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A Compact Jumping Robot utilizing Snap-through Buckling with Bend and Twist

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Abstract— **In this paper, we propose a robotic catapult based on closed elastica utilizing bending and twisting deformation of an elastic strip. By using snap-through buckling generated from not only bend but also twist of thin rectangle elastic strip, impulsive forces can be generated repeatedly by the frequency of 3[Hz] without changing added torque directions. The compact jumping robot based on the proposed robotic catapult can leap over 950[mm] away. In addition, by setting the parameters appropriately to make the best use of generating impulsive forces with high frequency , it can perform repeated low-altitude jumping motions with about 1.06[m/s] velocity including quick step of about 0.152[s].**

I. INTRODUCTION

Repeated quick motions are seen a lot in nature. Water slider can not only move on water surface by puddling legs but also jump repeatedly on the surface [12]. In the certain situation, hare [13] , gerbil [14], and ermine [15] can perform the tremendous agility with quick step. Their agilities with repeated steps suggest that to generate not a large impulsive force but repeated impulsive forces is needed for achieving these quick motions. Our motivation is that if generating repeated impulsive motions can be achieved by a simple mechanism, it may be expected not only to expand the active area of robotics but also to indicate unexpected usages of robot. Our research objective is to achieve such repeated impulsive motion by developing repeated impulsive force generator with simple structure.

In recent years, there are some researches of the compact jumping robot that shows outstanding motions by utilizing elasticity, especially of a metallic material which is easy to make robot compact. There are deformable robots by Hirai et al. actively using the large deformation of the elastica. These robots can jump up to 300[mm] and shows a safety after dropping [3]. Kovac et al. developed the only 7[g] jumping robot utilizing an eccentric cam which loads a torsional spring that actuates the robot leg and can jump about 1.4[m] [2]. Armour et al. developed a spherical jumping robot which is actuated by shape memory alloy and linear spring [1]. Scarfoglielo et al. proposed a robotic click mechanism for a jumping robot which aimes at a driving frequency of 2[Hz] [6]. These robots explained above can generate impulsive motions by storing elastic potential energy on each metal materials and releasing as kinetic energy. However, since it is not easy to achieve outstanding motions by generating impulsive motions repeatedly, there are few reports [8] [4].

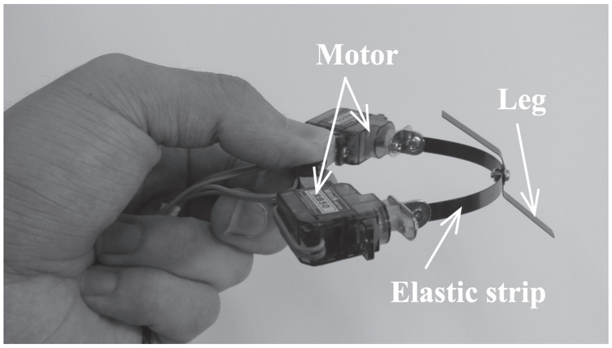

Fig. 1. The proposed compact jumping robot based on closed elastica with bend and twist

The author has proposed robotic catapult based on closed elastica which can generate repeated impulsive motions relative easily by storing elastic potential energy with bending a thin rectangle elastic material and releasing the stored elastic potential energy using snap-through buckling of the material [5] [10]. Since the robotic catapult is composed of simple elements, for example, two parallel rotational joints and thin rectangle elastic strip which two ends are fixed to the joints each other, some robots including the continuous jumping robot [8] and the impulsive swimming robot [7] succeeded in development. In this paper, we propose a novel robotic catapult utilizing bend and twist deformation of the elastic strip. By using elastic deformation of not only bend but also twist, we develop a compact continuous jumping robot which generates impulsive jumping motion with quick steps without changing rotational direction of the each motor.

II. A ROBOTIC CATAPULT BASED ON CLOSED ELASTICA WITH BEND AND TWIST

A schematic diagram of the proposed robotic catapult based on closed elastica with bend and twist is shown in Fig. 2. It has a very simple mechanical structure. It is just a bended elastic strip whose two ends are fixed to two rotational joints, respectively. As a result, it has a mechanical closed loop structure. The elastic strip is a thin rectangle shape which can be bent and twisted relative easily by hands. We note that the long axis of the elastic strip is on the axis of the rotational joints when it is seen from side view. Each joint fixed to the tip of the elastic strip is driven by motor, respectively and the angle of these rotational joint axes from a vertical line is θ, which is non zero value, as shown in Fig. 2.

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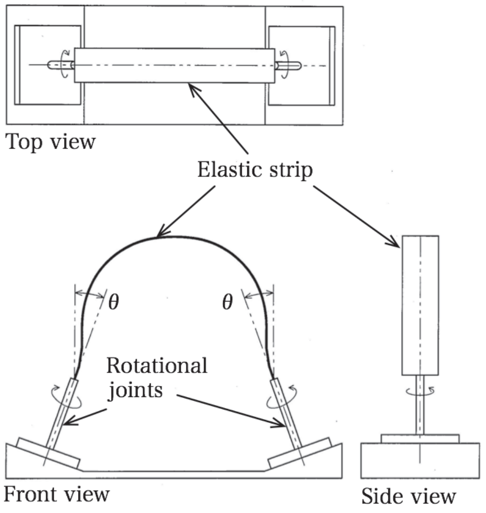

Fig. 2. A schematic diagram of the structure of the proposed robotic catapult based on closed elastica with bend and twsit

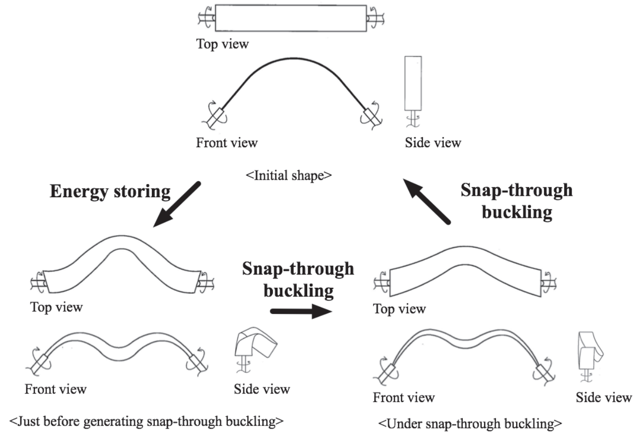

Fig. 3. A shape transition of the proposed robotic catapult based on closed elsatica with bend and twist. After snap-through buckling utilizing bend and twist deformation of the elastic strip, the elastic strip becomes the same shape of the initial one.

A shape transition of the proposed robotic catapult based on closed elastica with bend and twist is shown in Fig. 3. The shape of the elastic strip which has non twist deformation is considered as an initial shape. At the initial shape, by driving two active rotational joints in opposite directions each other, the elastic strip changes its shape from the arch shape to ”M” shape with bend and twist, that is, the elastic potential energy can be stored in the elastic strip. By continuing to drive the two joints, we can obtain impulsive motion based on snap-through buckling with bend and twist of the elastic strip by releasing the stored potential energy. When the snap-through buckling is generated, the elastic strip deforms rapidly from the complicated shape to the initial shape. Consequently, by only driving two active rotational joints in an inward direction, we can obtain the impulsive motion repeatedly.

We note that this point is very strong feature compared with the other robotic catapults based on closed elastica which have been developed by the authors [4]-[5], [7]-[10]. The other type robotic catapults can generate repeated impulsive motions by utilizing only bending deformation of the elastic strip. Then, after generating the snap-through buckling, to generate a next snap-through buckling requires to change the driving direction of the active rotational joint. On the other hand, in the case of the proposed type, it is not necessary to change driving direction of the rotational joint for generating impulsive motion repeatedly because the shape of the elastic strip can return to the initial shape after generating one snap-through buckling. As a result, it is expected that it can generate the repeated impulsive motions with higher frequency.

III. A COMPACT JUMPING ROBOT BASED ON CLOSED ELASTICA UTILIZING BEND AND TWIST

The proposed robotic catapult utilizing bend and twist needs not change the drive direction of the active rotational joints to generate repeated impulsive motion. In addition, this type catapult always generates impulsive motion to the one direction. On the other hand, the catapult which uses only bending has to generate impulsive force to two directions by driving the rotational joints back and forth for generating the force repeatedly [4]-[5], [7]-[10]. Then, the proposed catapult has a potential to become a repeated impulsive force generator for traveling ways which needs impulsive force only to one direction in general, for example, continuous jumping motion or repeated kick and sliding motion. In this chapter, we describe an compact jumping robot using the proposed robotic catapult as an impulsive force generator.

A. Construction

The proposed compact jumping robot is shown in Fig. 1. The robot is composed of a thin rectangle elastic strip which both sides are fixed two active rotational joints. The active rotational joints are connected to motors, respectively. The two rotational joints are fixed to a frame and the distance between two rotational joints is constant.

The specification of the robot is summarized in TABLE I. The elastic strip of the robotic catapult is a hardening, cold rolled, special steel strip (JIS G3311, SK85M) with 0.05[m] width, 0.20[m] thickness and 0.66[m] length. The both joints are driven by relatively small sized same RC servo motors which torque are 0.8[kg·cm], respectively. Wood is used for the main frame to make the robot as light as possible. A 9[V] dry cell battery is used as an energy source. Since the battery is out of the robot, the energy is transmitted by a cable. The total weight of the robot as shown in TABLE I is without a battery. The proposed compact robot is using two motors for generating acceleration based on snap-through buckling of the elastic strip. In this type, two impulsive motions can be generated by one rotation of the axes of the motors, respectively. The frequency of the impulsive motion is about 3 [Hz] without loads. It is 1.67 times higher than other robotic catapult mechanism by using only the bending deformation [4] or other impulsive generator [6].

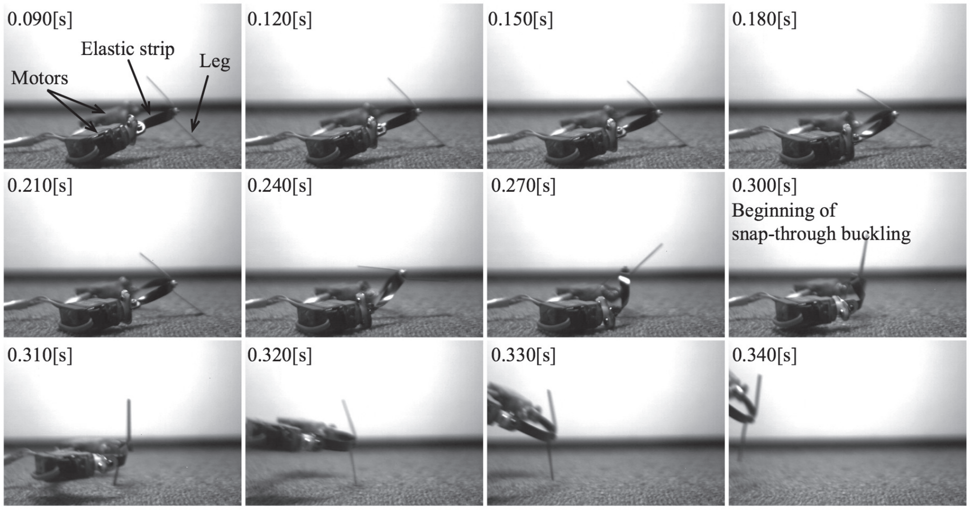

Fig. 4. A series of photos of the proposed robot's jumping motion using high-speed camera

TABLE I
PARAMETERS OF THE PROPOSED JUMPING ROBOT

Robot parameter	Value [unit]
Mass	0.018 [kg]
Body length	55 [mm]
Body width	110 [mm]
Body height	41 [mm]
Elastic strip length	66 [mm]
Elastic strip width	5 [mm]
Elastic strip thickness	0.20 [mm]

B. Degrees of Freedom of the Actuators

By driving the two active rotational joints with same angle velocity, the impulsive force is generated toward the parallel direction of a vertical axis which is on the center of the frame. On the other hand, if the angle velocity of active rotational joints are different from each other, the impulsive force is generated toward slight right and left. As a result, the jumping robot can move not only on a line but also on a plane utilizing two degrees of freedom of the motors effectively.

C. Passive Leg attached to the Elastic Strip

As shown in Fig. 3, the large deformation is generated at the center of the elastic strip when the snap-through buckling is occurred. As a result, the highest acceleration is obtained around the center of the elastic strip [7]. However, just before generating snap-through buckling, the center of the elastic strip can not contact the ground because that the center of the elastic strip becomes 'M' shape as shown in Fig. 3. Then, the passive type leg is attached to the center of the elastic strip so that the impulsive force might surely act on the ground. A schematic diagram of a leg attached to the elastic strip is shown in Fig. 5. The attached leg has two parameters, that is, leg length L[mm] and leg angle ψ[deg.].

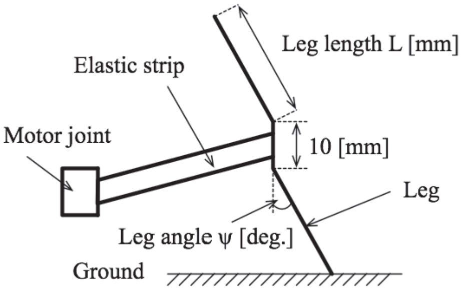

Fig. 5. A schematic diagram of the passive leg structure and its parameters

IV. JUMPING MOTION

Figure 4 is a series of photos showing the jumping motion of the robot recorded by a high speed camera at 250[fps]. The passed time from the initial time is shown on each scene picture. The initial shape of the elastic strip is only bended one without twist. When we drive the two active rotational joints, a twist deformation starts. By continuing to drive the two joints, the bend deformation is also progress and the center of the elastic strip is lifted (0.240[s] in the Fig. 4). Utilizing the twisted deformation, the leg part is rotated in counter clockwise direction as shown in the figure. As a result, the tip of the leg part, which is not contact side at the initial shape, is contact on the ground, that is, the robot has finished to ready to jump (0.270[s]). When the active rotational joints are driven furthermore, the snap-through buckling is generated (0.300[s]). At that time, since the tip of the leg contacts surely just before snap-through buckling, the enough impulsive force can be obtained as the reaction force from the contact ground.

The point of this jumping motion is to claw the ground by the tip motion of the leg as shown in the scene at 0.310[s]. This claw motion is result of the proposed snap-through

TABLE II

JUMP DISTANCE AGAINST PAYLOAD

Payload [g]	Distance [mm]	Height [mm]
0	950	15
2	773	13.3
4	740	15
6	683	15
9	670	10
13	616	10
15	503	8.3
17	523	10
18	550	5
27	503	5

buckling utilizing not only bending but also twisting. It is difficult to generate the same motion by the snap-through buckling generated by only bending deformation. This claw motion generated the snap-through buckling makes the robot leap ahead at that moment (0.310[s]-0.340[s]).

A. Long Distance Leap

The jumping motion is shown in Fig. 6. From the basic experiments, the robot has leaped about 950[mm] away and about 150[mm] high in one jump. In addition, from the figure, the robot has succeeded to leap about 1200[mm] away including bouncing motion just after landing. The proposed compact robot shows the higher performance about once jump than that of the continuous jumping robot utilizing the snap-through buckling with only bending deformation [9] in spite of using lower torque motor and heavier body.

The stored potential energy is estimated by the result of the long distance jump. Since few pitching motion is observed between a long jump motion, we approximate that this jump motion is a projectile motion of a mass. Then, a projection angle ϕ is given as follows.

$$\phi = \tan^{-1}\left(\frac{y+\frac{1}{2}gt^2}{x}\right), \tag{1}$$

where, x is leap distance, y is leap height, g is the acceleration of gravity and t is the passed time, respectively. On the other hand, the initial velocity v_0 is given as follows.

$$v_0 = \frac{x}{t\cos\phi}. \tag{2}$$

From Eq. 1 and Eq. 2, the kinetic energy K, which is converted from the stored potential energy, is given as follows.

$$K = \frac{m}{2}v_0^2, \tag{3}$$

where m is the mass of the robot. If it is assumed that there is nothing to loss of energy concerning the convert from the stored potential energy to the kinetic energy, the stored potential energy can be estimated from the result of the jumping experiment. As a result of calculation, the proposed jumping robot composed of the closed loop structure with bend and twist deformation can store about 18% larger potential energy by a motor than the jumping robot using only bend deformation [9].

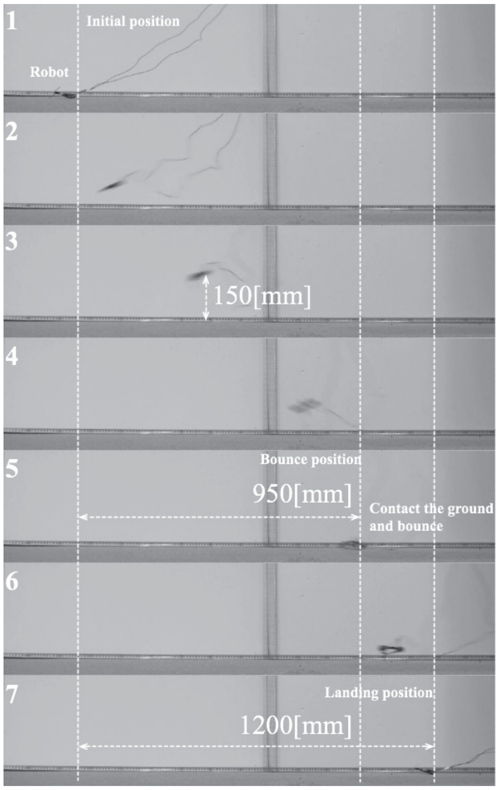

Fig. 6. A series of photos of the long jumping motion over 950[mm] away

B. Change of Leap Distance against Payload

The change of leap distance of the proposed compact jumping robot against load is measured. The adding load is fixed on both sides of motor frames. The experimetal result is shown in Table II. From the result, we can see that when the mass of the robot is two times larger by adding payload, the leap distance and leap height becomes about 66% and about 33%, respectively. The power source of the proposed robot is out of the platform. Then, if the battery is carried on the robot, the total mass of the robot is increased. From the result, if the light weight battery, for example lithium polymer battery, is carried on the robot, we can expect that it keeps efficient leap distances though the leap height is decreased.

C. Change of the Leap Distance against Leg Parameters

The proposed compact jumping robot has some design parameters such as length L[mm] and angle ψ[deg.] of the leg part as shown in Fig. 5 in addition to the length, thickness, width of the elastic strip and the angle θ in Fig. 2. The change of the leap distance and the leap height are shown in Fig. 7, 8, respectively. In this case, the parameters of the elastic strip are fixed to the values as shown in TABLE I. The angle $\theta = 60$[deg.].

From the figures, the length L and the angle ψ of the leg part are large influence for the leap performances. In addition, if the elastic strip has a long length, there is large offset between the center of the mass near by the motors

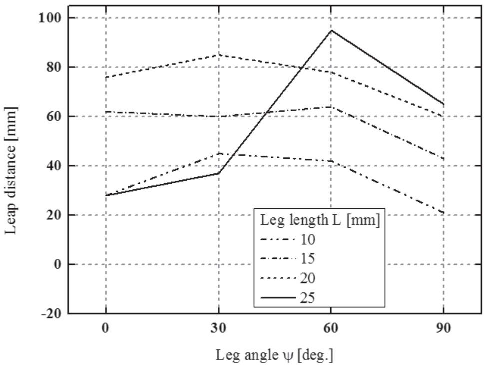

Fig. 7. The leap distance vs angle of leg

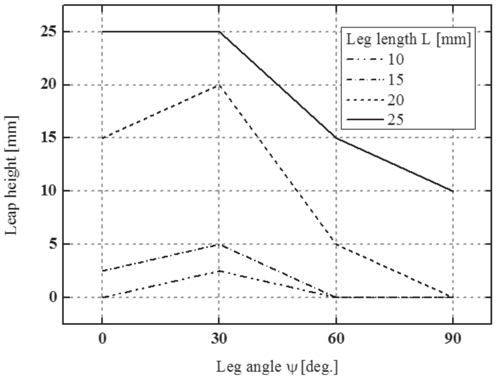

Fig. 8. The leap height vs angle of leg

and the contact point of the leg tip as shown in Fig. 4. As a result, since the pitching motion is large, it is difficult to maintain the fine landing motion. Then, it is better that the length of the elastic strip is shorter. However, in this case, the motor torque becomes larger to rotate the joint fixed to the elastic strip. The relation between the deformed shape of the elastic strip and the motor torque, and the optimized design method to decide the some parameters for desired jumping motion is future works.

V. REPEATED IMPULSIVE JUMPING MOTION

As described in Chapter II, the proposed compact jumping robot is mainly composed by the repeated impulsive motion generator which frequency is about 3[Hz]. For making the best use of this feature, we demonstrate repeated impulsive jumping motions which make us difficult to catch it by hands.

A. Parameters Setting

If the leap height is large in one jump, it is difficult to landing because it is possible that the next snap-through buckling starts before landing. Then, we regulate the leap height and the leap distance by choosing the length and the angle of the leg appropriately from the result in Fig. 7, 8, respectively. We choose that the length of the leg $L = 15[\mathrm{mm}]$ and the angle of the leg $\psi = 90[\mathrm{deg.}]$, respectively. From Fig. 7 and Fig. 8, it is considered that the jump distance is short and jump height is very low. As a result, it is expected that the robot can jump continuously and rhythmically by generating snap-through buckling just after landing at extremely short time. In addition, for generating sliding motion after landing, the acrylic plate is adopted as the underbody.

B. Passive Leg Structure to Realize Quick Step

As shown in Section III, if the each phase of the motor is different, the deformation and the shape just before snap-through buckling will become more complicated. As a result, the jump direction can be controlled. However, to control the jump direction quickly is not easy. Then, to make the best use of the feature that we can obtain repeated impulsive motions with higher frequency, a small invention about the passive leg is introduced. The deformation of the elastic strip at jumping motion is shown in Fig. 9. The impulsive jump motion is generated by utilizing the snap-through buckling with bend and twist. When the snap-through buckling is generated, the outer surface of the elastic strip becomes the inner one quickly. In next snap-through buckling, the inner surface becomes the outer one. To realize interesting quick motions by using this phenomenon, the passive leg is attached to a side of the elastic strip with the slight angle as shown in Fig. 10 . As a result, since the direction of the generated impulsive force vector by each snap-through buckling against the ground is represented each arrow in Fig. 10, it is expected that the robot can realize the left and right quick step in every leap and the distance of every step will be random.

C. Repeated Impulsive Motion with Quick Step

The repeated impulsive jumping motion is shown in Fig. 11. The circle points indicate the start position and the landing positions. Arrows indicate the pathways of the jumping robot. The jump distances, the passed times of each pathway and the passed time between landing and the next jump are shown in the figure, respectively. The each leap distance is about 350[mm], 450[mm] and 200[mm] and it takes 0.316[s], 0.112[s] and 0.204[s], respectively from the initial position. In addition, the passed times on the ground are 0.152[s] and 0.160[s], respectively. The average traveling speed is about 1.06[m/s]. From the measured distances, passed times and the traveling speed, it is clear that the proposed compact jumping robot achieved the quick repeated jumping motion. In addition, it is clear from the passway which indicates the leaping directions that the passive leg structures shown in Fig. 10 is effective in this quick motion. In fact, it is difficult to catch the robot between the repeated jumping motion by hands.

This repeated impulsive motion of the proposed compact jumping robot is effective in uncertain environment, for example, a hybrid environment of water and floated ices [11]. It was observed that the proposed robot swimming on water generated impulsive jump motion by pushing the floated ices since it could step up onto the floated ice and kick it by an attached fin type passive leg. On the other hand, using brisk

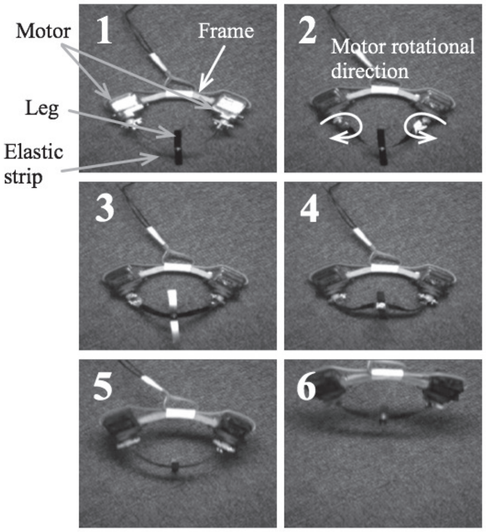

Fig. 9. The deformation of the elastic strip at jumping. The outer surface of the elastic strip becomes the inner one quickly by the snap-through buckling.

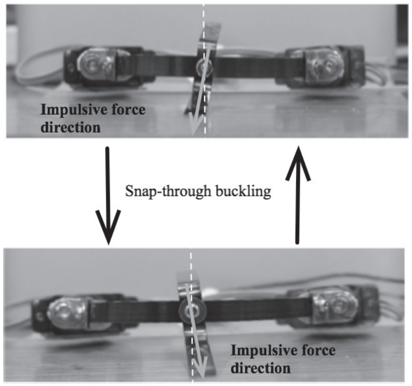

Fig. 10. The passive leg structure to realize the left and right quick step utilizing the feature of the snap-through buckling with bend and twist

motions generated by snap-through buckling, it is expected to using the robot for a rehabilitation for injury of shoulder or arm. We expect that large motions of whole shoulder and arm for catching the robot moving on a desk can be a patient rehabilitation for recovery of the movable area of the injured joint of one's shoulder or arm.

VI. CONCLUSION

In this paper, we proposed a robotic catapult based on closed elastica utilizing bending and twisting deformation of an elastic strip. This catapult can generate repeated impulsive motion by the frequency of 3[Hz]. The developed compact jumping robot could leap over 950[mm] away and demonstrated repeated quick jump motion with over 1[m/s] by setting the parameters appropriately to make the best use of generating impulsive forces with high frequency.

Optimal mechanical design including synchronization the motion of the two RC servo motors and the theoretical analysis of the spatial deformation of the elastic strip with bend and twist are future works.

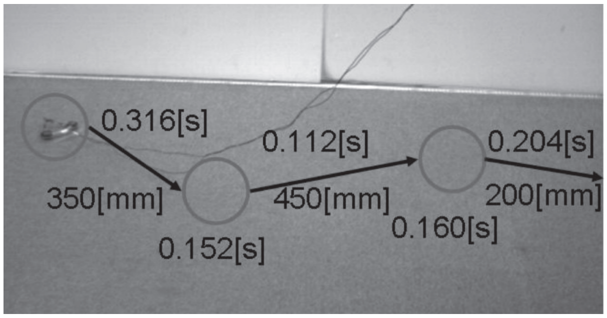

Fig. 11. Quick repeated jumping motion over 1[m/s] of the proposed compact robot recorded by high speed camera

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