Paper:

Design Principle of High Power Joint Mechanism Possible to Walking and Jumping Imitating Locust Leg Structure

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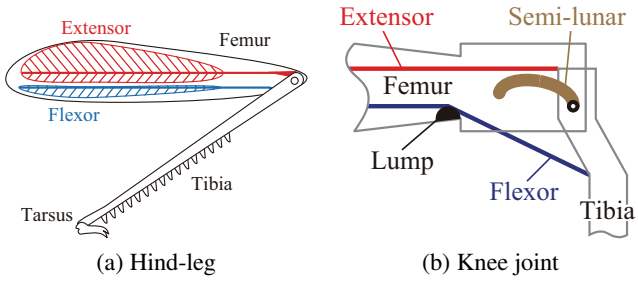
Many insects can jump several times their own body length. Locusts with their powerful hind legs can for example jump up to five times as high – 250 mm. We propose a high-power joint mechanism mimicking the locust leg structure in walking and jumping. The mechanism can produce power higher than motors mounted in the joint mechanism and separate walking and jumping using two motors. We also report the joint mechanism design principles.

Keywords: high power joint, locust leg, structure, Jacobian matrix, design principle

1. Introduction

This research on robot mechanism for jumping and walking is one of the important topics with a view to expanding the robots' activities [1, 2]. Especially in robot jumping, robot's body must be accelerated and ejected upward using own actuators, so that high-power actuators are necessary to realize jumping motion [3, 4]. As the general property of actuators, actuators can output high force and torque in low-velocity movement, and small force for high-velocity movement. Realizing actuator, which satisfies high velocity and torque at the same time, is not easy. Regarding power per unit – the power mass ratio – commercially available actuators of the same type do not differ much. In other words, to achieve jumping by actuator power alone, actuators must be drastically improved in performance or a new type of joint capable of accumulating energy must be developed.

Numerous living creatures in the natural world, although small, can jump several times their own body length [5–7], e.g., locusts 50 mm long can jump 250 mm – five times their length [8]. **Fig. 1** shows the locust hind leg, where they accumulate power in a semilunar process identical to springs, and locust jumps by releasing accumulated power instantaneously – something not possible with muscles alone [9, 10]. Locusts change between walking and jumping by moving their antagonistic muscles differ ways. Kovac et al.'s 7 g robot can jump up 760 mm using a series of cams, although the robot generate almost same jumping power, that is, the robot has difficulties in controlling jump performance [11, 12].



(a) Hind-leg (b) Knee joint

Fig. 1. Locust leg overview.

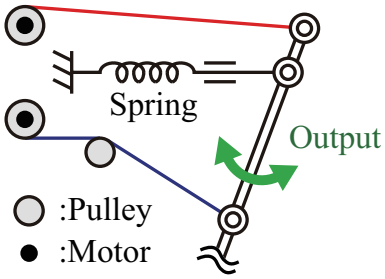


Fig. 2. Model of the high-power joint mechanism.

We have been working on a joint mechanism capable of walking and jumping simultaneously, and proposed a model and analysis for a high-power joint mechanism that produces power – a work rate – over ten times that of actuators installed [13]. Our proposed joint consists of muscles represented by two actuators, a semilunar process by springs and leg parts by links. The joint mechanism enables motion, walking and jumping, by controlling the antagonizing muscles represented by two actuators. Considering actual joint manufacture, we have analyzed a model in which translational joint-mechanism actuators are replaced by motors and pulleys as shown in **Fig. 2**. The proposed joint mechanism design principles, including motors selection, are also described.

Table 1. Variables used in analyzing the joint mechanism.

l_i	Ling length (i=b, e, $f1$, $f2$, $o1$, $o2$, sp)
$\dot{l}_e$	Velocity of wire w_e
$\dot{l}_f$	Velocity of wire w_f
θ_o	Absolute angle of output link
φ	Joint angle
$\dot{\theta}_o$	Angular velocity of output link
f_e	Viscous force from motor m_e
f_f	Viscous force form motor m_f
F_e	Tension of wire w_e
F_f	Tension of wire w_f
T_o	Torque of output link
τ_e	Load torque from motor m_e
τ_f	Load torque from motor m_f
μ_f	Viscosity coefficient of motor m_e
ξ_e	Gear ratio of motor m_e
ξ_f	Gear ratio of motor m_f

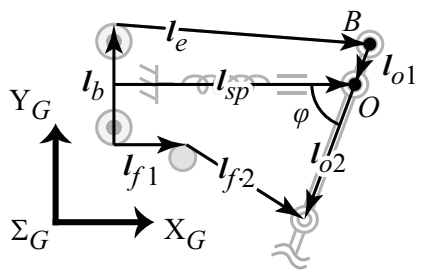


Fig. 3. Link vectors in the high-power joint mechanism.

2. High-Power Joint Mechanism Operation and Principles

Variables used in joint mechanism analysis are shown in **Table 1**. The proposed high-power joint mechanism, which consists of two motors, three pulleys, two wires, one spring, and one link, as shown in **Fig. 2**, controls the output link using the tension provided from the motors to wires connected to the link. Power transmitted to the output link from the motors works only to create tension to the wires and the spring is displaced in the direction of the X-axis in **Fig. 3**. **Fig. 3** shows link vectors for the high-power joint mechanism in absolute coordinates Σ_G.

As shown in **Fig. 4**, operation of either of the two motors, $\boldsymbol{F}_f$ or $\boldsymbol{F}_e$, enables flexional and extensional motion (walking). With velocity vectors generated in wire w_e by motor m_e denoted by $\dot{\boldsymbol{l}}_e = [\dot{l}_{e,x} \;\; \dot{l}_{e,y} \;\; 0]^T$, angular velocity $\dot{\boldsymbol{\theta}}_o$ of the output link is expressed by the following equations based on the Jacobian matrix derived from vector products [13]. Spring length is assumed to remain unchanged.

$$\dot{\theta}_o = J_e^{\#}\dot{\boldsymbol{l}}_e \quad (1)$$

$$\boldsymbol{J}_e = \boldsymbol{l}_{o1} \times \boldsymbol{e} \quad (2)$$

$\boldsymbol{e} = [0 \;\; 0 \;\; 1]^T$ denotes unit vectors and $\boldsymbol{J}_e^{\#}$, the pseudoinverse matrix of $\boldsymbol{J}_e$. According to the virtual work principle in Eq. (2), output torque T_o in extensional motion is expressed as follows:

$$T_o = \boldsymbol{J}_e^T \boldsymbol{F}_e - \tau_f. \quad (3)$$

$\boldsymbol{F}_e = [F_{e,x} \;\; F_{e,y} \;\; 0]^T$ represents tension in wire w_e, and τ_f, load torque generated by viscous forces $\boldsymbol{f}_f$ of passively operated motor m_f. Output torque and angular velocity in flexional motion is derived the same way.

$$\dot{\theta}_o = J_f^{\#}\dot{\boldsymbol{l}}_f \quad (4)$$

$$T_o = \boldsymbol{J}_e^T \boldsymbol{F}_e - \tau_f \quad (5)$$

$$\boldsymbol{J}_e = -\boldsymbol{l}_{o2} \times \boldsymbol{e} \quad (6)$$

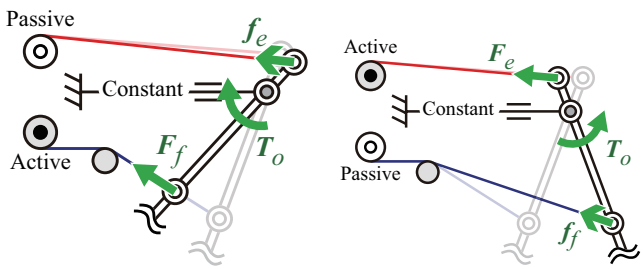
$\dot{\boldsymbol{l}}_f = [\dot{l}_{f,x} \;\; \dot{l}_{f,y} \;\; 0]^T$ represents the velocity vector of wire w_f and τ_e, load torque generated by viscous force $\boldsymbol{f}_e$ of passively operated motor m_e.

With the joint mechanism put into complete flexion using motor m_f, simultaneous operation of motors m_e and m_f accumulates power in the spring as shown in **Fig. 5(a)**. Shutting down motor m_f releases power accumulated in the spring to generate T_o as shown in **Fig. 5(b)**. T_o in jumping is expressed using the Jacobian matrix in the following equations, assuming that repulsion $\boldsymbol{F}_{sp}$ of the spring equals $\boldsymbol{F}_e$ and l_e remains unchanged.

$$T_o = \boldsymbol{G}_{sp}^T \boldsymbol{F}_{sp} = \boldsymbol{G}_{sp}^T \boldsymbol{F}_e \quad (7)$$

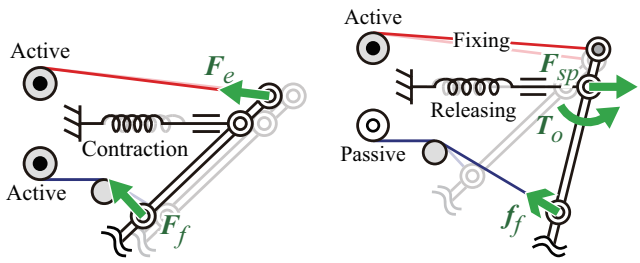
$$\boldsymbol{G}_{sp} = -\boldsymbol{l}_{o1} \times \boldsymbol{e} \quad (8)$$

$\dot{\boldsymbol{\theta}}_o$ in jumping cannot be derived the same way as extensional and flexional motion, however, because spring velocity $\dot{\boldsymbol{l}}_{sp} = [\dot{l}_{sp,x} \;\; \dot{l}_{sp,y} \;\; 0]^T$ is unknown. We use viscosity coefficients μ_f of motor m_f to obtain $\dot{\boldsymbol{\theta}}_o$ in jumping. Vec-



(a) Flexion (b) Extension

Fig. 4. Walking.



(a) Charging (b) Releasing

Fig. 5. Jumping.