# Development of Antagonistic Wire-Driven Joint Employing Kinematic Transmission Mechanism

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**Abstract:**

*Antagonistic mechanisms attract attentions as joint actuators of linkage mechanisms, which control output torque, joint stiffness and position simultaneously. As the actuators or components of antagonistic driven joints, special devices with nonlinear elasticity property such as pneumatic actuators, nonlinear springs are often utilized to satisfy the requirements of antagonistic mechanisms. However, these devices have difficulties in control caused by complex and nonlinear properties, downsizing of actuator, and response time of articular compliance. In order to solve these problems, we propose a new antagonistic joint mechanism using kinematic transmission mechanism (KTM), which is composed of links and cams with dedicated design. The performance of KTM is evaluated through stiffness and position control simulations and experiments.*

***Keywords:*** *antagonistic-driven joints, equilibrium point hypothesis, controllable stiffness mechanisms.*

## 1. Introduction

Main applications of robotics research in the 1960s and 1970s target the automation of industrial processes using industrial robots/manipulators [1], and manipulators resembling human arms are deployed for various automation tasks of the factories. In the 1980s, robots began to spread to the manufacturing floors in the form of wheeled or legged mobile mechatronic systems called AGV and extreme environments such as space, underwater, nuclear plants. The roles of robots are no longer limited to tasks in automated factories and expand into exploration of hazardous, human-unfriendly, extreme environments. Recently, various kinds of robots are provided to surveillance, security, and cleaning tasks [2]. Ingenious autonomous robotic systems emerging in late 1990s have artificial intelligence, e.g. Sony's Aibo robotic dog [3]-[5], and Hondas humanoid robots from P2, P3 to Asimo [6], [7], and make robots familiar to our surrounding and daily life. One of recent research topics in robotics is the co-habit of human and robots. It is expected that robots with different degrees of autonomy and mobility will play an increasingly important role in all aspects of human life. To enable coexistence of human and robots, robots will be much more complex in their hardware, software and mechanical structures, and biomimetic technology and brain inspired processing would be a breakthrough of future robotics.

One of the important technical issues in robotics is motion control problem. In the most of application, robots are required to work quickly, precisely and safety, however, these requirements sometimes make conflicts and trade-off. In order to realize precise, stable and less vibration motion control, the robot joints should be rigid. On the other hand, the more rigid robot joints become, the less safe and flexible to unexpected things. To overcome this problem, the compliance control of robot joint should be considered from the viewpoints of hardware and software developments. Hardware approaches are; for example, to use soft materials as the mechanical structure components, cover the body with shock absorbers, or implement soft actuators such as pneumatic actuators. In the software approaches, force control and impedance control are often used, where virtual springs and dampers model are supposed to exist in the working space. Morita *et al.* showed the possibility to absorb shocks not only by protections using shock-absorbing materials but also by softness of the joints. In the tasks which need skillful motion control such as peg-in-hole insertion, inaccuracy of position control of robot arm should be compensated by compliance methods. As one of the methods, the remote center compliance (RCC) device with elastic elements is proposed. However, the position and orientation control are not enough for the peg-in-hole problem, because the information about the forces around the joints in the control aren't employed.

Although the industrial robots are preferred to be made rigid as much as possible, the service robots should have soft joints to avoid damages to their environments and to humans. As a solution of this problem, bio-inspired approaches attract attentions. Animals including human can control articular impedances during motion [8], and human can realize the quick motion and the supple behavior. The system, which can change articular impedances of robots, is one of research trends in robot joints and software impedance controls have been developed [9].

One of the most important technical problems in the compliance control is the time delay caused by electric factors and computing time. Regarding collision, the time delay in the response becomes very critic problem. So, the robot joints with mechanical softness are researched and proposed, for examples, programmable passive impedance (PPI) which controls its compliance by using nonlinear springs slotting directly between the actuator and the wire [10], nonlinear spring tensioner (NST) which controls its compliance by using the movable pulleys and the linear springs [11], the mechanism with L-type link added to NST [12], mechanical impedance adjuster (MIA) which controls its compliance by changing the moment arm by using a flat spring and a slider connected to the spring [13], actuator with nonlinear elastic system (ANLES) which produces nonlinear elasticity by winding a linear spring around a guide shaft [14], and the mechanism using pneumatic rubber muscles [15].

The above mechanisms have quick response to sudden external forces because they can set the stiffness of joints beforehand, and guarantee delays mechanically. Koganezawa et al. assert that above mechanisms have two problems as following:

A) Design of the nonlinear elastic elements is difficult.
B) The mechanisms employing nonlinear elastic elements become large size.

Including these above problems, we also consider a new item:

C) Slow responsiveness in the dynamic compliance control.

In the conventional mechanisms, elastic materials must be deformed to obtain target stiffness, and the delays occur by deforming. Animals change the articular impedance during the sequence of motion from one moment to the next. For example, the joints are well adjusted to high or low stiffness at an instant in the hopping motion. That is, in a series of motion, the joints of robots should have good responsiveness regarding articular compliance. The conventional joint mechanisms with stiffness adjustment function show better performance than software-based methods in the static compliance control responsiveness, on the other hand, have difficulty in the dynamic compliance control responsiveness.

In our research, we especially address controlling compliance by variable mechanical impedance. We propose an antagonistically wire-driven mechanism, which has good control performance regarding dynamic compliance. We describe the viscoelasticity property of musculoskeletal system, and propose the model describing the compliance control system of musculoskeletal system. Then we show the antagonistically wire-driven mechanism realizing the model mechanically.

## 2. Impedance control mechanisms of musculoskeletal system

### 2.1. Kinetic features of muscles

In general, regarding the mechanical impedance, three elements: mass, viscosity and elasticity, are controllable parameters, and musculoskeletal systems control only the viscosity and the elasticity because the change of mass is not so easy. Although the mechanism of impedance control system in the musculoskeletal systems is not fully understood yet, a few researches report on kinetic features of muscles as follows [16]:

1) A muscle can work in the contracting direction only.
2) A tension of the muscles is bigger when the frequency of the input pulses to the muscle is higher.
3) A tension force of the muscle depends on the muscle length.

A mechanism which rolls round the wire using actuator is generally used to realize the kinetic feature regarding the above 1). However, this mechanism alone cannot produce a similar feature of muscles. The input pulses of the 2) are neural pulses, which transmit contraction signals to muscles. The contracting force of muscles becomes large when the pulses arrive more frequently. This pulse input is a manipulating variable in the control. The item 3) means that a muscle force is the function of the muscle length (or joint's position; see Fig. 1). Muscles change their outputs depending on their length (that is joints' angles), however, conventional actuators don't change the output according to their position, which is the main difference between muscles and general actuators.

### 2.2. Neural system of muscles and servo system

In muscles, there is an organ called muscle spindle, which sends the afferent signals by sensing the change of position and velocity of the muscle, and neurotendinous spindle in tendons responding to the tension of the muscle, which also sends the afferent signals. Those signals are transmitted to the central nerve system *via* alpha motor neuron. Then, the alpha motor neuron sends the contraction signal to the muscles, so that the muscle spindles, the neurotendinous spindles and the alpha motor neuron comprise a structure that has a servo system characteristic with feedback loop regarding the motion (see Fig. 2). There is a response called stretch reflex generating in this servo system. In stretch reflex the muscle contracts to the resisting direction to stretch of the muscle. However, it is still disputable at the point of whether the impedance control of musculoskeletal system is also realized by structured servo system mentioned above.

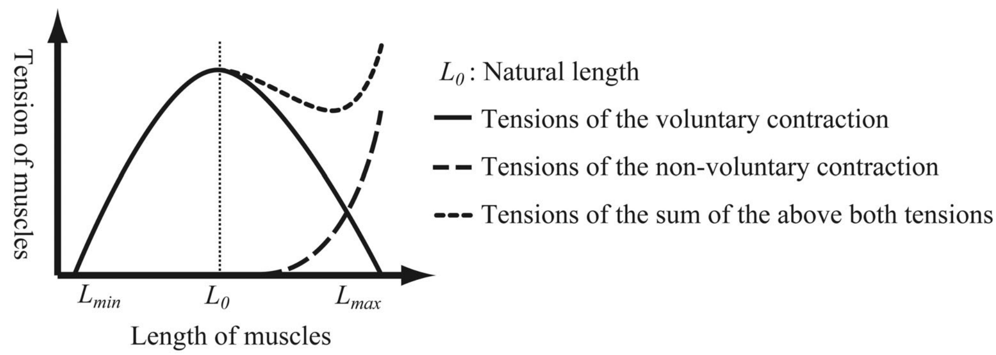



*Fig. 1. Length vs. tensions of muscles.*

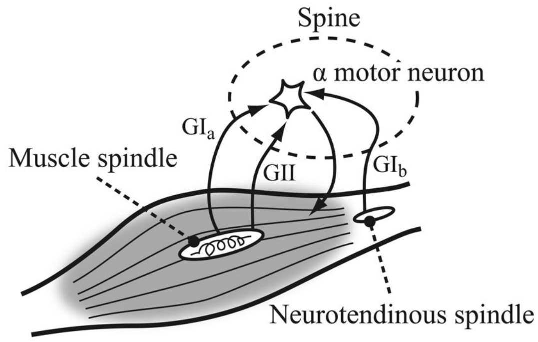



*Fig. 2. Neural system of the muscle.*

Regarding to position control of the joints in the motion, such as reaching, even if the neural pathways of muscle spindles and neurotendinous spindles are interrupted, the position control is possible [16], however, the accuracy of position control decreases. This fact means that the position control is possible in open-loop and, in a musculoskeletal system, the result suggests that the position control is realized by balancing the muscle's tensions, which is called equilibrium point (EP) hypothesis in reference [17]. An articular EP is a point of balanced forces between extensors and flexors (see Fig. 3). At EP external forces are not generated. The muscles generate only the returning forces to EP, if articular position moves away from EP. The articular position therefore changes when EP changes. This is the principle of thinking in the position control by EP hypothesis. As the external forces are not generated around EP, the joints don't move. Important point is that the internal forces are generated, so that the forces realize the articular stiffness. For example, in isometric contractions, which change the muscle tensions and don't change the position of the joint, the articular stiffness is proportional to the muscle tensions [8]. Moreover, in closed-link mechanisms and antagonistically wire-driven mechanisms, it is known that the internal forces define the mechanical stiffness [18], [19].

Summarizing the above:

- Controlling the position without a neural servo system is possible.
- Internal forces are proportional to the muscle tensions.
- Internal forces relate to articular stiffness.

## 3. Modeling of musculoskeletal system

### 3.1. Antagonistic wire-driven models

Two kinds of wire-driven mechanisms models with 2-input (torques $\tau_1$ and $\tau_2$ in Fig. 4) and 2-output (joint angle $\theta$ and stiffness) are shown in Fig. 4. Figure 4a) shows a conventional antagonistically wire-driven mechanism, and 4b) is the EP hypothesis-based antagonistically wire-driven mechanism. The main difference between Fig. 4 a) and Fig. 4b) is the torque around the equilibrium point. In the wire-driven system of Fig. 4a), the reaction torque will not occur and not go back to the original position against to external forces, because the joint can take any angles if the input torques $\tau_1$ and $\tau_2$ are equal. However, in the case of Fig. 4b), the reaction force will be generated to go back to the equilibrium point caused by the non-linear property of muscle-like actuators, when the external force is given to the joint. That is, the

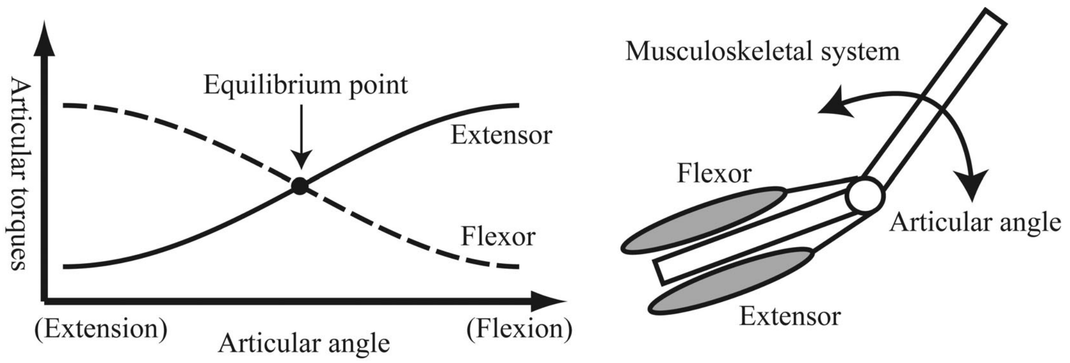
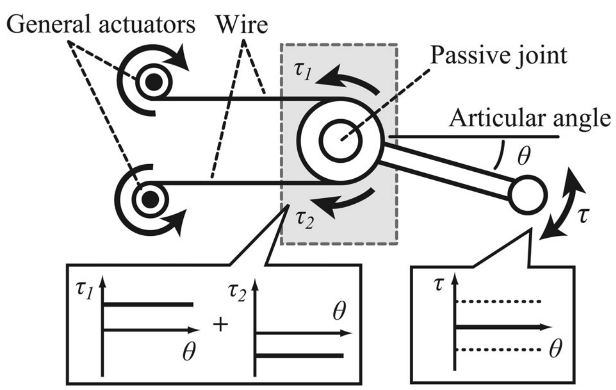



*Fig. 3. Equilibrium point hypothesis.*

*(a) The mechanism using general actuators.*




*(b) The mechanism using actuators like muscles under the equilibrium point hypothesis.*

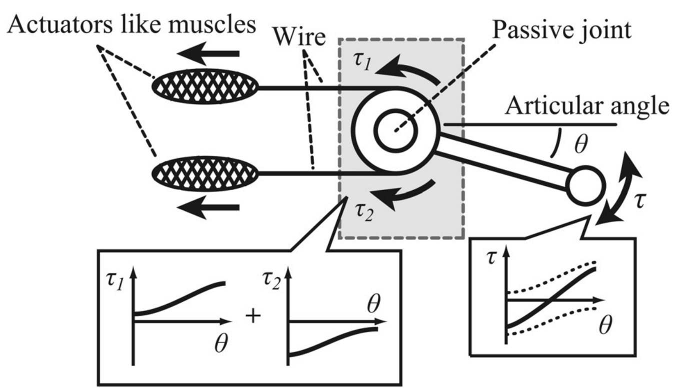



*Fig. 4. Wire-driven mechanisms.*

wire-driven mechanism in Fig. 4b) can keep the position of the joint without feedback control regarding position.

Another important aspect of the joint is the stiffness. The gradient of output torque, $\tau/\theta$, means the stiffness of the joint, which is proportional to the output of muscle-like actuator in the mechanism in Fig. 4b). The higher the gradient, $\tau/\theta$, becomes, the larger the stiffness. This fact shows that the actuator mechanism, which changes the output according to its position, is needed to realize musculoskeletal system. In the following sections, we describe a mathematical model considering these characteristics.

### 3.2. Proposed mathematical model

We use sigmoid function as the output model of muscle-like actuator for the joint as shown in Fig. 3. The musculoskeletal system is the antagonistic system, so this system is expressed by using two sigmoid functions as:

$$\tau_o = -\left\{\frac{k_{11}}{1+e^{-k_{12}(\theta_o-\varepsilon_1)}}+k_{10}\right\}\tau_{c1}+\left\{\frac{k_{21}}{1+e^{-k_{22}(\theta_o-\varepsilon_2)}}+k_{20}\right\}\tau_{c2} \quad (1)$$

where the constant parameters, $k_{ij}(i=1,2; j=0,1,2)$, are arbitrary design parameters, constant parameters $\varepsilon_i$ are the offset values to decide the initial position, variable $\theta_o$ is the joint angle, variable $\tau_{ci}$ are the torques of the actuators, and variable $\tau_o$ is the torque around rotation axis of the joint. Equation (1) expresses the curve shown in Fig. 1. Next, the elastic coefficient is obtained by partial derivative of $\tau_o$ with respect to $\theta_o$ as:

$$\frac{\partial\tau_o}{\partial\theta_o} = -\frac{k_{11}k_{12}\tau_{c1}e^{-k_{12}(\theta_o-\varepsilon_1)}}{\left(1+e^{-k_{12}(\theta_o-\varepsilon_1)}\right)^2}+\frac{k_{21}k_{22}\tau_{c2}e^{-k_{22}(\theta_o-\varepsilon_2)}}{\left(1+e^{-k_{22}(\theta_o-\varepsilon_2)}\right)^2}. \quad (2)$$

In the right side of the above equation, all values are constants except for $\tau_{c1}$ and $\tau_{c2}$. So, we can set the elastic coefficient by changing only the values, $\tau_{c1}$ and $\tau_{c2}$. This means that the joint stiffness of the mechanism which has the relation of eq. (1) is controllable without elastic materials by the principle of eq. (2). And, at $\tau_o = 0$, the joint converges to the EP, which is decided by the ratio of $\tau_{c1}$ and $\tau_{c2}$. Within the range to satisfy $\tau_o = 0$, the position of $\theta_o$ can be changed.

## 4. Kinematic transmission mechanism (KTM)

In order to realize the mathematical model in eq. (1), we propose a wire-driven mechanism shown in Fig. 5. In the mechanism, the cam (the input axis) rotation moves the passive link, where the wire is connected, and the passive link pulls the pulley (the output axis). Figure 5a) shows the geometric design of the proposed model. In the whole mechanism, because it is an antagonistic joint mechanism, the mechanism is symmetric. The cam shape can be determined based on the kinematic input-output relation of mechanism. We call this mechanism Kinematic Transmission Mechanism (KTM), as the kinematic elements such as the cam and the link are used instead of elastic materials. Although in case of employing elastic materials, analysis of its feature is not easy, the design of KTM is clear because we can design the cam to satisfy the kinematic constraints of the mechanism. Moreover, regarding to miniaturization of KTM, the similarity shape keeps the same input-output relation because its kinematic relationship depends on only the ratio of lengths, so that it will be possible to realize small size KTM.

### 4.1. Analysis of KTM

The relation between the output torque $\tau_{oi}$ $(i=1,2,\ldots)$ (around the output axis of the joint mechanism) and the input torque $\tau_{ci}$ (around the rotation axis of the cam) is expressed by eqs. (1) and (2):

$$\tau_{oi} = \pm C_i(\theta_o)\tau_{ci} \quad (3)$$

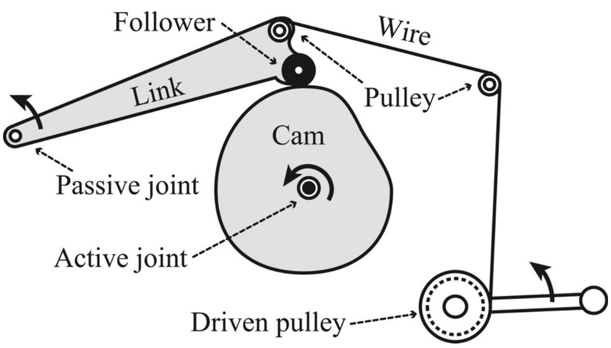
$$C_i(\theta_o) = \frac{k_{i1}}{1+e^{-k_{i2}(\theta_o-\varepsilon_i)}}+k_{i0}. \quad (4)$$

Equation (4) means the kinematic transmission property of the cam, which corresponds to the gear ratio between output and input of KTM. Here, the relation between $\tau_{ci}$ and $\tau_{oi}$ can be obtained by the principle of virtual work as:

$$\delta\theta_o\tau_{oi} - \delta\theta_{ci}\tau_{ci} = 0, \quad (5)$$

where $\delta\theta_o$ and $\delta\theta_{ci}$ are the virtual displacements. Solving the above equation with regard to $\delta\theta_o$, eq. (6) is obtained.

*(a) Structure of KTM.*




*(b) Analysis of kinematics.*

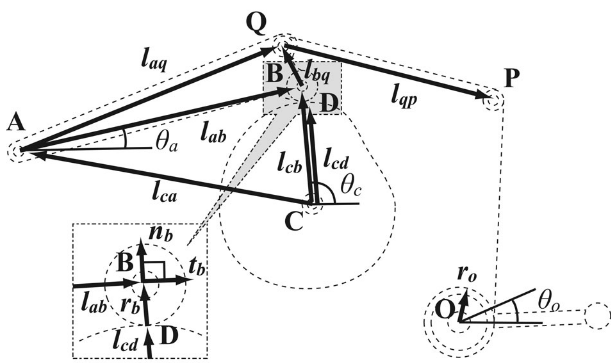



*Fig. 5. Kinematic transmission mechanism (KTM):(This image shows only one side. Practically, a symmetrical mechanism is added).*

$$\delta\theta_o = \frac{\tau_{ci}}{\tau_{oi}} \delta\theta_{ci}\,, \tag{6}$$

Here, $\delta\theta_o$ and $\delta\theta_{ci}$ are nearly zero, so the above equation is transformed into the following form:

$$\Delta\theta_o = \frac{\tau_{ci}}{\tau_{oi}} \Delta\theta_{ci}\,, \tag{7}$$

where, $\Delta\theta_o$ and $\Delta\theta_{ci}$ is small displacement. Integrate the above equation with regard to , and then we obtain:

$$\theta_o = \int \frac{\tau_{ci}}{\tau_{oi}} d\theta_{ci} \approx \pm \sum_{\Delta\theta_{ci}} \frac{1+e^{-k_{i2}(\theta_o-\varepsilon_i)}}{k_{i1}+k_{i0}(1+e^{-k_{i2}(\theta_o-\varepsilon_i)})} \Delta\theta_{ci}\,. \tag{8}$$

The obtained $\theta_o$ and $\theta_{ci}$ from eq. (8) are the displacements regarding the input and the output which satisfy eq. (3). From here on, we discuss only one-side KTM except when especially noted. So, the subscript $i$ denoting the distinction number of KTM is abbreviated. Using obtained $\theta_o$ and $\theta_{ci}$ we analyze the KTM. The final purpose is to obtain the cam shape satisfying the kinematic constraints on the KTM. Figure 5 (b) shows the vectors and the angles of the KTM.

The meaning of each symbol is:

$A,\ldots D, O,\ldots, Q$ : Names of each point

$l$ : Position vectors from a point to a point Subscripts express the points e.g. $l_{cb}$ is the position vector from point $C$ to $B$

$r$ : Vectors that express the diameter of a circle

$n_b$ : Normal vector of a follower

$t_b$ : Tangent vector of a follower

$\tau$ : Torque around a joint

$\theta$ : Joint angle

The wire is rolled round *via* point P when the input displacement increases. And $\theta_o$ is displaced by $\Delta\theta_a$. Then displaced wire length $\Delta l_{qp}$ is:

$$\Delta l_{qp} = |\boldsymbol{r_o}|\Delta\theta_o\,. \tag{9}$$

From law of cosines we obtain the increment $\Delta\theta_a$ of $\theta_a$ when the side length of the triangle AQP is increased by $\Delta l_{qp}$. From the $\Delta\theta_a$, we obtain $l_{ab}$ after rotation, where

$$\boldsymbol{l_{cd}} = \boldsymbol{l_{ca}} + \boldsymbol{l_{ab}} - \boldsymbol{r_b} \tag{10}$$

The coordinate of cam shape vector $l_{cd}$ can be transformed to the coordinate frame of the cam as:

$${}^{C}\boldsymbol{l_{cd}} = \boldsymbol{R}(-\theta_c)\boldsymbol{l_{cd}} \tag{11}$$

where, $\boldsymbol{R}(\theta)$ is rotation matrix. The cam shape is obtained by calculating ${}^{C}l_{cd}$ by using eq. (11).

### 4.2. Design of KTM

In this section, we discuss about the design of KTM. The parameters regarding dimensions such as the link length, the size of the bearing and the positioning of each rotary shaft are decided by adjusting to the designer's purpose.

The design steps are:

1. Decide the design parameters regarding the dimensions such as the lengths of the links.
2. Decide the design parameters regarding the sigmoid function from eq. (1) or (3).

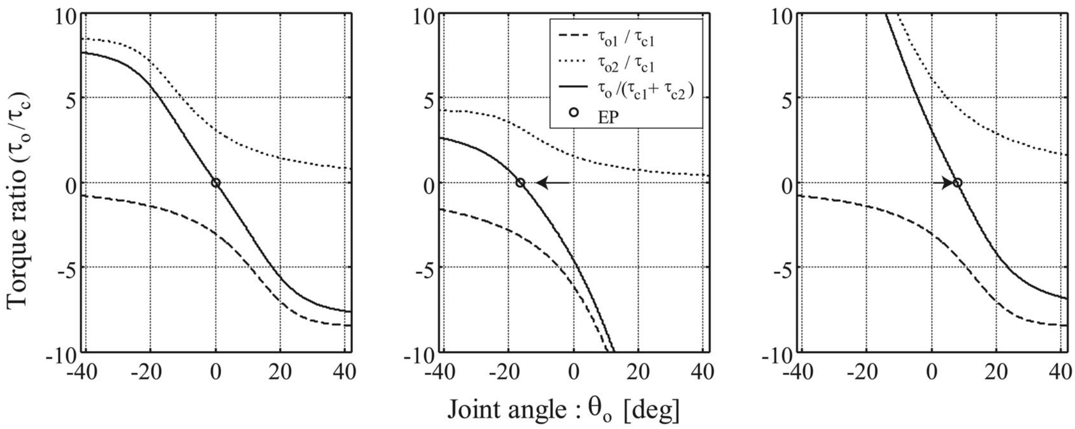



*Fig. 6. Joint angle $\theta_o$ vs. input-output torque ratio, and transitions of the equilibrium points.*

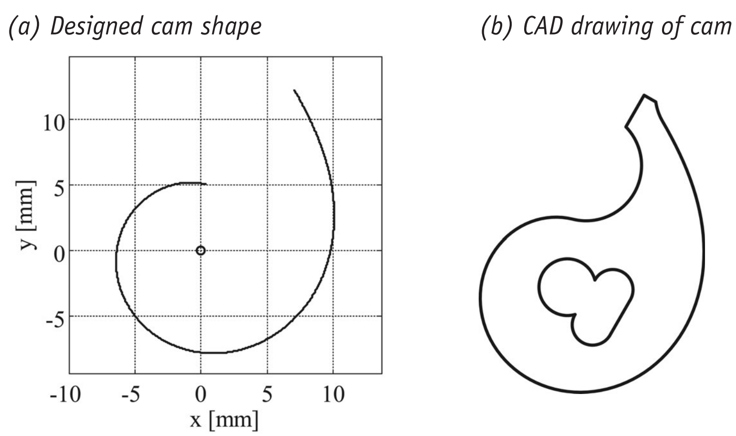



*Fig. 7. Cam for KTM.*

*Table 1. Parameters.*

| Parameters | Values | Units | Parameters | Values | Units |
|---|---|---|---|---|---|
| $\|\boldsymbol{r_o}\|$ | 7.5 | mm | $k_{10}$, $k_{20}$ | -0.5 | Nm |
| $\|\boldsymbol{r_p}\|$ | 2.0 | mm | $k_{11}$, $k_{21}$ | 9 | |
| $\|\boldsymbol{r_q}\|$ | 2.0 | mm | $k_{12}$, $k_{22}$ | 1.2 | |
| $\|\boldsymbol{r_b}\|$ | 4.0 | mm | $\varepsilon_1$, $\varepsilon_2$ | 1.4879 | rad |
| $\|{}^{C}\boldsymbol{l_{cd}}\|$ | *5.0 | mm | $\boldsymbol{l_{op}}$ | $[-0.5, 2.0]^T$ | mm |
| ${}^{A}\boldsymbol{l_{ab}}$ | $[30.0, 0.0]^T$ | mm | $\boldsymbol{l_{oc}}$ | $[2.0, 2.0]^T$ | mm |
| ${}^{A}\boldsymbol{l_{aq}}$ | $[40.0, 0.0]^T$ | mm | $\boldsymbol{l_{oa}}$ | $[50.0, 20.0]^T$ | mm |

*initial value

3. Obtain $\theta_o$ and $\theta_c$ from eq. (8).
4. Derive the cam shape coordinates from eq. (9) to (11).

Figure 6 shows the graphs of the output torque of joint vs. the joint angle when the ratio of the input torques of two actuators is changed. These graphs are obtained by eq. (1) and Table 1 show the corresponding parameters. In phase 2, we decide some parameters by checking the curves such as shown in Fig. 6.

*Table 2. Specifications of developed joint mechanism.*

| | |
|---|---|
| Size | W 106 x H 98 x D 77 mm |
| DOF | 1 DOF |
| Wire | Dyneema(polyethylene fiber) |
| Actuator | Maxon RE-MAX24 11W x 2 (Gear ratio 5.4:1) |
| MPU | PIC18F8720 (20[MHz]) |
| Current controller | PI controller |
| Sensor | Potentiometer x 1<br>Rotary encoder x 2<br>Current sensor x 2 |
| Sampling rate | 100[sps] (from MPU to PC)<br>500[sps] (ADC of MPU) |
| Communication | RS-232 (19.2[kbps]) |

The designed cam is shown in Fig. 7-(a). Fig. 7b) shows the CAD drawing of the produced cam. Figures 8a) and 8b) are the graphs that show kinematic transmission feature expressed by the gear ratio $C(\theta_c)$ with respect to the output joint angle $\theta_o$ and the input cam angle $\theta_c$. We verified the cam functioning whether it works according to design.

The verifying way is check of the matching ratio about the curves of the theoretically designed cam and the made cam when the abscissa is the input angle and the ordinate is the output angle. The result is shown in Fig. 9. The actual values match to theoretical values well. So, we conclude that the cam made according to our design behaves as expected.

## 5. Experimental Prototype

Using designed KTM, we developed the 1-DOF joint mechanism (see Fig. 10). The specifications of the joint mechanism are shown in Table 2.

The EP moves by changing the ratio of input torques as shown in Fig. 6. Changing the ratio, we examined the position control capability of the joint mechanism employing KTM without position feedback. Only the motor's currents are controlled by the PI-controller in the equipment. The joint angle and the motor angles are measured by using a potentiometer and two rotary encoders. In the experiment, the responses of the current and the joint angle are measured; at first, the joint angle is set to a position of 40[deg], then the current values are changed and the joint angle target is set to 0[deg]. The currents are controlled to be a constant value while measuring. The same values of the currents are set to the two motors in the joint mechanism while targeting the joint angle to 0[deg]. In order to investigate the difference of the joint stiffness, we compared the responses with respect to the joint angle in cases of 0.04[A] and 0.08[A]. The results are shown in Fig. 11, where (a) is the response of the joint angle and (b) is the response of the motor's currents. The joint angle gets close to the target angle 0[deg], by controlling only the current inputs. However, there are the steady-state errors caused by the effect of friction and the loss of back drivability. The main factor of loss of back drivability is the counter electromotive force, which is caused by the motor. The size of the steady-state error in the case of 0.08[A] is smaller than in the case of 0.04[A]. And the responsiveness in the case of 0.08[A] is better than in the case of 0.04[A] as well. As the next step, we evaluate the responsiveness regarding dynamic stiffness control when the joint mechanism is loaded by the external force. The currents are controlled at 3 seconds and 6 seconds after the experiment starts, and the joint stiffness is changed. The loaded external force is cyclic and the value of amplitude is invariable. The result is shown in Fig. 12. As shown in the figure, the amplitude of the joint angle becomes large when the current values are set low. This occurs due to the decrease of the joint's stiffness. The amplitude changes, immediately after the change of currents. So it is verified that the joint mechanism's stiffness can be controlled dynamically.

## 6. Joint Mechanism and Biogenic Motion Control

Here, we discuss about the relationship of motion controls and brains. Marr and Albus have been proposed a theory that cerebellums have the function of perceptron from their minute observation at the part [20],[21]. Therefore, cerebellums output a pattern when a pattern is inputted to them, such as perceptron. In biogenic motion controls, it has cerebral-cerebellum loop, and it has been shown that cerebellums participate in the motion control. The movement disorder occurs when cerebral-cerebellum *(a) The input (cam) angle $\theta_o$* *(b) The joint angle $\theta_o$*

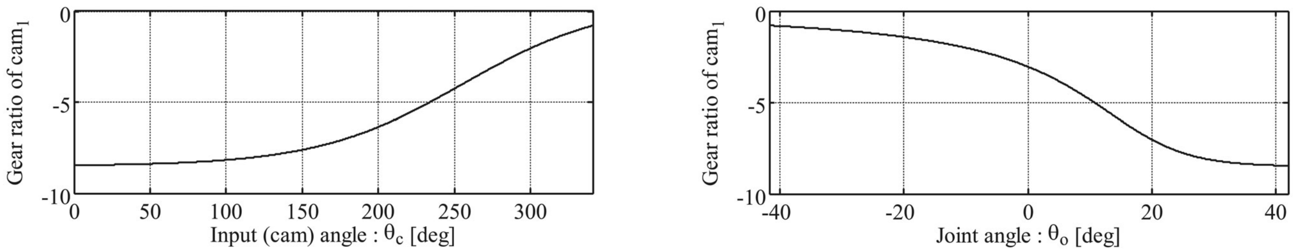



*Fig. 8. Gear ratio of designed cam (the case of cam$_1$).*

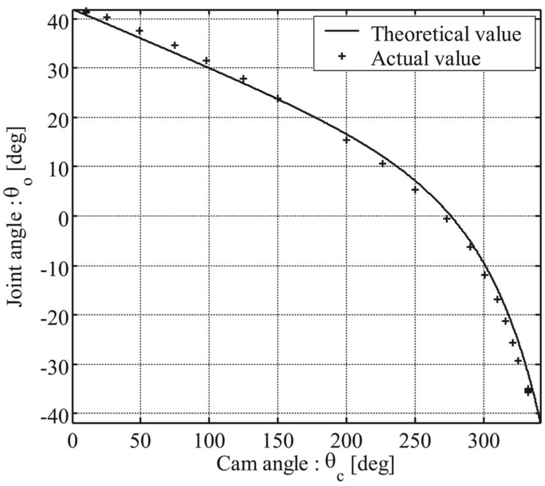



*Fig. 9. Cam curves of theoretical and actual value.*

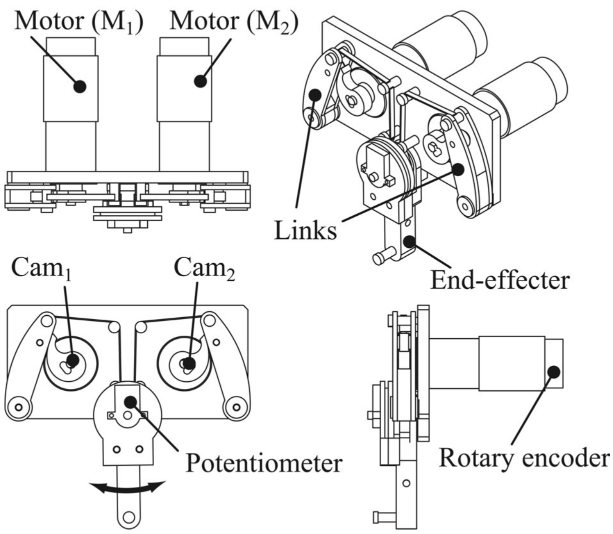



*Fig. 10. Antagonized wire-driven mechanism using KTM (1 DOF).*

*(a) The joint angles $\theta_o$*

*(b) The currents of the motors of the joint ($M_1$ and $M_2$ are the motors of left and right side)*

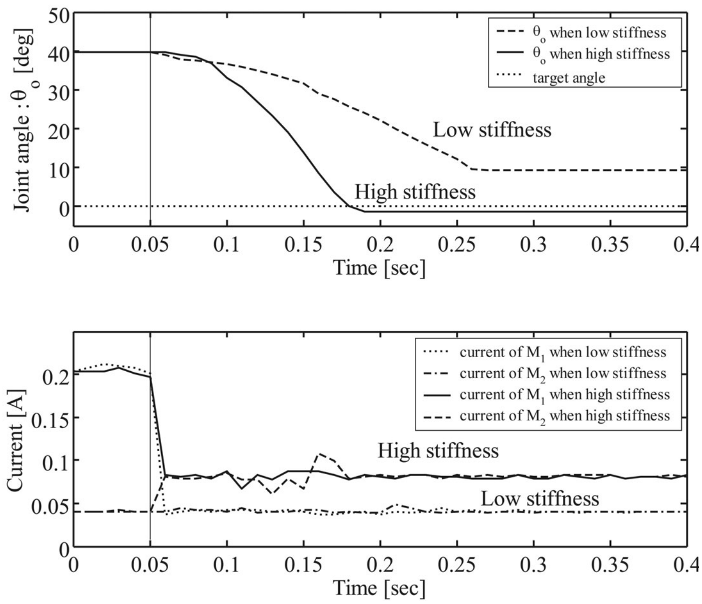
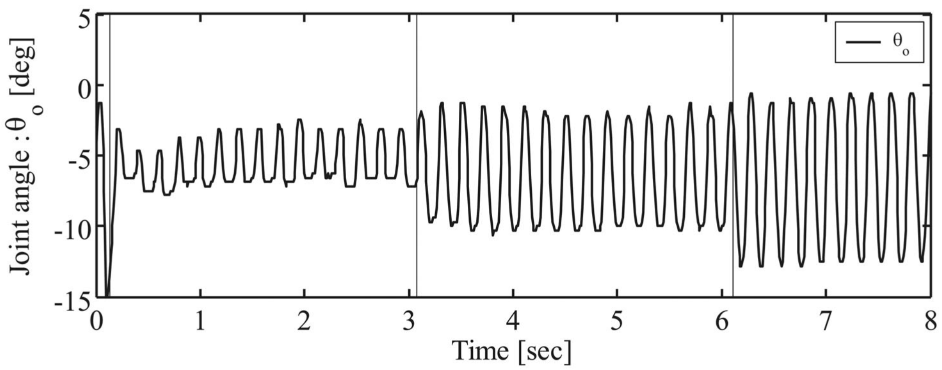



*Fig. 11. Experimental results of angle and stiffness control of the joint (The cases of low and high stiffness).*

loop has broken, but the intention of trying to move (voluntary motor control) is not inhibited. So, it has been suggested that cerebellums participate in the motion skill. If the theory of cerebellar perceptron is true, the motion should be converted to any patterns as the input or the output to the central nervous system. The proposed joint mechanism is able to control the position and the compliance of the joint by changing the motor output (this equals the tension of a muscle) . So, controlling the joint position, it is able to control the joint directions. Therefore, the joint mechanism is possible to control the motion by the static inputs and not the dynamic inputs. This means that the position, the compliance, the direction and the outputs of the joint are regarded as the static patterns. We suggest that the mechanism changing the movement elements to the static patterns such as the proposed mechanism by us is able to connect the biogenic motion control to neural system models.

*(a) The joint angle*




*(b) The currents of the motors of the joint*

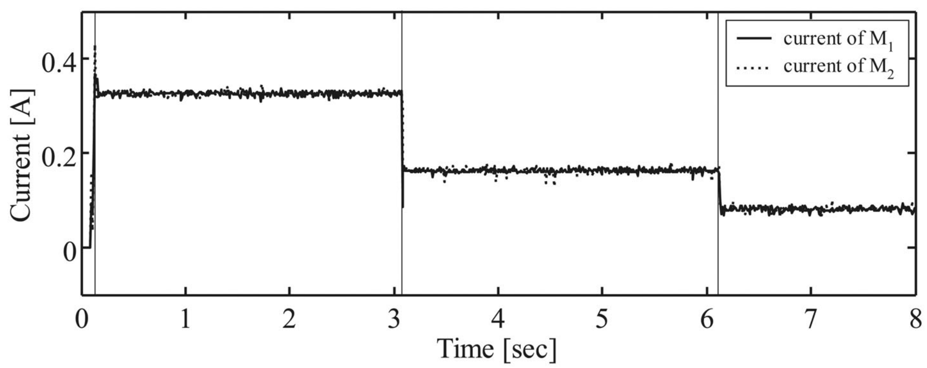



*Fig. 12. Experimental results of response of changing stiffness.*

## 7. Conclusions

In this paper, we proposed the robot joint "KTM" which is based to the EP hypothesis, which is a leading hypothesis of the position control system of musculoskeletal system. One of the important issues of the EP hypothesis is that the nonlinear kinetic features of muscles are the essential to control the articuler position and stiffness. In the conventional mechanical softness joints, elastic materials are employed for obtaining nonlinear performance. However, deformation of elastic materials occur delays. KTM has the advantage of the nonlinear kinematic transmission features such as linkage mechanisms have it. We proposed an EP hypothesis based kinetic model, and we discussed the kinematic transmission feature expressing by the model with the design steps. And we showed that the position and the stiffness control are possible from experiments. We proved that the joint angle moves to around the target angle but the steady-state errors remains. The steady-state errors become smaller by making the articuler stiffness higher. However, the improvement of position controllability is expected by dealing with the counter electromotive force of the motors.

We observe the responsiveness of the stiffness control by loading the constant cyclic external force to the joint. Then, we verified that oscillation of the joint angle just the changing of the articuler stiffness. A future work is to verify the response in loading high frequency external force to the joint. As other problems, there are the stretch of wire, optimization of KTM, multi-DOF and closed loop control. KTM is more simple mechanism than conventional mechanical softness joints. Moreover, freedom of design is higher, and minimizing is possible. We expect the large applications of KTM such as an active shock absorber for vehicles and such as the application to manufacturing and household robot.

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