Biological Characteristics Analysis and Mechanical Jumping Leg Design for Frog Robot

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Abstract. This paper describes the biological observation and kinematic analysis of frog jump modality from three phases, and the use of these data to combine and simplify the frog's movement. The dynamic simulation based on these data provides the ground reaction forces which aid in robot design. A kind of hindlimb model is put forward, and corresponding jumping leg robot is designed according to trajectory and function of the limb's main joints. The robot has 5-bar spring/linkage leg and actuated by a DC motor. Its jump ability that studied and compared with frog is proved to be good efficiency. The results of analysis, simplified model and mechanical leg will be employed to develop and control a whole robot capable of mimicking the jumping behavior of the frog.

Keywords: frog jump modality, kinematic analysis, jumping robot, modeling.

1 Introduction

For some time, roboticists have used animal behavior as inspiration to design a robot. Locomotion, and in particular jumping, has received a large portion of this attention. An effective mobile robot should possess the ability of traversing over large obstacles, and agilely maneuvering in tight surroundings. Jumping robots exemplify the need for this ability.

Previous work has shown that the application of biological principles into the robot design can improve its performance. Raibert developed one-, two-, and four-leg hopping and running robots by incorporating biologically-inspired dynamics into their design [1]. These robots had telescoping legs with internal air spring for compliance, and hydraulic actuators. Birch constructed a cricket microrobot. It fit within a two-inch cube, and could both walk and jump to navigate the obstacles [2]. Hyon developed a hopping robot "KenKen" inspired by dog. The robot used two hydraulic actuators as muscles and a tensile spring as tendon. It could succeed in hopping in a plane [3]. Yamakita proposed a robotic system from cat's behavior, which moved in a vertical direction as a cat kicks a wall to jump up to a roof [4].

We select frog as a model for the development of jumping robot because of its remarkable jumping capability (bullfrog could jump even more than 15 times of its body length). In order to produce such a robot, we first make kinematic observation and analysis of the frog and obtain the raw data for simulation and modeling, as well as get the insights into robot construction. Then we identify a model that is simplified

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from frog's complex movement and capable of jumping. Finally we develop a jumping leg robot on basis of the hindlimb model of frog, and make analysis and experiment on its jump ability and efficiency.

2 Biological Observation and Analysis

2.1 Frog Morphology

Three frogs (Rananigromaculata) were obtained from a commercial supplier for the research, and measurement were made of each animal's body mass (M_b) in grams, snout-vent length (L_{sv}), hindlimb length (L_{hl}) and forelimb length (L_{fl}) in millimeters, as well as the distance from the sacral joint to the vent (L_{sac}), in millimeters (Table 1).

Table 1. Mass and size of the frogs

No.	M_b (g)	L_{sv} (mm)	L_{hl} (mm)	L_{fl} (mm)	L_{sac} (mm)
01	20.4	57.5	96.3	32.0	21.2
02	25.2	59.0	93.5	30.5	19.7
03	21.8	56.0	94.0	30.6	20.5

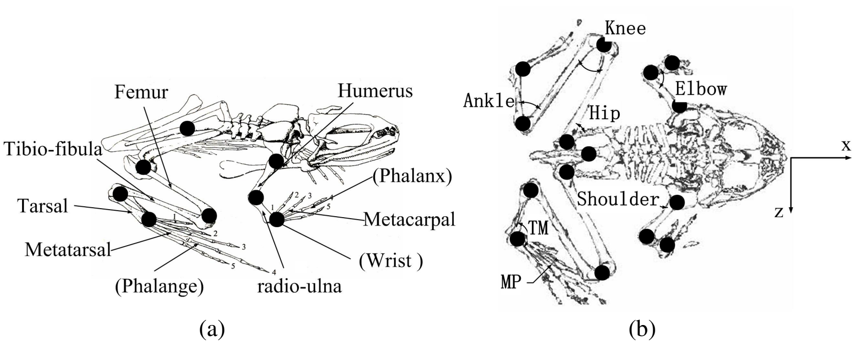


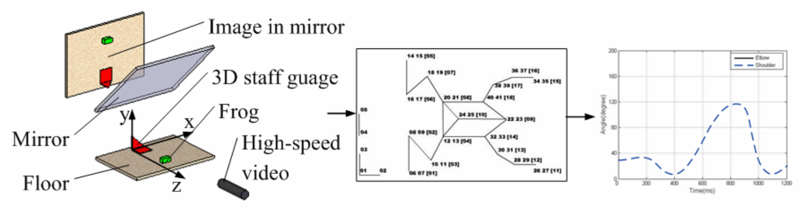
Fig. 1. Skeleton of frog. (a). Side view of frog with digitizing points marked and segments identified. (b). Dorsal (top) view of frog with digitizing points and joints identified.

Frog evolved marked disparity in the relative size of hindlimbs and forelimbs. The forelimbs that served in steering are small. But the hindlimbs are relatively large and strong, enabling them to propel frog in both jumping and swimming. Both forelimb and hindlimb have five distinct segments (Fig. 1(a)). Starting from the body attachment point, the forelimb segments are: humerus, radio-ulna, metacarpal, wrist and phalanx. The hindlimb segments are: femur, tibio-fibula, tarsal, metatarsal and phalange [5]. We regard metacarpal, wrist and phalanx of forelimb as a whole segment, also metatarsal and phalange of hindlimb as a whole segment for the convenience of observation. To enable complex positioning of the entire hindlimb, the hip joint has 3 DOF. The knee, ankle and TM (displacement of the tarsal relative to the metatarsal) joints are simple 1 DOF joints and act in the same plane. For the same reason, the shoulder joint has 3 DOF. Elbow and wrist are simple 1 DOF joints.

Although the forelimb and hindlimb are not arranged in complete orthogonal planar fashion, we have determined a relative x-y-z axis orientation to assist in analysis. By definition, the animal's horizontal, longitudinal line (directed tail to head) is the x-axis. The lateral, horizontal side-to-side line is the z-axis. Finally, the vertical line directed upward is the y-axis (Fig. 1(b)).

2.2 Experimental Setup

In order to observe and measure frog's movements, we built a platform to collect the necessary data such as individual joint angles. The platform was consisted of a High-speed video (100 frames per second), a mirror and a three-dimensional (3D) staff gauge (Fig. 2). The mirror was mounted above arena at a 45° angle to allow simultaneous filming of both side and top views. 3D staff gauge that provided x (longitudinal), y (vertical), and z (lateral) orientation coordinates, helped us get accurate data. 3D information of the black dots that locating on the joints of limbs and body was obtained from video images by program (Fig. 1 and Fig. 2). After the correction of these digitized data from the effect by perspective, the program finally reconstructed the true angles of the joints in 3D as frog jumped on the arena [6]. The temperature was kept at 20-25°C during the experiment.



(a) (b) (c)

Fig. 2. Schematic showing data collection methodology. (a). The experiment platform. (b). The program used to deal with video and get digitized data. (c). Example of digitized shoulder joint.

2.3 Jumping Performance

On the basis of frog's actions, three phases in the jump were identified from the video recordings (Fig. 3): (i) the take-off phase, which lasts from the first movement from the 'jump-ready' or crouched position to the point at which the frog leaves the ground; (ii) the aerial phase, which lasts from this point until the frog first touches the ground again; (iii) the landing phase, measured as the time from the first contact with the ground to the resumption of the 'jump-ready' position.

At the beginning of take-off phase, the hip and knee are greatly flexed; in fact, the thigh and shank that bent underneath the body are completely folded. The TM joint is flexed about 120° to elevate the ankle so that it is not in contact with the ground. Forelimbs act to support body and position for take-off.

As the muscles are activated and shorten, the generated power leading to a rapid extension of the hindlimbs which, in turn, propels the frog into the air. While the hip, knee, and ankle extend during initial take-off phase, most of the foot (metatarsals and phalanges) remains in contact with the ground, and the TM joint extend just slightly.

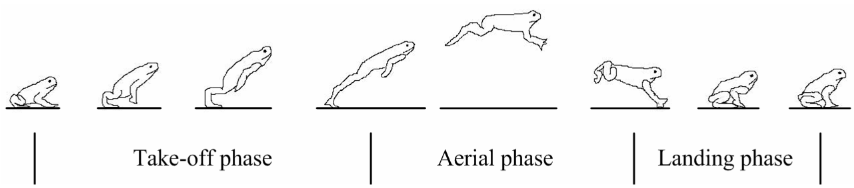


Fig. 3. Three phases of frog jumping movement

During initial take-off phase, the elbow extends and the humerus retracts as the forelimbs come off the ground. It seems unlikely that this extension of the small forearm segments contributes much, if any, power to the jump. Nevertheless, the forelimbs probably supply balancing and steering as the animal initiates a jump [7].

During the aerial phase, the hip, knee, ankle, and TM joints of hindlimbs begin flexing, and the forelimbs are extended to prepare for landing.

In the final landing phase, the hindlimbs flexion is completed. The forelimbs act to support and decelerate the frog before its body is pivoted ventrally about the shoulder until the hindlimbs contact the ground. At that point, the bulk of the body weight is transferred posteriorly to the hindlimbs, and the toad is ready to jump again.

The long, soft and multi-jointed foot is one critical element for successful jump performance. Its movements with leg keep most of the plantar surface in contact with the ground for as long as possible, and also cause the site of push off to shift continuously from the back of the foot forward. For an animal with feet the length of a frog's, this would allow for more controlled extension. Keeping the broadest part of the foot in contact with the ground throughout propulsion also permits continuous adjustment of balance so that rapid changes in direction and/or trajectory could be made. Additionally, these movements maximize the velocity of limb extension and the final takeoff velocity by maximizing the contact of the foot (to keep pushing for the longest possible time as the upper limb segments extend) and by combining velocities of as many joints as possible. Thus, the elongated foot of the frog functions to produce very large takeoff velocities [8], and the foot with TM joint should be regarded in robot design.

2.4 Analysis of Joint Trajectory

In order to find the characteristic of jump movement, we compared and analyzed the joint trajectory based on the kinematic data from experiment. Five similar jumps (the take-off angle is about 30° and jumping distance is about 0.5m, take-off angle was measured from the frame at take off) were selected. Fig. 4(a) and 4(b) show the mean joint angles of the forelimb and hindlimb respectively.

From Fig. 4(a), we get that the shoulder and elbow joints change greatly from the time that frog touches the ground. But the former has more extension, because it perhaps contributes more to support and decelerate the frog.

During the take-off phase, joint extension appears to be temporally staggered, with the hip and knee beginning to extend prior to or initially faster than the more distal ankle joint (Fig. 4(b)). However, the hip, knee and ankle joints of hindlimbs have very similar trajectory and range during the whole jump (Fig. 4(b)). The TM joint has relative small range and extends until the end of take-off phase. This movement pushes the tarsal upward and forward throughout propulsion, through which to realize the function of foot mentioned above.

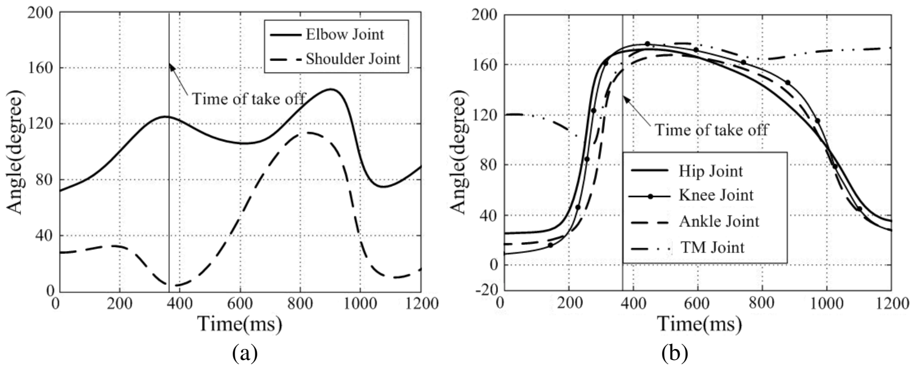


Fig. 4. The mean joint angles of 5 jumps. (a). Elbow and shoulder joints of forelimb. (b). Hip, knee, ankle and TM joints of hindlimb. The time of take off from the ground is at about 360ms.

2.5 Biological Summary

Kinematic analysis of frog jumping provided critical 3-dimensional space point data for simulation and modeling of these behaviors. Additionally, insights into mechanical construction were also obtained. Notably, the role of forelimb (in supporting and positioning more than in taking off), the similar trajectories of hindlimb joints during jump and the function of foot during take-off phase is issues that must be addressed in design.

3 Dynamic Model of Frog

We developed a dynamic model of frog to help us understand the biological data and assist in design of the robot. There are a total of 18 DOF in the model. Each hindlimb has 3 DOF at the hip joint, 1 DOF at the knee joint, and 1 DOF joint at the ankle joint. Each forelimb has 3 DOF at the shoulder joint, and 1 DOF at the elbow joint.

The inputs to the simulation include the lengths and inertia of all limbs segments and the body, and joint trajectories from the biological kinematics study of frog. We choose the parameter of No.01 frog as the inputs to the model (Table 1). The output from the simulation provides the overall body movement and ground reaction forces.

Fig. 5 shows the ground forces during take-off phase. Early in the jump, the forces exerted on the ground are low (the ground force of Fig. 5 at onset includes the gravity of frog) and they then increase to a peak before falling rapidly as the frog approaches

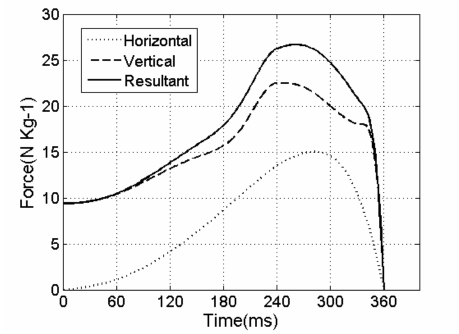


Fig. 5. Ground reaction force during take-off phase of frog

to takeoff. The high peak power late in takeoff could be explained by the redistribution of power output by elastic elements, for example tendons, in series with muscles [9]. This character is very helpful in the design of jumping leg robot.

4 Hindlimb Model and Jumping Leg Robot

According to the kinematic analysis of frog jumping that hip, knee and ankle joints of hindlimbs have similar trajectory and range during jump, we put forward a kind of model to mimic the movement of hindlimb (Fig. 6). Like the elastic elements of frog that used for energy store, we employed spring as a convenient and robust storage mechanism. Three joints could be simplified and compressed just by one motor via a cable.

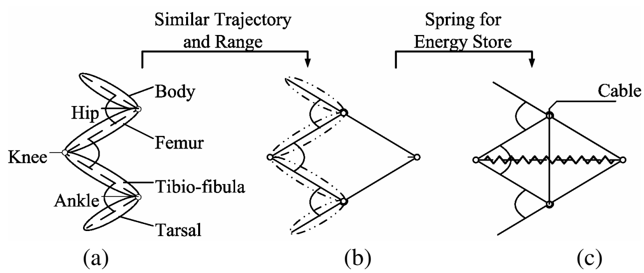


Fig. 6. The model is identified according to kinematic analysis. (a). Simplified leg of frog. (c). 4-bar spring/linkage of hindlimb model.

Fig. 7 and Fig. 8 depict the jumping leg robot according to this model. Though the cooperation of tooth-lack gear, one-way bearing, ratchet wheel and pawl, it can realize the action of jumping and leg retracting in the air by a single DC motor. Plate spring is used to keep balance temporarily in stead of forelimb. The angle of take off could be adjusted by bolts on the plate spring. The robot weights 0.7kg, and its length, width and height are respective 270mm, 95mm and 136mm under compressed state.

We adopted 5-bar spring/linkage mechanism instead of 4-bar because there is only 1 DOF due to restriction of the gear on linkage b, and the leg extension can be along *y*-direction. One end of spring is fixed on the axis of knee, and another is connected with reel 2 by cable 2 (used for adjusting the length of spring). There was a TM joint (passive) on the foot, it could prevent slipping and enhance stability by keeping the plantar surface in contact with the ground for as long as possible during take-off, and that it could elevate the ankle joint in case the leg contacts with the ground.

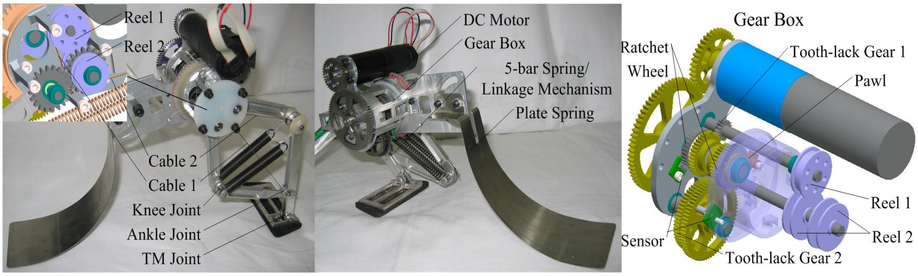


Fig. 7. Jumping leg robot (under compressed and uncompressed state) and gear box

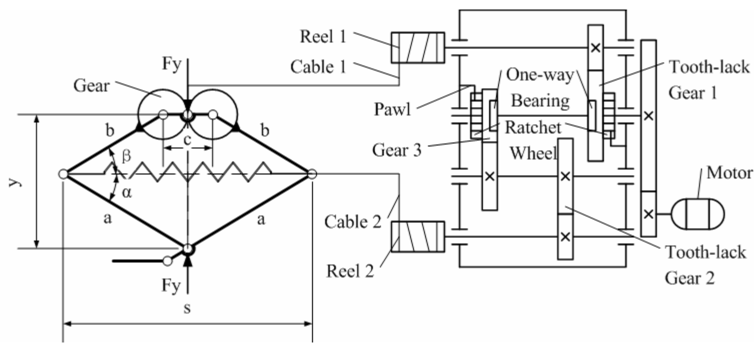


Fig. 8. Schematic transmission system of jumping leg robot

In effect, the 5-bar spring/linkage creates a nonlinear spring from a linear spring. In addition, this concept can be practically implemented in a stiff structure with low internal friction. The thrust force verse y displacement relation for this mechanism can be determined as follows. From the geometry of the 5-bar linkage in Fig.8 one can derive the expression:

$$\begin{cases} a\sin\alpha + b\sin\beta = y \\ a\cos\alpha = b\cos\beta + \dfrac{c}{2} \end{cases} .$$

Where a, b, c denote the length of linkage. After expunction of β, we can obtain:

$$2y\sin\alpha + c\cos\alpha = \left(y^2 + c^2/4 + a^2 - b^2\right)/a \ .$$

If $\lambda = \left(y^2 + c^2/4 + a^2 - b^2\right)/a$, $\rho = \sqrt{4y^2 + c^2}$, $\phi = \arcsin(c/\rho)$, we can obtain:

$$\alpha = \arcsin\frac{\lambda}{\rho} - \phi \;; \tag{1}$$

$$\beta = \arcsin\frac{y - a\sin\alpha}{b} \;. \tag{2}$$

If F_y denotes the thrust force in y-direction, s is the length of spring, F_a and F_b denote the force of linkage a and b respectively, s_0 is spring's undistorted length and k is spring's constant, through analyzing the force of linkage we can derive the expression:

$$\begin{cases} F_a\cos\alpha + F_b\cos\beta = k\left(s - s_0\right) \\ 2F_a\sin\alpha = F_y \\ 2F_b\sin\beta = F_y \\ s = 2a\cos\alpha \end{cases} .$$

After expunction of F_a, F_b and s we can obtain:

$$F_y = \frac{2k\left(2a\cos\alpha - s_0\right)}{\left(\dfrac{1}{\tan\alpha} + \dfrac{1}{\tan\beta}\right)} \;. \tag{3}$$

An expression for F_y as a function of y can be obtained by substituting Eq. (1) and (2) into Eq. (3). Fig.9 plots F_y vs y for the case where a=80mm, b=70mm, c=20mm, k=1.4N/mm, s_0=60mm.

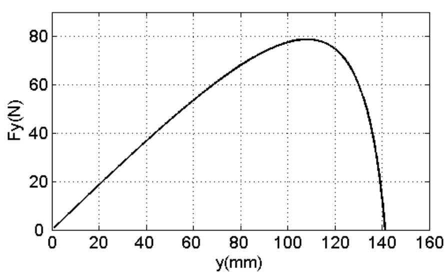


Fig. 9. Fy vs y of the 5-bar spring/linkage mechanism

We found that the mechanism had similar process of the thrust force with frog during take-off phase by comparing Fig. 9 with Fig. 5. At the onset of take-off, the thrust force is quite low and it then increase to its maximum before falling rapidly as the mechanism approaches to the end of take-off. The jump with this characteristic possesses the advantages of low likelihood of premature lift-off and low energy loss. Moreover as most of the elements concentrate on the body of robot, the relatively light foot could make jumping to be high efficiency.

Control of the robot by the motor is implemented with the aide of two one-way bearings (Fig. 8). Ratchet wheels that assembled in one side of gear 3 and gear 1 match with pawls, which insure that those two gears can rotate only in one direction. With the opposite orientation limit of the bearings, the positive rotation of the motor drives tooth-lack gear 1 and reel 1, and realizes the retraction and release of the leg by cable 1. While the negative rotation of the motor drives tooth-lack gear 2 and reel 2, and could adjust the length of spring by cable 2. Sensor is used to detect the position of tooth-lack gear. Fig. 10 depicts the relative phasing and motor rotations for each operation.

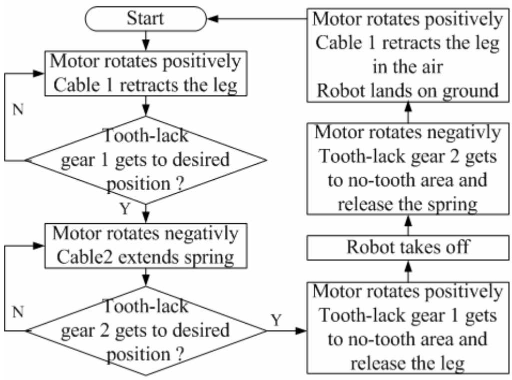


Fig. 10. Control flow of jumping leg robot

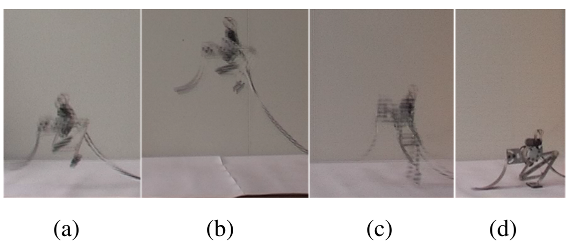


Fig. 11. The experiment results of jumping leg robot. (a). Landing phase. (b). Flight phase. (c). Take-off phase. (d). Start phase.

A number of tests were performed to assess this design especially on its jumping ability. Fig. 11 illustrates a complete jump of the robot, and Fig. 12 shows its joint trajectory. By comparing it with Fig. 4(b), we found that the robot's knee, ankle and TM joints has similar characteristic with that of frog during take-off phase, while the range of hip joint is about half of the knee or ankle joint because of the restriction of 5-bar spring/linkage. So we plan to add 1 DOF at hip joint (rotation about z-axis, Fig. 1(b)) to increase its range in the next design of frog robot. During aerial phase the frog starts its hindlimb retraction from the moment that it is falling from the highest point, however the robot begins to retract leg just after taking off from the ground for economizing time.

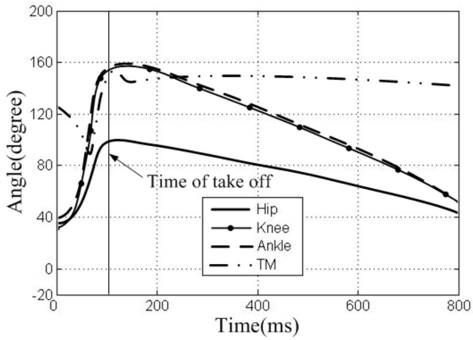


Fig. 12. The hip, knee, ankle and TM joints of leg robot during jump, and the time of take off from the ground is at about 100ms

The robot could jump a horizontal distance of 1120mm (4 times of the length of robot), and reaches a vertical height of 500mm (3.5 times of the height of robot) at best. That is nearly 70% conversion. The frog robot with this leg could potentially overcome large physical obstacles. Further more the robot can also realize the leg retraction in the air, which would increase the height of object that it is capable of jumping over, and decelerate the robot and land on the ground with stability.

5 Conclusion

Biological kinematic data were obtained from a jumping frog. These data and the function of chief joints at each phase were analyzed. A kind of hindlimb model was put forward and based on which a jumping leg robot was designed and studied. Ground forces of frog during take-off phase were derived from the simulation, and compared with the thrust force of the robot.

The result shows that the design achieves satisfying jump ability, good efficiency and leg retraction in the air. Hence it could be used as the hindlimb of frog robot. Moreover, the hindlimb will require another 3 DOF (rotation about x-axis, y-axis and z-axis, Fig. 1(b)) at hip joint for adjusting the direction and trajectory and increasing the range of hip. Because the function of forelimb is balancing and steering, there will be 1 DOF (rotation about z-axis, Fig. 1(b)) at shoulder joint to simplify the mechanism, and 1 DOF (passive) at elbow joint to support and decelerate the robot during landing phase. Continuing work will involve the design of whole frog robot, and corresponding control methods.

Acknowledgments

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