Novel Reaction Force Control Design Based on Biarticular Driving System Using Intrinsic Viscoelasticity of Muscle

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***Abstract*—This paper suggests a novel reaction force control design of two-link manipulators based on a bi-articular driving system. Considering muscles' viscoelasticity, the animal link model can control its reaction force against ground surface using a position feedback without a force feedback. To verify this characteristic, we explain the model of muscle and the animal link model. And then, the analogy between the force generating mechanism of muscle and a two degrees of freedom control is shown, and the intrinsic reaction force control of bi-articular driving system based on a position feedback is suggested. Finally, simulation results ensure this characteristic.**

***Keywords*—bi-articular muscle, two-link manipulator, two-degree of freedom control, nonlinear feedback, reaction force**

I. Introduction

A. Background

Recently, many approaches which support humans by robotics are attempted against the health and welfare problems [1][2][3].

However, many existing power assist machines still have the conventional robots' structure that has actuators in each joint. This structure is suitable for the very precise and fast move like assembly lines, but unsuitable for cooperation with humans. The big difference between animals and robots is the location of actuators. Unlike the conventional robots, almost animals in the earth have the bi-articular muscles. This muscles exist in from primitive to modern animals because of its important characteristics for animals' flexible and stable motions. These important characteristics have been revealed by recent studies [4][5].

So, there are many efforts to equip bi-articular muscles on robots [6]-[11]. However, these robots still have not yet realize dynamical motions.

Meanwhile, the hopping robots which have linear hydraulic actuator can mimic the animals' quick movements, for example, running or jumping [12][13]. However, animals don't have these linear actuator, so these structures can not be use directly for humans as the power assist devices.

As seen above, there are many methods of emulations of the animal's movements by direct ways. On the other hand, there are few works to build the mathematical model from the muscle system to the end effector.

In this paper, we developed the muscle model and intrinsic muscle viscoelasticity control model based on two-degree-of-freedom. And then, we focus on the position feedback control function of muscles which adjust the stiffness and suggest the nonlinear feedback control to drive the two-link manipulator as the linear spring actuator. Moreover, we verify the roles of each muscles and verify this by simulation results.

This paper is organized as follows; in Section II, the model of animal limbs are explained and the force output characteristic is analyzed. Furthermore, the two-degree-of-freedom control model is defined and 6-muscle 3-pair animal model is approximated to simple 2-joint actuator and 1-linear actuator model. In Section III, the relationship between the position feedback control and the force at the end effector is analyzed based on the Jacobian matrix. And then, we suggest the reaction force control design based on optimal viscoelasticity and the nonlinear feedback control. Finally, in Section IV, the simulation results is shown and the effectiveness of the suggested control design is verified.

II. Principle of bi-articular muscle

Conventional robots have actuators which drive only one joint and usually these actuators are rotational motors. On the other hand, animals have mono-articular muscles and bi-articular muscles; the former rotates only one joint, but the latter rotate two joints at the same time. These bi-articular muscles have been ignored in conventional robotics since it is inefficient to constrain two joints and make them independent. However, recent research proved that bi-articular muscles play an important roll in motion control.

Fig.2 shows a model of animal arm with muscles. In Fig.2 e_1 and f_1 are a pair of antagonistic mono-articular muscles attached to the first joint. e_2 and f_2 are a pair of antagonistic mono-articular muscles attached to the second joint. e_3 and

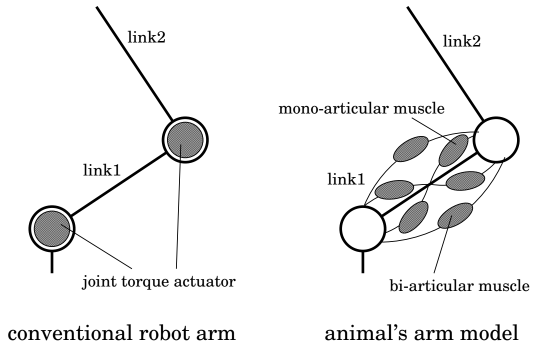

Fig. 1. Arms of robot and animal

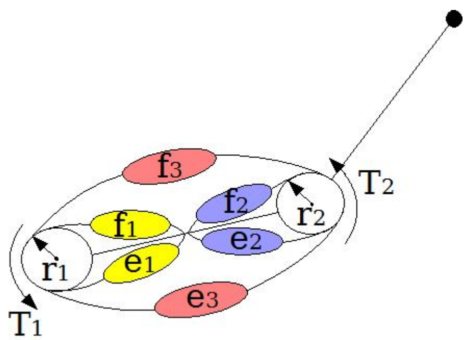

Fig. 2. Animal arm model

f_3 are a pair of antagonistic bi-articular muscles attached to both joints. Each muscle has unique viscoelasticity and the muscular output force F is modeled as follows.

$$F = u - ku\Delta x - bu\Delta\dot{x} \tag{1}$$

Here u is contractile force, Δx is contracting length of the muscle and $\Delta\dot{x}$ is shortening velocity. Elasticity and viscosity are proportional to u, so k and b are elastic coefficient and viscosity coefficient. Based on this force output model, the antagonistic muscle pair can be realized using a motor. Fig.3 is a typical muscle mechanism where two muscles - flexor muscle and extensor muscle - generate a certain torque working in a antagonistic way, where f^f and f^e are forces generated by flexor and extensor muscles, r is the radius of the joint, θ is the rotated angle driven by two forces f^f, f^e and Δx represents the absolute amount of the change in the length of muscles caused by the rotation θ

Note that one angle θ will lead to two different length changes since the directions of length change are different in two muscles: $\Delta x = -r\Delta\theta$ in the flexor muscle and $\Delta x = r\Delta\theta$ in the extensor muscle. This antagonistic muscle pair can be identified with the following two-degree-of-freedom control input [14].

Fig.4 illustrates the roles of two modes in muscle torque; the difference mode working as a torque and the sum mode which adjusts the stiffness. The following 2 describes this

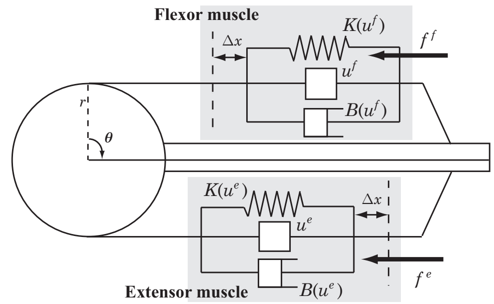

Fig. 3. Segment rotating on a joint driven by a pair of muscles

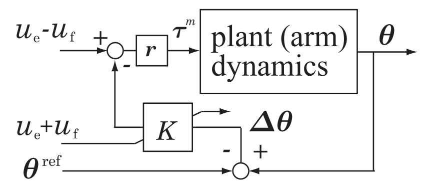

Fig. 4. Two-degree-of-freedom control input characteristic of a muscle pair

characteristic.

$$\tau^m = r(f^e - f^f) = r(u^e - u^f) - (u^e + u^f)(K + Bs)r\Delta\theta \tag{2}$$

The difference between two contractile forces works as a torque to rotate the link and the sum of two forces works as the feedback gain of the angle θ. Δx is interpreted as the variation from the natural muscle length but also can be generalized as the difference from a certain reference value θ^{ref}. With this reference angle θ^{ref} and the designed stiffness $(u^e + u^f)(K + Bs)$, the angle will converge to θ^{ref}.

Now, we define τ^m as the torque caused by each antagonistic muscular pair (see Fig.4) and T_1^j and T_2^j as joint torques that are generated in two joints by the muscle torques. With only two mono-articular muscles in each joint, muscle torques and joint torques will be the same. With the bi-articular muscle, however, the relationship is defined as follows.

$$T_1^j = \tau_1^m + \tau_3^m \tag{3}$$
$$T_2^j = \tau_2^m + \tau_3^m \tag{4}$$

III. Reaction Force Control Design Based on Muscle Viscoelasticity

In this section, a novel reaction force control algorithm is suggested based on the Jacobian matrix and the muscle viscoelasticity. Based on this algorithm, we can drive a two-link manipulator like a linear actuator on the straight line from the center of the first joint and the end effector.

A. Joint Torque from Muscle Contractile Force

Now, we suppose that the two-degree-of-freedom control is the base of the muscle control algorithm. So, the sum mode and difference mode are appropriate to the inputs for a pair of the antagonistic muscles. Then, we define the D_i, S_i as new inputs for the muscles, and K_i' and θ_{12} as follows,

$$D_i = u_i^e - u_i^f \tag{5}$$
$$S_i = u_i^e + u_i^f \tag{6}$$
$$K_i' = K_i + B_i s \tag{7}$$
$$\theta_{12} = \theta_1 + \theta_2 \tag{8}$$

where $i = 1$, 2 and 3, θ_1 is the angle of the first joint and θ_2 is of the second joint. In this definition, we can derive the joint torque from 2, (3) and (4) as follows,

$$T_1^j = r(D_1 + D_3) - r(S_1 K_1' \Delta\theta_1 + S_3 K_3' \Delta\theta_{12}) \tag{9}$$
$$T_2^j = r(D_2 + D_3) - r(S_2 K_2' \Delta\theta_2 + S_3 K_3' \Delta\theta_{12}) \tag{10}$$

where we assumed $r_1 = r_2 = r$. In addition, we consider only the feedback control and set the references of joint angles to 0, because we suppose the straightforward movement like vertical landing. As a result, the equations noted above are simplified as follows.

$$T_1^j = -r(S_1 K_1' \theta_1 + S_3 K_3' \theta_{12}) \tag{11}$$
$$T_2^j = -r(S_2 K_2' \theta_2 + S_3 K_3' \theta_{12}) \tag{12}$$

Note that equations ((11)) and ((12)) are the equations which is considering only feedback control of Fig.4. The torques generated from the difference modes are not considered in this paper.

B. Calculation of Force at End Effector Based on the Jacobian Matrix

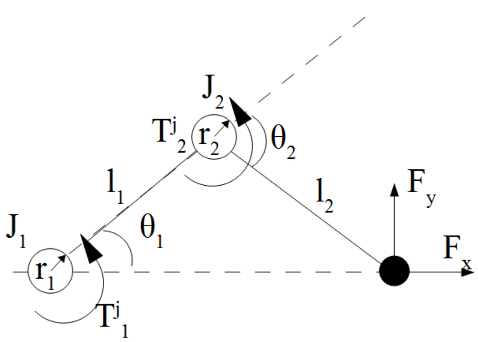

Fig. 5. Two-link Manipulator

Fig.5 shows the two-link manipulator. In Fig.5, the force at the end effector is described as $F_e = (F_x, F_y)^T$. Now, we know the joint torques generated by three muscles from (11) and (12), so we can derive the F_e using the Jacobian matrix.

$$\begin{pmatrix} F_x \\ F_y \end{pmatrix} = \frac{1}{l_1 l_2 \sin\theta_2} \cdot \begin{pmatrix} l_2 \cos\theta_{12} & -l_1 \cos\theta_1 - l_2 \cos\theta_{12} \\ l_2 \sin\theta_{12} & -l_1 \sin\theta_1 - l_2 \sin\theta_{12} \end{pmatrix} \begin{pmatrix} T_1^j \\ T_2^j \end{pmatrix} \tag{13}$$

And then, to consider only straightforward movement and simplify the structure, we assume $K_1' = K_2' = K_3' = K'$, $l_1 = l_2 = l$ and x axis is the same as the line from the center of the first joint to the end effector. In this assumption, we can get F_e.

$$\begin{aligned} \begin{pmatrix} F_x \\ F_y \end{pmatrix} &= \begin{pmatrix} -\frac{1}{2l\sin\theta_1} & \frac{1}{l\sin\theta_1} \\ \frac{1}{2l\cos\theta_1} & 0 \end{pmatrix} \begin{pmatrix} T_1^j \\ T_2^j \end{pmatrix} \\ &= \begin{pmatrix} \frac{rK\theta_1}{2l\sin\theta_1}(S_1 + 4S_2 + S_3) \\ \frac{rK\theta_1}{2l\cos\theta_1}(S_3 - S_1) \end{pmatrix} \end{aligned} \tag{14}$$

(14) shows following important things.

- To make $F_y = 0$, we have to set $S_1 = S_3$.
- Without bi-articular muscle, the torque of the first joint, T_1^j, cannot generate the force only x direction.
- The second mono-articular muscle does not effect to adjust F_y, but play the important role for create the reaction force to ground, F_x.

In addition to (14), if $S_1 = S_3$, $F_y = 0$. Therefore, we can focus F_x only.

$$F_x = \frac{rK\theta_1(S_1 + 2S_2)}{l\sin\theta_1} \tag{15}$$

Note that S_1 and S_2 are the controllable inputs, so we set these parameter to the function of θ_1 as follows.

$$S_1 = s_1 \frac{\sin\theta_1(1 - \cos\theta_1)}{\theta_1} \tag{16}$$
$$S_2 = s_2 \frac{\sin\theta_1(1 - \cos\theta_1)}{\theta_1} \tag{17}$$

s_1 and s_2 are parameters to be designed. Using this non-linear feedback, we can describe F_x as a linear function of Δx.

$$F_x = \frac{rK(s_1 + s_2)}{2l^2}\Delta x \tag{18}$$

(18) shows that the two-link manipulator can be driven like linear spring and damping actuator. Fig.6 represent the image of this.

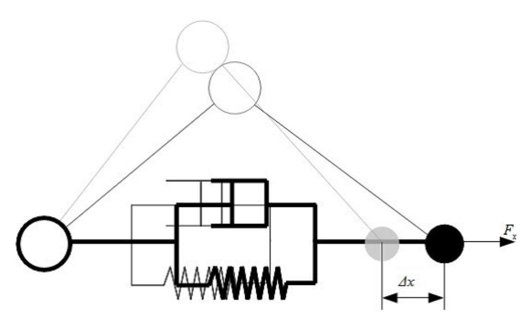

Fig. 6. Two-link Manipulator Driven as Linear Actuator

Using this control algorithm, we can drive a two-link manipulator like a linear actuator and it enable robots to run fast, jump quickly and walk on irregular ground.

IV. Simulation Results

A. Function of τ_2^m and τ_3^m

In the following simulations, we set $r = 0.1[\mathrm{m}]$, $l_1 = l_2 = 0.27[\mathrm{m}]$ and assume that K' has only elasticity, so $K = 1$. We changed θ_1 from $\frac{\pi}{6}[\mathrm{rad}]$, to $\frac{5\pi}{6}[\mathrm{rad}]$ per $\frac{\pi}{6}[\mathrm{rad}]$. The calculation is based on (14) and the block diagram of simulation is Fig.7.

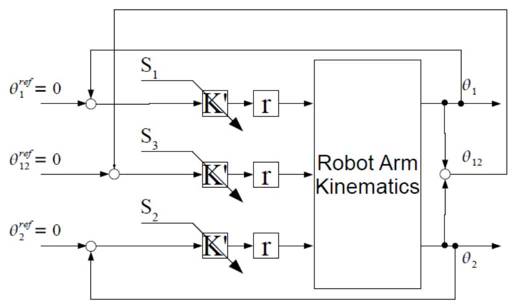

Fig. 7. Block Diagram of Simulation

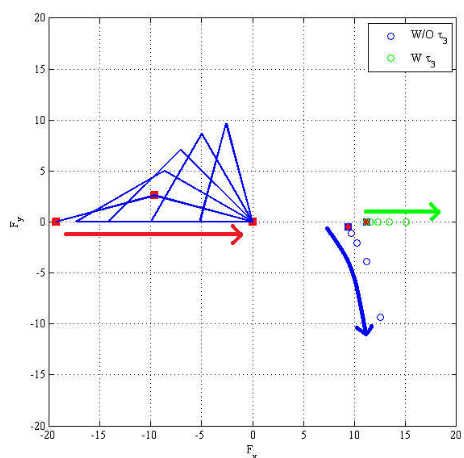

Fig. 8. Comparison of the Case With Bi-articular Muscle v.s. Without Bi-articular Muscle

In the Fig.8 shows advantage of bi-articular muscle. The blue circles are the case of $S_1 = S_2 = 10[\mathrm{N}]$.and green circles are the results when $S_1 = S_2 = S_3 = 10[\mathrm{N}]$. Red points are the initial posture and forces. Image that there is a ground surface or a wall along the y axis and the end effector pushes on different five postures. The red arrow indicates the movement of body and the blue and green ones are the flow of force along the change of posture.

This result shows that τ_3^m plays a significant role to align the end effector force straight. In (14), F_y is not zero when the manipulator does not have τ_3^m, bi-articular muscle and this misalignment becomes large as θ_1 becomes big. Just without bi-articular muscle, the blue circles in Fig.8, the direction of the force at the end effector goes down in the y direction as the joints bends. On the other hand, if the manipulator have the bi-articular muscle, the direction keeps straight in the x direction as the green circles in Fig.8.

In fact, robots without bi-articular muscle can not generate force against the ground surface straightforward in jumping or randing, so that it cannot keep the COM balanced in the y direction. However, robots with bi-articular muscle can.

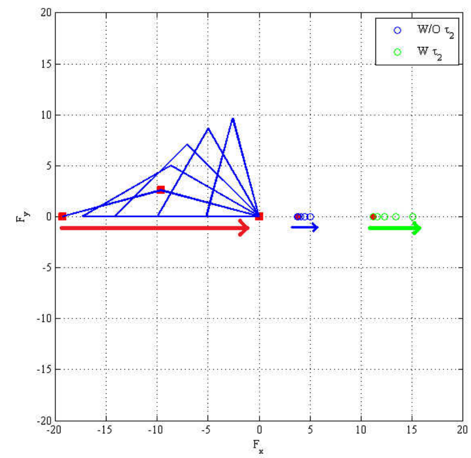

Fig. 9. Comparison of the Case With τ_2^m v.s. Without τ_2^m

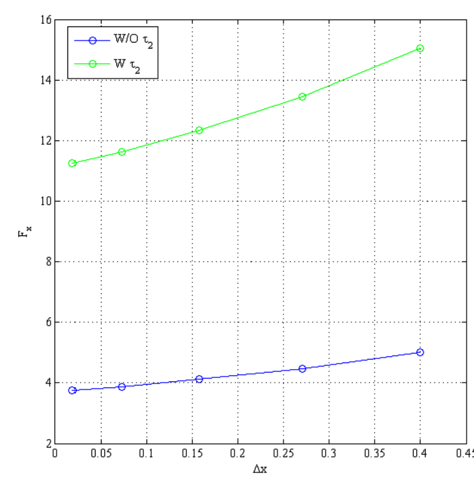

Fig. 10. The Relationship of Δx and F_x With τ_2^m v.s. Without τ_2^m

Fig.9 is the simulation result on the situations with and without τ_2^m, mono-articular muscle on the second joint. In Fig.9, the blue circles are the force when $S_1 = S_3 = 10[\mathrm{N}]\mathrm{and}\mathrm{S}_2 = 0[\mathrm{N}]$, and the green circles are when $S_1 = S_2 = S_3 = 10[\mathrm{N}]$. In each case, the forces at the end effector is generated to straightforward because of contribution of bi-articular muscle. This results indicates that the two-link manipulator moves as a linear spring, and Fig.10 is the relationship between Δx and F_x. Please note that the relationship betweenΔx and F_x is not proportional.

Moreover, this result teaches us the another fact that mono-articular muscle on the second joint can generate the force to the direction of F_x.

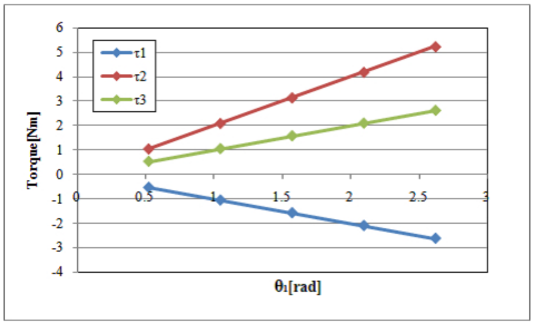

Fig. 11. Torque Outputs of Three Muscles

Fig.11 shows that torque outputs in the case of $S_1 = S_2 = S_3 = 10$[N]. Torque outputs are calculated from (11) and (12). The mono-articular muscle of the second joint, τ_2, needs a torque greater than the other muscles. However, following figure shows that τ_2 is more efficiently to generate the straightforward torque.

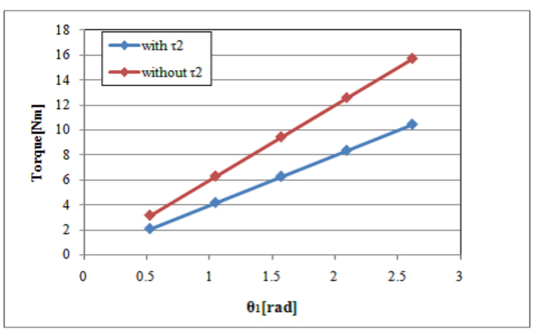

Fig. 12. Summation of Absolute Torque Outputs to generate the same F_x $(|T_1^j| + |T_2^j|)$

Without τ_2, other two muscles need torque three times as much as with τ_2. In Fig.12, the blue line is the case with τ_2 and the red line is without τ_2. In the latter case, the summation is the torque of τ_1 and τ_3. This figure shows that the manipulator without τ_2 needs larger output to generate the same force generated by three muscles.

These two simulation results verify that bi-articular and mono-articular muscles on the second joint are necessary to generate the straightforward force which is important for basic motions like a running, jumping or randing. These also indicates that animals' 6-muscle and 3-pair structure have an advantage on the motion control over the conventional robots.

B. Suggested Control Method to Mimic Linear Actuator

There are some research of running robot using no-joint linear actuators. However, animals can run with legs which have two or three links. In this subsection, we show the simulation result using suggested control method based on (16) and (17).

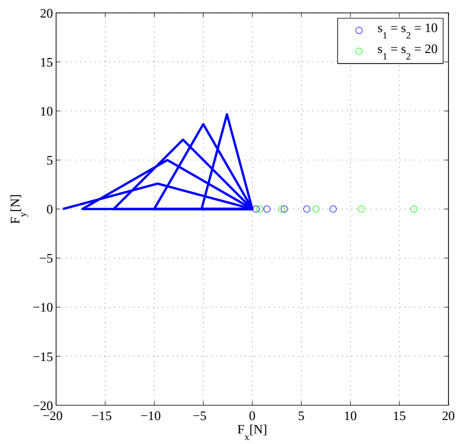

Fig. 13. Using Two Link Manipulator Like a Linear Actuator

Fig.13 is the result of suggested control method. On (16) and (17), we set $s_1 = s_2 = 10$ or 20. Because we assumed that muscles have only viscosity, the two-link manipulator behave like a linear spring. This characteristic is shown clearly in Fig.14.

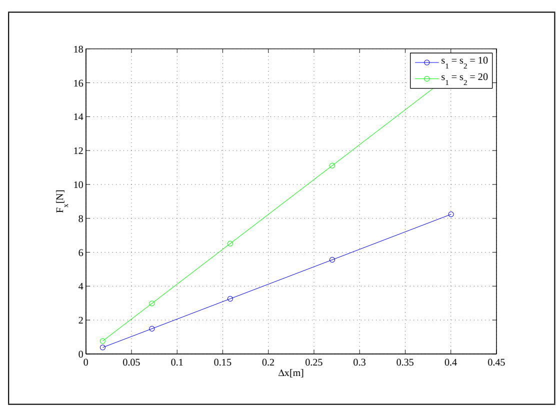

Fig. 14. Linear relation between Δx and F_x

From (16) and (17), $\sin\theta_1$ and θ_1 of (15) are canceled and F_x becomes the function of $\Delta x = 2l\cos(1 - \theta_1)$. Compared to Fig.9, the suggested algorithm can realize the proportional relationship between Δx and F_x. These results give us the insight for the reaction force control that we can change easily the reaction of two-link manipulator to the ground or wall by setting the parameters of muscle impedance.

Fig.15 is the torques in all three muscles generated by the suggested nonlinear feedback based on (16) and (17). Fig.15

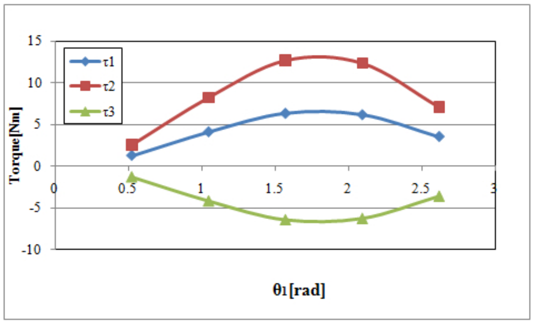

Fig. 15. Generated Torque of Each Muscle

is the case of $s_1 = s_2 = 10[\mathrm{N}]$. This result indicates that there is the maximum point of torque, so we can choose appropriate actuator for the desired reaction force.

From above the all the results, it is verified that the animals' 6-muscle and 3-pair structure is appropriate for the straightforward motions. Furthermore, the effectiveness of the suggested control method is confirmed.

V. Conclusions and Future Works

A. Conclusions

In this paper, we explained that the two-degree-of-freedom control algorithm and applied to the muscle viscoelasticity control. And, we focused on the straightforward reaction force generated from intrinsic muscle stiffness and calculated this force from Jacobian matrix because the straightforward reaction force is very important when we consider the animals' basic movement like running. Moreover, the simulation results verified that animals' muscle structure is very suitable for the straightforward motion and suggested control algorithm can drive the two-link manipulator as the linear actuator like a linear spring.

B. Future Works

As a future work, we would like to verify the suggested algorithm in experiments. We developed the novel bi-articularly driven robot arm [15] shown in Fig.16 .

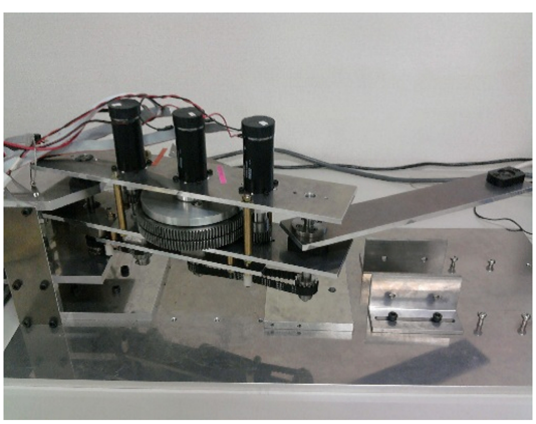

Fig. 16. Two-link Robot Arm With Biarticular Driving System

This robot arm has a planetary gear system as the part for mixing torques generated by three motors. So, we can mimic the animals' limbs which have two mono-articular muscles and bi-articular muscle.

After that, the dynamical model have to be considered to drive more faster. In addition, we have to care about the back-drivablity of actuators because a manipulator needs the characteristic which is perfectly back-drivable when the end effector contacts with environment in order to control the reaction force using the position feedback.

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