional (3D) space. The robot actuators are Futaba servomotors.[15]

Snake robots are not new in robotics and much research has already been done on this topic. However, despite their potential abilities, mobile snake robots are still nothing more than a research project or toy. This is due to several reasons listed below:

1 Modules are identical units with joints and sometimes actuators repeated through the whole length of a snake robot

2 Colubrid snakes, or snakes of the family *colubridae* are the largest family of snakes in the world. They are very successful snakes (high adaptation power to different habitats and environmental conditions), are widely distributed in the world (except at poles), and occupy different habitats from deserts to ponds, and from tropical forests to high mountains.

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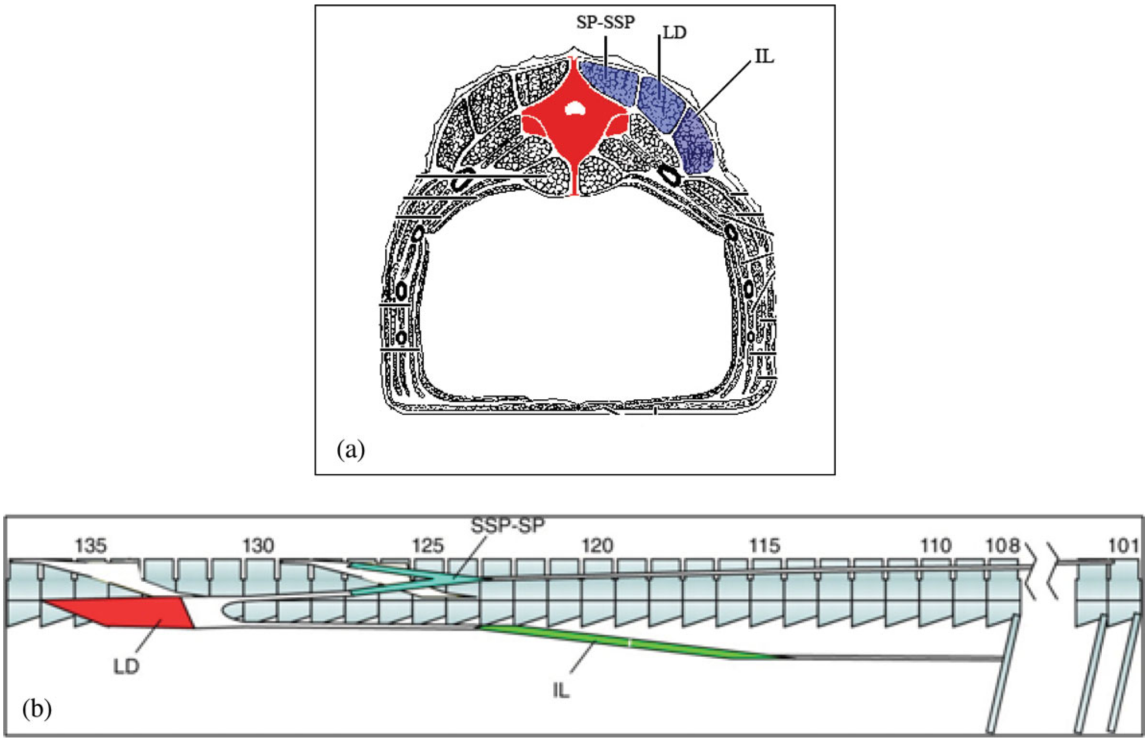

Fig. 2. (Colour online) (a) A cross section of snake's epaxial muscles. (b) Epaxial muscular anatomy of the mid-trunk of gopher snake, *Pituophis melanoleucus* (IL5M: iliocostalis, LD5M: longissimus dorsi, MF5M: multifidis, SP–SSP 5 M: spinalis–semispinalis). The oblique insertions (described in the text) suggest that these muscles can contribute to longitudinal twisting of vertebral column.[22]

- Most of the snake robots are mobile platforms equipped with active/passive wheels. Wheeled motion is limited to operating over perfectly smooth substrata.[5]
- They have poor power efficiency, and a large degree of freedom (DOF) to be controlled.[16]
- They have limited payload capacity.[16]
- The common designs of joints lacking the required flexibility for versatile motion and configuration, as well as simple control.[17]
- The versatility of snakes is due to their capability to switch between different locomotion gaits. They can swim in water, climb trees, escape through holes, move on sand, and crawl over rough trains. The snake robot prototypes are limited to a few types of locomotion and are very specific to certain environments.[5,18,19] Developing innovative snake-like mechanisms, especially for 3D snake-like motion, is still an open problem.[5]
- In most of the published literature, the robot has a modular structure[1] whereby each module is actuated by actuators installed in the rear module. The disadvantage of this design is increase in torque, and size of actuators from head to tail. However, in a real snake the head and tail are narrower in comparison to the rest of the snake body. This is an indication of smaller muscle volume at these parts. Muscle volume indicates the size of force it can apply.[20]

This research is the extension of our previous research on snake robots.[20] In the previous research the snake anatomy was only considered for actuators' location. In this paper, the recent publications on the kinematics of lateral undulation in colubrid[2] snakes have been reviewed. Field observations, fluoroscopy studies, and autopsy have been performed, and it has been tried to explain observations with simulation. We hope the results will help to build wheel-less snake robots.

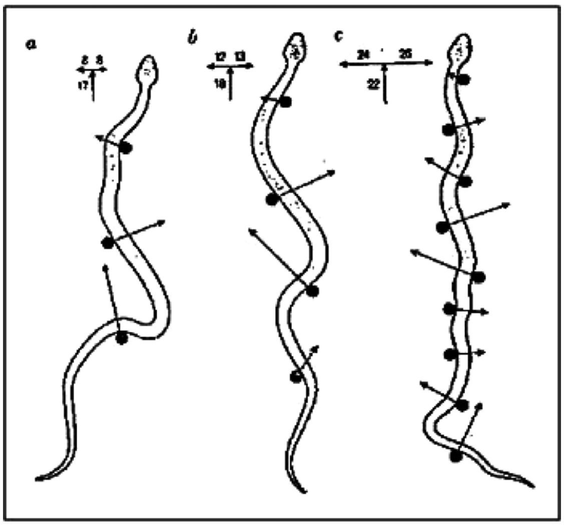

Fig. 3. The reaction forces of contact points push the snake forward.[25]

2. Biological Researches on Snakes

Snake has displayed several solutions to leg-less locomotion. So far four types of motion have been documented for snakes: *concertina* movement to move in a narrow passage, *rectilinear*, which is a slow but effective way of moving

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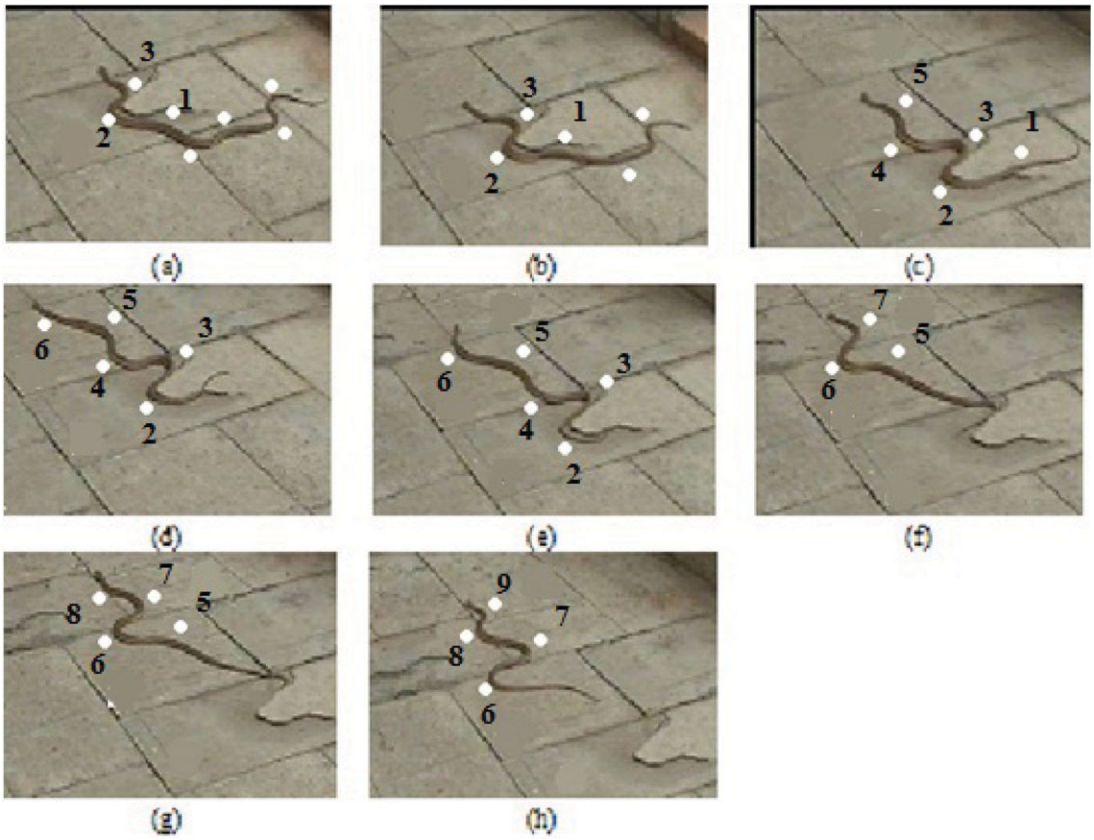

Fig. 4. (Colour online) Field observation of lateral undulation of snake on smooth tiles: the white points are the peg points and the numbers are the identical peg points in different figures.

inconspicuously for heavy bodies using belly muscles, *side-winding* that enables snakes to move across loose and sandy surfaces with minimum surface contact, and, finally, *lateral undulation*, which is the fastest and the most common type of motion in snakes.[21]

Lateral undulation generates propulsive force by lateral vertebral flexion. The body of snake is pushed against irregularities of ground to anteromedially generate direct reactive forces that are great enough to overcome sliding frictional forces.[19] Kinematics and muscular mechanism of this locomotion in colubrid snakes are discussed in ref. [22–24].

In summary, vertebral axis consists of metameric (repeated) chain of procoelous[3] vertebrae and ribs. Numerous vertebrae of snakes, which are shorter and wider than those of tetrapods, permit quick lateral undulations through grass and over rough terrain. The ribs increase rigidity of the vertebral column, providing more resistance to lateral forces, which permit lateral undulation in snakes.

According to the studies[22–24] done on colubrid snakes, three epaxial[4] muscles are important in lateral undulation locomotion. The model proposed by these researchers had a triad muscular unit, which consisted of spinalis–semispinalis, longissimus dorsi, and iliocostalis muscles. This triad unit is repeated along the vertebral axis (Fig. 2).

In Fig. 2(b), a section of snake spine between vertebrae 100 and 130 is shown. Figure 2(b) shows that the actuating muscle for a particular vertebra is located on several vertebrae farther.

3. Observations to Understand Lateral Undulation from Engineering Standpoint

Lateral undulation is the most common method of movement for snakes and maybe the most amazing one for wheel-less locomotion. Lateral undulation is more efficient compared with other patterns due to use of normal contact forces to drive snake forward.[25]

In most of the published articles, lateral undulation is described by moving the sideways against the irregularities of the ground such as rocks, plants, or debris, thereby enabling animal to grip ground at places along its body[28] (peg points). The places along the body and on ground where the snake pushes its body against them are called "peg points" (Fig. 3). Therefore, peg points are static (ground-fixed) locations on ground. If the irregularities of ground are used as peg points,

[3] Indicate the shape of reptiles' vertebrae. Reptiles have two shapes of vertebrae: (1) Procoelous: centrum concave on anterior surface, convex on posterior surface, characteristic of some reptiles and amphibians; (2) opisthocoelous: centrum convex on anterior surface, concave on posterior surface, characteristic of some of the vertebrae of reptiles and mammals.

[4] Epaxial means of or pertaining to vertebral column. For example, epaxial muscles mean muscles that are located on vertebral column and are responsible for the movement or stabilizing of vertebral column. In snakes, these muscles are responsible for the movement of vertebral column resulting in the movement of the animal, and in advanced animals, such as cow, these muscles are responsible for lifting and stabilizing of vertebral column in a straight shape.

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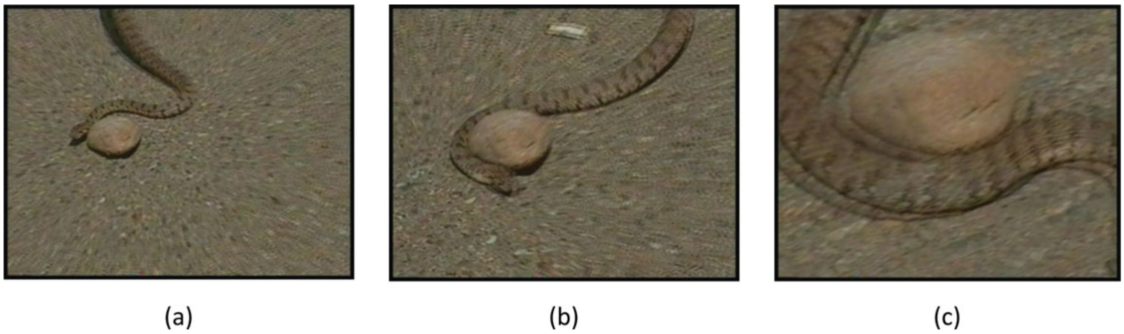

Fig. 5. (Colour online) Lateral undulation of snake around a stone.

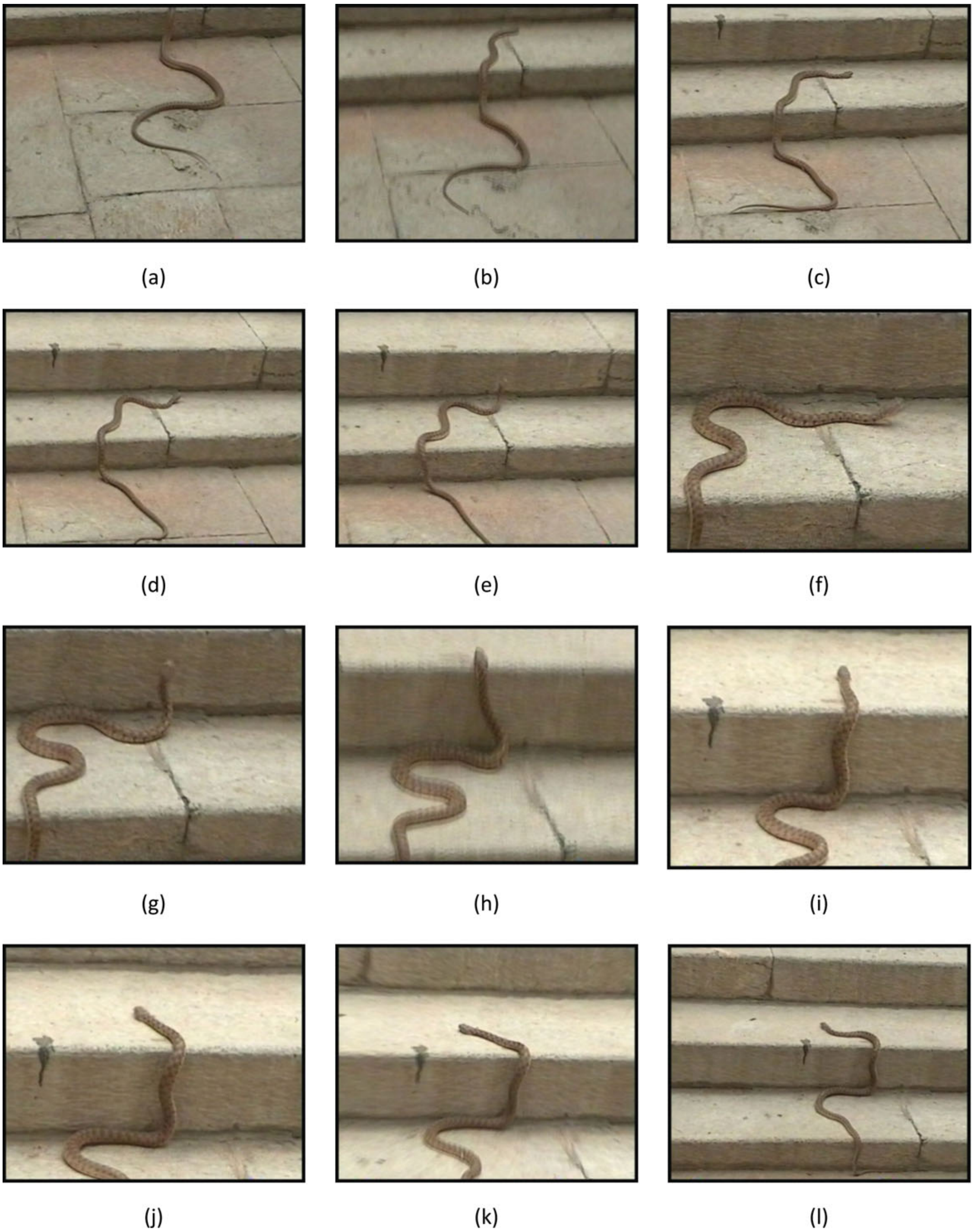

Fig. 6. (Colour online) Field observation of lateral undulation of snake during stair climbing.

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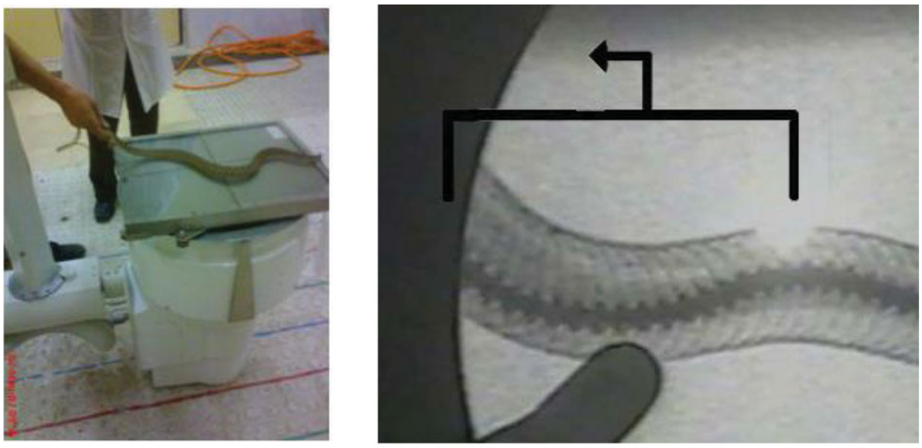

(a) (b)

Fig. 7. (Colour online) Fluoroscopy of *Hemorrhois ravergieri* snake. (a) fluoroscopy machine; (b) twist of spine: equal distance (right side of picture), and unequal distance (left side of picture) of spine from the body borders.

the authors refer them as external peg points. On flat surfaces, a snake may deform its body such that a supporting area or peg point is established. The authors refer to such areas as internal peg points. It then uses its rib muscles to push off from each contact point starting from the head and moving backward creating the forward movement.[25] As snake moves forward, new points on the body are continuously coming in contact with the same points and so all the parts of the body follow the same line and the snake moves forward steadily with almost fluid grace.[26,27]

In order to investigate the accuracy of this statement, the authors decided to arrange field experiments to watch the lateral undulation of a real snake on a smooth surface (tile here). Figure 4 shows the result of this investigation on *Hemorrhois ravergieri*, which is a colubrid snake widely spread in Iran. It mainly takes advantage of lateral undulation to move. As Fig. 4 shows, the peg points are almost constant; however, there was really no irregularity for the snake to push its body against ground. Replication of the experiment strengthen this idea that snake establishes the peg point by deforming its body.

This may come to mind that the snake uses small indentations on the ground to push against by deforming its body to create a better grip. Although the authors do not have enough evidence to argue this statement, it will not challenge the idea of deforming body to establish a peg point. Hence, if the snake deforms its body to use indentation as a peg point during locomotion, it means the natural peg point is not established by itself and requires to be established by deforming the body.

In another experiment, a stone was placed along the animal route during snake undulation (Fig. 5). The animal changed its direction toward the stone and took advantage of it as a peg point (Fig. 5(c)).

Another interesting feature was lateral undulation during stair climbing and establishment of peg points (Fig. 6).

Fluoroscopy of *Hemorrhois ravergieri*was was done to see and study lateral undulation in real snakes, as well as study vertebral arrangement and movements, and their effect on lateral undulation locomotion. The fluoroscopy result revealed twist of spine and deformation of ribs during lateral undulation (Fig. 7(b)).

In order to find out more about the stiffness of ribs and the configuration of muscles, an autopsy was performed on snake. Figure 8 shows some pictures of the autopsy. The autopsy showed that the ribs were as soft and tiny as ribs of a fish. They could easily bend and deform. It was also found that the connections of muscles to vertebrae were not exactly as depicted in Fig. 2(b). In this schematic, only the connections of three basic epaxial muscles, including SP–SSP, LD, and IL, are shown. In a real snake there are many of these basic units (same as the number of vertebrae) repeated continuously while following each other (the real picture is shown in Fig. 8(a)). In general, they make three long epaxial muscles, namely SP–SSP, LD, and IL muscles (Fig. 2(a)).

(a) (b)

Fig. 8. (Colour online) The autopsy of *Hemorrhois ravergieri*snake: (a) muscles; (b) ribs.

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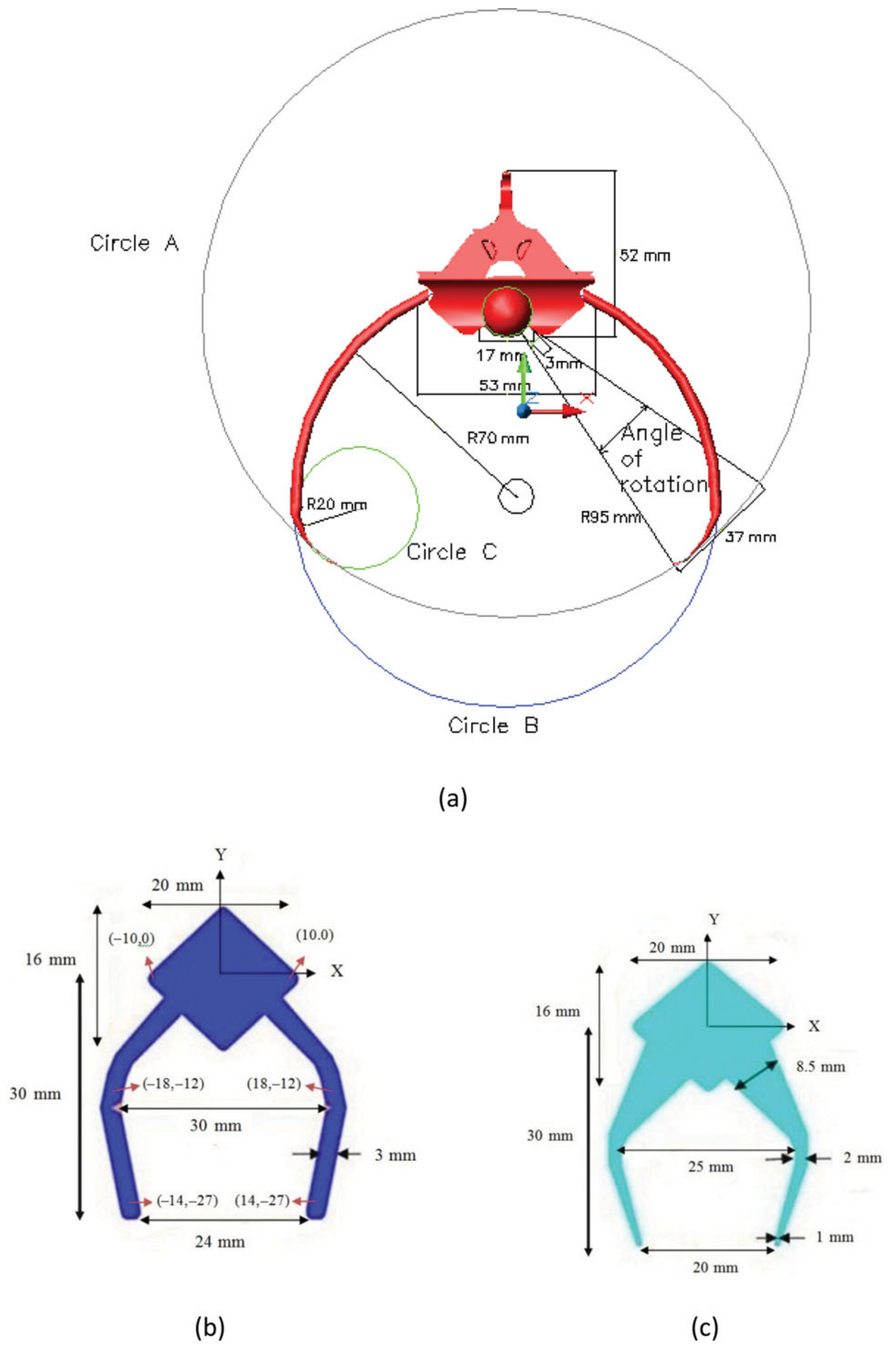

Fig. 9. (Colour online) Three different rib designs: (a) design 1; (b) design 2; (c) design 3.

The muscles were lying on either side of the backbone (all over the length of the body) with a tiny attachment to the side of each individual rib. Although it is hard to imagine the real muscle connection, but Fig. 2(b) provides a usable template of snakeSOFTPWSHANKARBREAK;muscle mechanism to be adopted here.

These muscles produce the flexing of the body. Since the backbone is not compressible, the body is able to shorten only through bending when the muscles attached to it contract.[26,27]

The flexibility of ribs, twist of spine during undulation, and the ability to do serpentine movement on smooth surfaces strengthen the idea that snakes establish peg points by deforming its body when external peg points are not available. In order to investigate the truth of this idea, simulation was run (Section 4). More details of this are mentioned in Section 5.

4. Simulation of snake movement

In order to understand that a snake can launch peg points during lateral undulation by deforming its body, a series of simulations were performed with Visual Nastran and later with ADAMS. These are two mechanical simulation software programs for the dynamic analysis of moving parts. Due to rope modeling capability of Visual Nastran, this software was the first candidate. The rope modeling capability was

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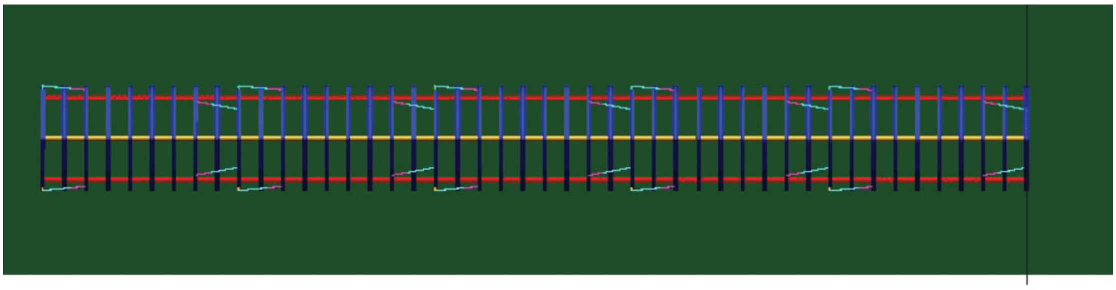
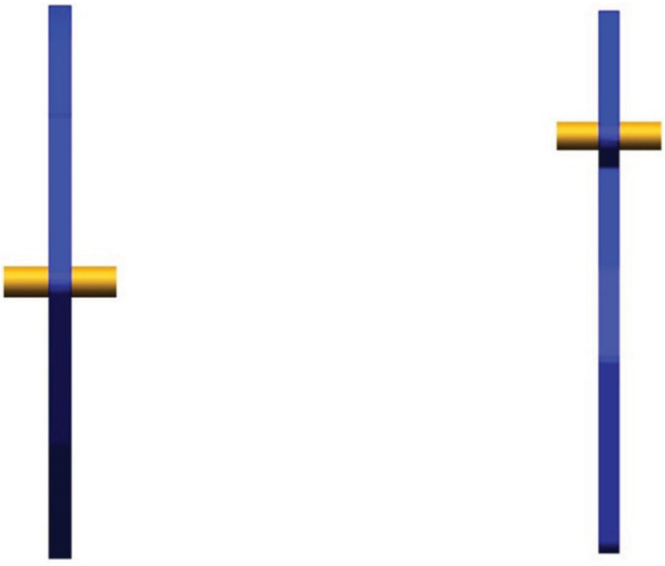


(a)



(b)

Fig. 10. (Colour online) Schematic of the snake model built in simulation software. (a) The whole model. (b) 1. Top view of a single vertebra, 2. side view of a single vertebra. (c) Connection of two vertebrae (both top and side view). Note: ADAMS does not show actuators on the screen; usually a blank area appears. Hence, to avoid any ambiguity, the authors replaced the blank area with double-sided black arrows.

required to model tendons. As it would be explained later, this option didn't work the way the authors expected. Also, the software failed to model a large number of models. Therefore, ADAMS was considered as the next simulation option.

Three different rib designs were considered for simulation to understand the effect of rib shape in snake robot movement. These designs are shown in Fig. 9.

In design (1) the rib is composed of a main arc (circle B in Fig. 9(a)) and two small arcs (circle C). The main arc is the main support for body and internal organs. Arc C facilitate rapid rotation of rib. This structure was designed with more details to better resemble a real snake structure. Naturally, the model is heavier and takes more time to simulate.

Designs (2) and (3) are simpler ones. These are considered in case attempts to simulate design (1) fail. Design (2) possesses only the necessary details and has uniform ribs, while design (3) has ribs with non-uniform cross section to check whether rib's end rigidity affects the snake's progress speed.

The model built in simulation software consists of 46 vertebrae. Two cylindrical extensions are connected to each rib's sides (Fig. 10(b)).[5] These cylindrical extensions are connected by 2-DOF joints (the hook joint in ADAMS) on two immediate ribs. Each joint allows bending in two orthogonal planes and resists against torsion. The properties of Links and Cylinders are shown in Tables II and III respectively. There are two series of springs and dampers employed at each side of the spine,[6] located between two consequent ribs (Figs. 10(c) and (d)).

In order to resemble a muscle and its tendon, two connected ADAMS links (with spherical joint connection) and a linear

[5] At point (0, 0) (the coordinate axes are shown in figure 9).
[6] At points (−14, −27) and (14, −27). Please pay attention that the coordinates mentioned here are not based on a real snake anatomy. These are just the coordinates selected by authors to check if the deflection of body can make peg points to make the structure move. The location of points will not affect the idea under discussion in this paper.

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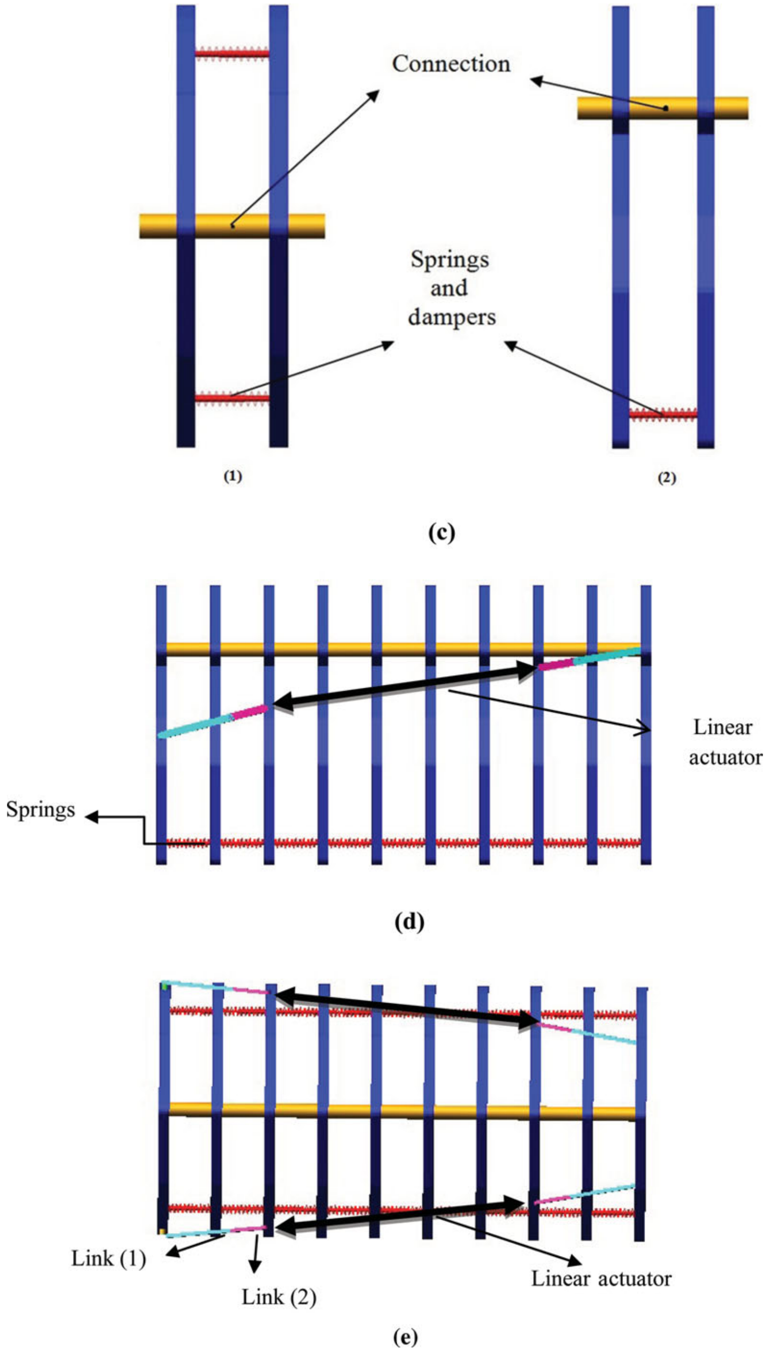

Fig. 10. (Colour online) Continued.

actuator are employed. The muscle–tendon set is extended along 10 ribs on each side of the spine (Figs. 10(d) and (e)).[7] The directions of the two connected links at first and tenth ribs are toward each other.

Since the snake moves over a frictional surface, impact contacts are defined between each rib and the ground with various dynamic and static friction[8] and stiffness.

In order to select the proper material for ribs, different choices, such as plastic, wood, steel, etc., were tested. Their property did not affect the simulation considerably. As it will be explained later, here the contact stiffness plays a major role rather than the type of material used. This is not really what happens in practice, but this is the way the software works. The material properties of ribs listed in Table I are mainly the steel properties. However, any other material can also be used.

Modeling of ribs, tendons, and muscles was a tedious job. Two available modeling software programs were Visual Nastran and ADAMS. None of these had a flexible component to model tendons. Visual Nastran has a rope element. However, the rope does not recognize collision.

[7] One end at point $(-10, 0)$ on the first rib and another end at the point $(-18, -12)$ of the other rib.

[8] To clarify the discussion, dynamic friction occurs when two objects are moving against each other (like a sled on the ground), and static friction is the friction between two solids that are stationary with respect to each other (http://en.wikipedia.org/wiki/Friction).

Table I. Material properties of ribs.

	Density (kg/mm^3)	Young's modulus (N/mm^2)	Poisson's ratio	Mass (kg)	Spring constant (N/m)	Damper value (N/m)	Depth (mm)
Design (2)	7.801×10^{-6}	2.07×10^5	0.29	4.63×10^{-3}	1000	1	1.5
Design (3)	7.801×10^{-6}	2.07×10^5	0.29	4.73×10^{-3}	1000	1	1.5

Table II. Properties of links.

Dimensions	Dimensions	Variable
	Link (2)	Link (1)
10 cm	30 cm	Length
1 cm	1 cm	Width
0.5 cm	0.5 cm	Depth
7.801×10^{-3} kg/cm^3	7.801×10^{-3} kg/cm^3	Density
2.07×10^3 N/cm^2	2.07×10^3 N/cm^2	Young's modulus
0.29	0.29	Poisson's ratio

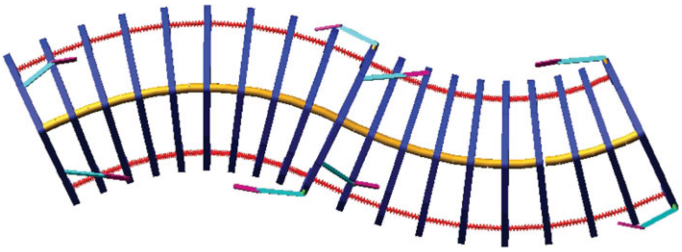

Fig. 12. (Colour online) Model 2 for the simulation of muscles and tendons.

Table III. Properties of a cylinder.

Dimensions	Variable
5 cm	Height
1.5 cm	Radius
7.801×10^{-3} kg/cm^3	Density
2.07×10^3 N/cm^2	Young's modulus
0.29	Poisson's ratio

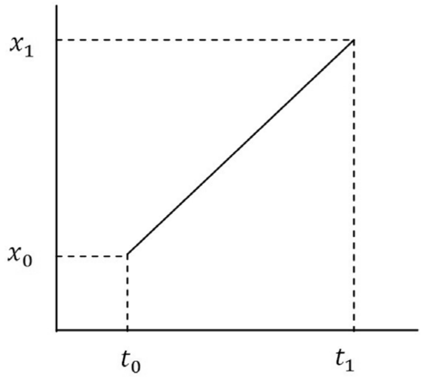

Fig. 13. Actuator expanded length.

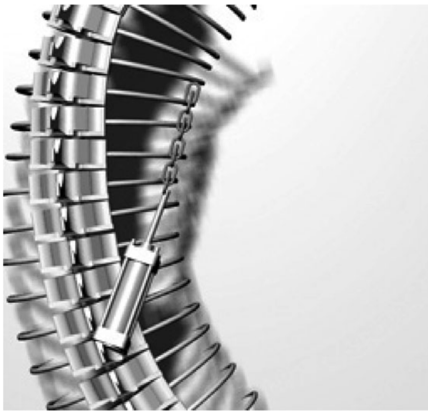

Fig. 11. Model 1 for the simulation of muscles and tendons.

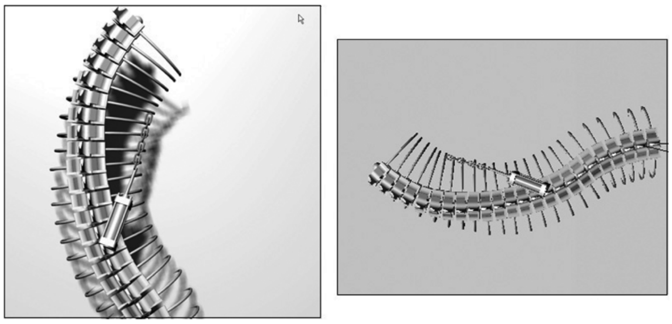

Fig. 14. Model 1 twist in body.

It was tried to combine existing elements in the software to resemble the flexibility of tendons without making the simulation heavy. The following two models were the most successful ones to resemble snake muscles and tendons:

- Model 1: A set of linear actuator (as muscle) and a seven-link chain (as tendon, Fig. 11).
- Model 2: A set of linear actuator and two connected links with a spherical joint at the end of each link (Fig. 12). Each set is extended over every 10 modules. The combination of linear actuators, springs, and dampers facilitate contraction and expansion modeling of muscles. Actuators also follow the following equation for performing:

$$\text{Actuator expanded length} = \text{Step}\ (\text{Time},\ t_0,\ x_0,\ t_1,\ x_1), \quad (1)$$

where t_0 and x_0 are initial time and position, and t_1 and x_1 are second time and position. The graph is presented in Fig. 13.

Visual Nastran was unable to simulate a large number of ribs, muscles, and tendons, while ADAMS could handle these easily.

There exist a lot of muscles in snake's body and since it is impossible to utilize all of them, only the most effective ones in locomotion were considered.

Another problem in simulation was the understanding of the way the software considered stiffness in simulation. ADAMS defines stiffness between two adjacent points without considering the material of the structure and its

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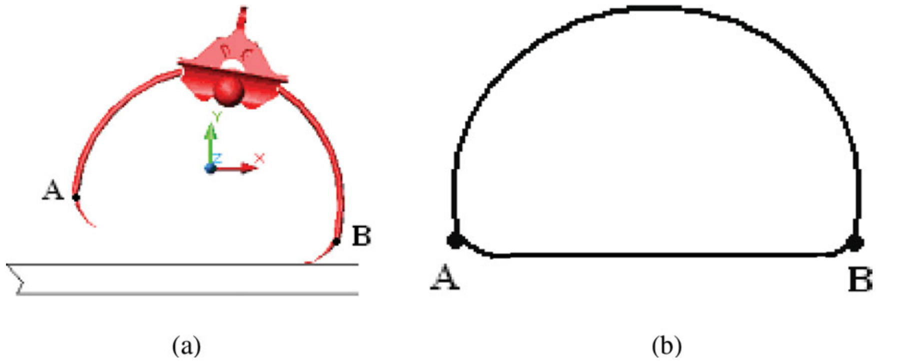

Fig. 15. (Colour online) (a) Arcs C facilitate rapid rotation; (b) it is easier to rotate a mass when the edges are curved.

flexibility, or the ground. In other words, stiffness is a relative parameter defined between two contact surfaces independent of the surfaces' construction material. The higher the stiffness, the harder the contact between two points. Therefore, it is impossible to compare the simulation results of the motion of a snake with hard ribs on a loose surface with the motion of a snake with flexible ribs on a hard surface if their relative stiffness is same.

5. Results and Discussion

5.1. Successful simulation runs

On the basis of field, fluoroscopy, and autopsy observations, as well as simulation runs on lateral undulation, the following results were achieved.

Rib design 1 is the closest model among the three designs of snake's rib construction. The maximum number of vertebrae that the authors could simulate with this design was 24. The other two designs were successfully utilized in the simulation of a 48-vertebrae spine. Regarding the muscle–tendon model, model 1, which was the closest model to real tendons and muscles, was very heavy for simulation. A maximum number of 10 muscles were simulated with this model. Muscle–tendon model 2 was successful in simulation.

5.2. Investigation of muscle arrangement on spine twist

A simulation was performed based on the rib design model 1, muscle–tendon model 1, and muscular arrangement given in Fig. 2. The simulation result showed that the muscular arrangement described in Figs. 10(b) and (c) causes twist in body (Fig. 14). Twist of spine helps easier deformation of tiny ribs under local body weight to establish a good supporting area or peg point for snake locomotion.

Arc C at the two ends of rib design 1 (Fig. 9(a)) facilitate rapid rotation of spine (Fig. 15(a)). In fact, less force is required to twist the spine with the help of these arcs. In the real life experience, it is easier to displace mass with curved edges (Fig. 15(b)). Rapid rotation increases the speed of peg points' formation during rapid undulation. As the reader can see in Fig. 8(b), similar extension exists in the ribs of a real snake.

5.3. Impact of rib design, rib stiffness, and static and dynamic friction on progress

In this section a number of lateral undulation simulations have been carried out for a 46-vertebrae snake model. The run time was 4 seconds for two complete undulation steps. Figure 16 shows the initial stand point of snake (Fig. 16(a)), as well as the body shape and the active/relaxing actuators during simulation steps (Figs. 16(b) and (c)) along with progress of head (Fig. 16(d)).

In order to find out the impact of rib design and stiffness on the progress of snake, a series of simulations with different rib designs (designs 2 and 3) under different surface dynamic and static coefficients of friction (μ_d, μ_s) with diverse rib stiffnesses (shown by parameter k) were performed. The results of simulation are given in Fig. 17.

As graphs in Fig. 17 show, rib design (2), which is less rigid, causes larger displacement of robot's head in forward direction compared with rib design (3), which is more rigid. Also, the robot progress improves with increase in surface friction. This might be because the peg points are essentially static points; hence, larger friction establishes a better support. In addition, the progress of snake under low stiffness is more effective. Lower stiffness is the result of flexible ribs.

In order to check the idea that peg points are essentially static, a series of simulations were performed for rib design (2) under different dynamic and static coefficients of friction (Figs. 18 and 19). The results show that dynamic friction (μ_d) does not impact snake displacement (Fig. 18). However, an increase in static friction (μ_s) will increase displacement up to certain level. This justifies that with lower stiffness (more flexible ribs), peg points are better established on a smooth surface. This is also a supporting evidence for the idea that peg points are essentially static. This explains why snake in Fig. 4 can move over smooth surfaces. With flexible ribs, snake can establish its own peg points regardless of the surface texture (although this is not true for very smooth surfaces).

In order to investigate the impact of joints' quality and muscle behavior on the locomotion of snake, further simulation was done for different joint spring constants (Fig. 10(b)) and muscle deformation (retraction/expansion, Fig. 10(c)). The results are depicted in Figs. 20 and 21. For spring constant there is an optimum value for which the maximum displacement is achieved (Fig. 20). The most interesting result is the impact of muscle deformation on progress. As muscle deformation increases, the snake

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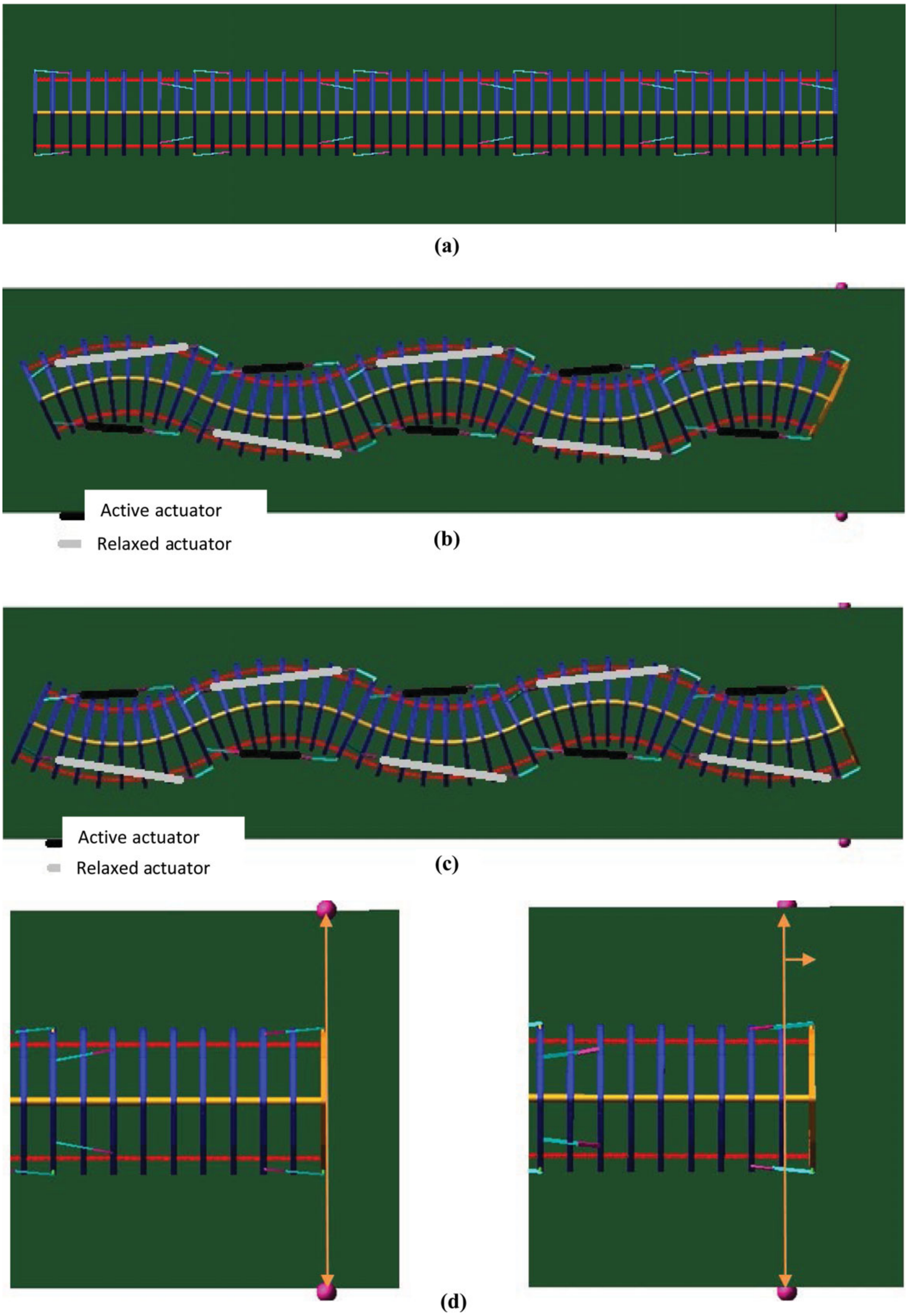

Fig. 16. (Colour online) (a) The snake model standpoint; (b) first undulation step; (c) second undulation step; (d) shows the snake robot progress after two undulation steps.

progress in each undulation increases. A larger muscle deformation results in a larger twist in spine (Fig. 21). Therefore, ribs experience a larger load and consequently a larger deformation. As explained earlier, the deformed ribs establish wider and stronger peg points. As described in Section 3, it should be emphasized one more time that the peg points are static areas on ground and do not move with snake.

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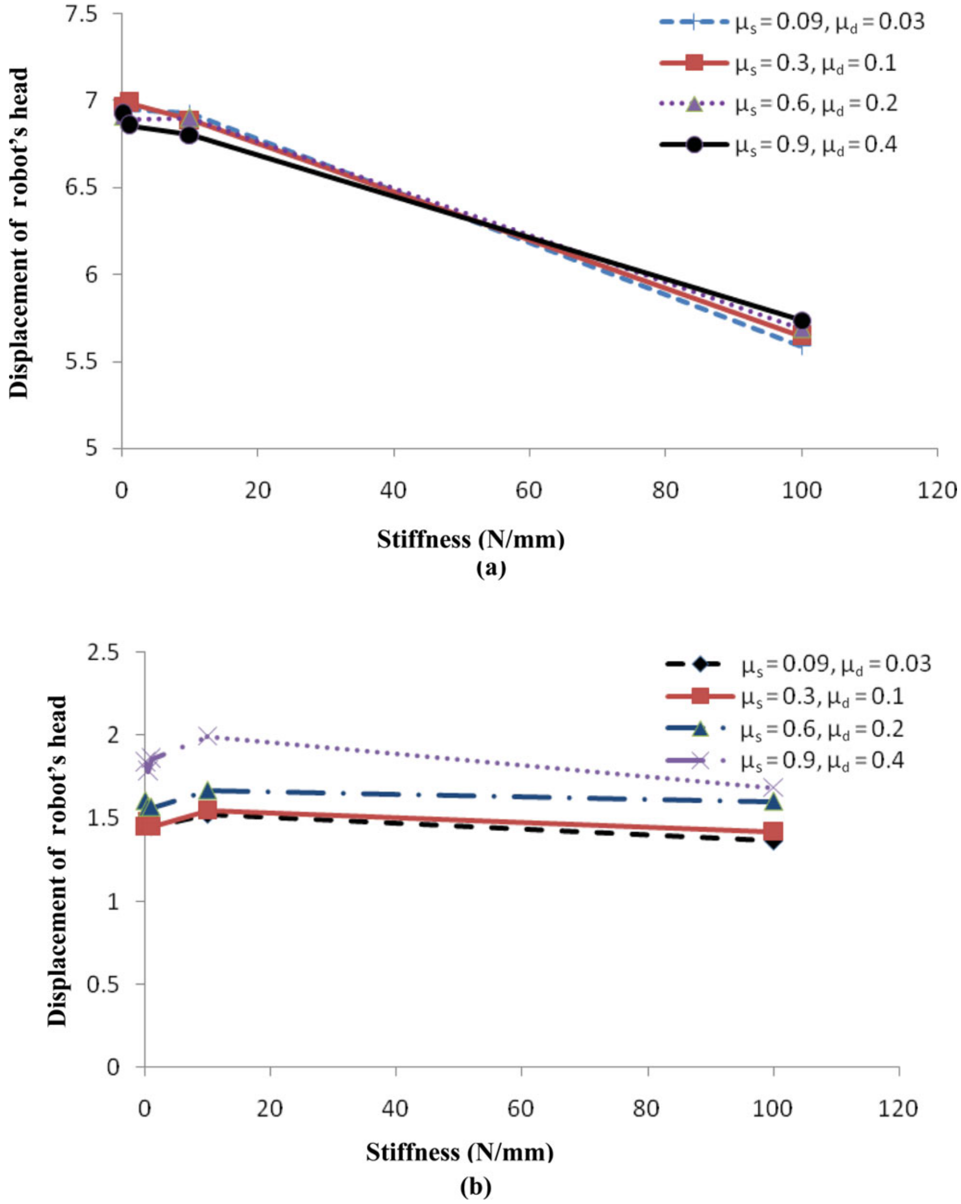

Fig. 17. (Colour online) Effect of stiffness on displacement of snake (a) rib design (2); (b) rib design (3).

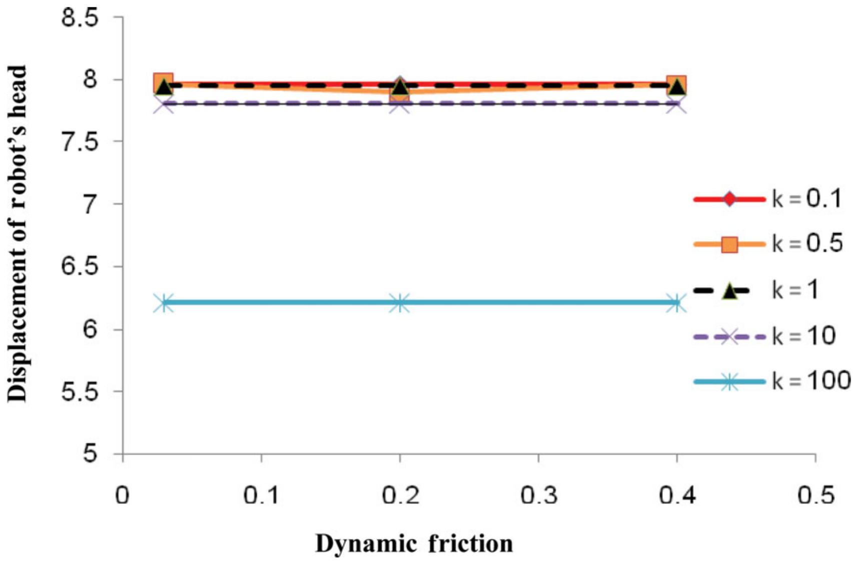

Fig. 18. (Colour online) Effect of dynamic friction on displacement of snake robot for $\mu_s = 0.3$ (rib design (2)).

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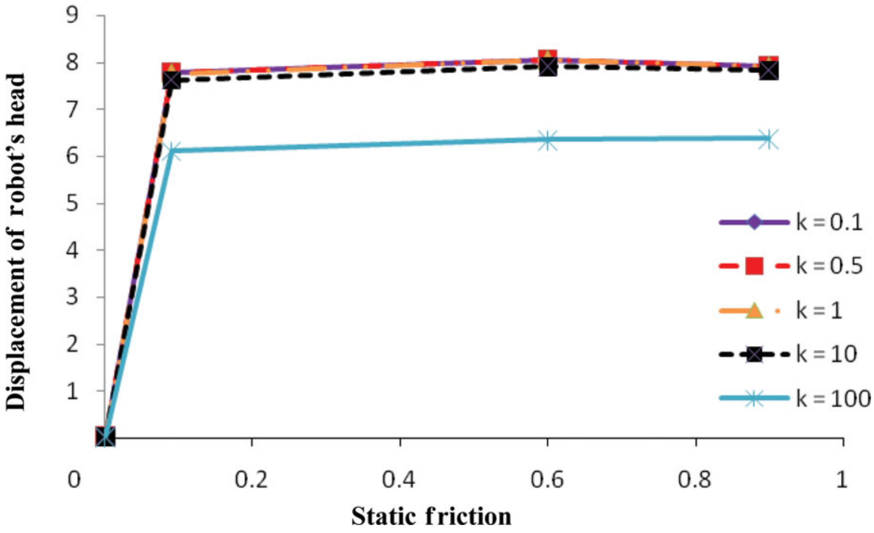

Fig. 19. (Colour online) Effect of static friction on displacement of snake robot for $\mu_d = 0.1$ (rib design (2)).

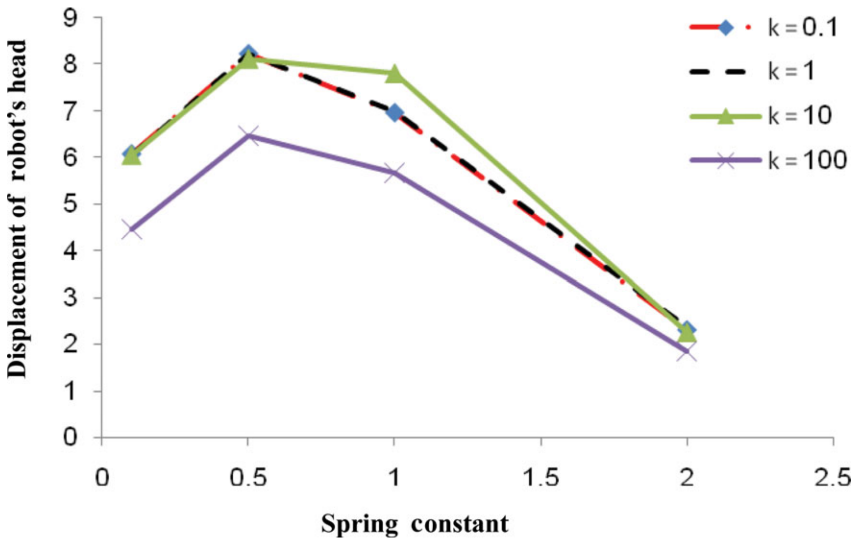

Fig. 20. (Colour online) Effect of spring constant on displacement, rib design (2).

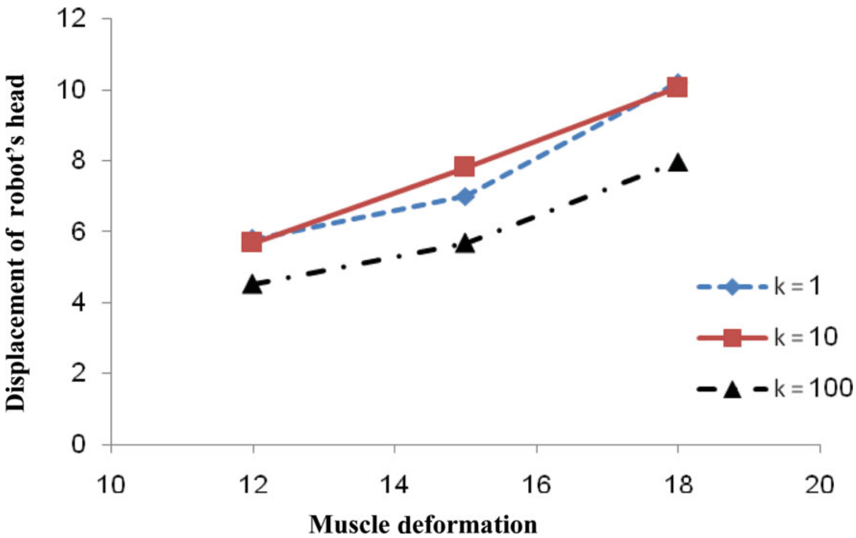

Fig. 21. (Colour online) Effect of muscle deformation on displacement, rib design (2).

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6. Summary and Conclusions

In this paper we tried to understand wheel-less locomotion mechanism in snakes and find an engineering justification for these observations. Field study, fluoroscopy imaging, autopsy, and simulation were performed together to realize the reality. Some differences were found with respect to previous publications. The major contribution was the ability of snake to establish peg points and move forward by deforming the body rather than seeking irregularities on ground. As the simulation results in Section 5 show, progress can be obtained on a flat surface where only body deformation exists.

It was also found that rib flexibility, rib design, and spine twist angle assist in better initiation of peg points. The static friction of surface will improve locomotion of snake. The authors hope these results will help to design wheel-less snake robots.

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