Anthropomorphic Finger Mechanism with a non-elastic Branching Tendon

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Abstract. To realize both grasp stability and manipulation dexterity is a central problem in development of robot hands. In recent years, many underactuated robot hands have been developed to flexibly conform to an object's surface with simple control. In contrast, it is difficult to realize dexterous manipulation by such underactuated hands in which all degrees of freedom (DoFs) should be controlled. In this research, to overcome the problem to realize dexterous manipulation by simple mechanism and control, we develop a robot gripper consisting of two tendon-driven robotic fingers with non-elastic branching tendons. The branching tendon is a tendon that branches and connects an actuator to different links. In this robotic finger, the two joints are coupled by the non-elastic branching tendon when no external force is exerted. If a certain amount of external force is applied on the fingertip, one of tendons slacks and the coupling between two joints will be lost. This means that the two-DoF robotic finger is easily controlled as one DoF mechanism in reaching to an object, but it can still move by releasing the coupling provided by the branching tendon while the fingertip is fixed on the object. Based on this idea, we develop and control the two-DoF robotic finger that equipes two tendons including the non-elastic branching tendon. In addition, we analyse the condition, where the branching tendon gets slack, and confirmed in an experiment. As the result, the availability of controlling the slack of branched tendon was successfully confirmed.

1 Introduction

Robot hands have been intensively studied to achieve humanlike stability and dexterous object manipulation. There are two types of robot hands in terms of hardware design: actuating joints directly by motors and actuating joints through tendons. When a robot hand is designed to imitate a compact human's hand, a tendon-driven mechanism is often employed since it does not necessarily put motors at the joints. For instance, JPL/Stanford Hand[1], Utah/MIT Hand[2], and DLR-Hand[3] are all employing the tendon-driven mechanism. In particular, ACT Hand[4] has very similar musculotendinous structure to a human hand. Generally speaking, when we try to design a dexterous robot hand, we tend to put many degrees of freedom (DoFs) to the hand so that we can make it

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more versatile. However in order for these tendon-driven hands to this end, tendons more than the number of joints (i.e. the number of DoFs) have to be controlled. Therefore, control becomes complex and difficult as the number of DoFs increases.

To overcome this problem, a hand which has less actuators, which is called an underactuated mechanism, has been researched[5]. For instance, Soft Gripper realized flexible encapsulation grasping[6] and 100G Hand accomplished fast catching task[7]. These hands can be simplified since they employ passive mechanical elements such as springs instead of actuators. TUAT/Karlsruhe Hand has five underactuated fingers consisting of rigid linkages and is capable to realize various types of grasping[8]. However, an underactuated hand is often designed to be specialized for specific tasks because it basically has less DoFs.

Shirafuji et al. focused on the fact that a distal extensor tendon in a human hand branches before the PIP joint, and developed a three-DoF robotic finger with the branching tendon structure[9]. If the branching tendon is non-elastic, two joints are constrained geometrically when both linkages are tight. When the fingertip touches an object, it receives a certain amount of external force, and the constraint disappears because one of two branches slack. Therefore, the finger can be controlled as a two-DoF mechanism when it does not touch the object and a three-DoF mechanism when it touches the object.

Adopting non-elastic branching tendons for robot hands is supposed to be useful, but it is still not fully understood, how large external force and tensions of tendons should be to changes the configuration, and how the mechanism can be applied for object manipulation tasks. So far, Sawada et al. has studied branching tendon mechanisms, but they employed elastic tendons and did not considered slack.

In this research, we develop a robot gripper consisting of two-DoF fingers with non-elastic branching tendons to realize stable grasping and dexterous manipulation. Firstly, we propose a finger mechanism with the branching tendons and derive the condition when one of branching tendon slacks. Secondly, develop a two fingered robot gripper and demonstrate that the finger can be controlled as one-DoF one when it does not get external force, and that the finger can be released from the constraint when it touches the object and fulfills the condition of slack.

2 Kinematics of Manipulator with Non-elastic Branching Tendon

Fig. 1 shows the schematic illustration of the proposed robotic finger. The finger has two-DoF and two tendons noted as tendon 1 and tendon 2. We assume that these tendons has no elasticity. Tendon 2 is branched into two different routings of tendon noted as tendon 2a and 2b from a branching point placed between joint 1 and the corresponding actuator. One of the divaricate tendons is attached the link that connect joint 1 and joint 2, and another is attached the end link. The motions of two joints of this manipulator are coupled by the geometric constraint

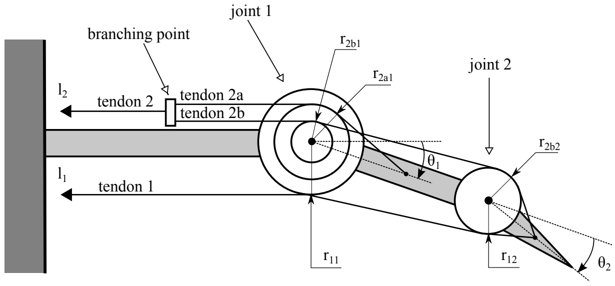


Fig. 1. Robotic finger with two-DoFs and two tendons. One of the tendons branches at the branching point.

generated by the branching tendon under the certain condition. In this section, we express the kinematics of manipulator with non-elastic branching tendon briefly, and derive the condition to keep the coupled motion of the two joints. In the tendon-driven manipulator, the representation of the relation between its joint angular velocities and its tendon displacement velocities is needed in addition to the general expression of the relation between its end-point velocity and its joint angular velocities to describe its kinematics. Given a vector of joint angular velocity $\dot{\boldsymbol{\theta}}$ and a vector of tendon displacement velocity $\dot{\boldsymbol{l}}$, the relation between them are represented as follows:

$$\dot{\boldsymbol{l}} = \boldsymbol{P}\dot{\boldsymbol{\theta}}, \tag{1}$$

where $\boldsymbol{P}$ is called a tendon Jacobian matrix and determined by the routing of each tendon. The relation between tensile force of each tendon and each joint torque also can be represented using with $\boldsymbol{P}$ as follows:

$$\boldsymbol{\tau} = -\boldsymbol{P}^T \boldsymbol{f}, \tag{2}$$

where $\boldsymbol{\tau}$ is a vector of joint torque and $\boldsymbol{f}$ is a vector of tensile force. In the case of that the manipulator has tendons which number is larger than joints and $\boldsymbol{P}$ is a column full-rank matrix, using with the vector of joint torque, the tensile force vector is given as

$$\boldsymbol{f} = -\boldsymbol{P}^{+}\boldsymbol{\tau} + \boldsymbol{f}_b, \tag{3}$$

where $\boldsymbol{P}^{+}$ is a pseudo-inverse matrix of $\boldsymbol{P}$ and $\boldsymbol{f}_b$ is its null-space. $\boldsymbol{f}_b$ is called a bias tensile force. More details of the kinematics of general tendon-driven manipulator can be seen in Kobayashi et al.[10] or some textbooks of robotics[11, 12]. Regarding the branching tendon in the proposed robotic finger as independent two tendons, the manipulator can be considered as a manipulator with three tendons as shown in Fig. 2. In this case, (1) can be represented as follows:

$$\begin{bmatrix} \dot{l}_1 \\ \dot{l}_{2b} \\ \dot{l}_{2a} \end{bmatrix} = \boldsymbol{P} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}, \tag{4}$$

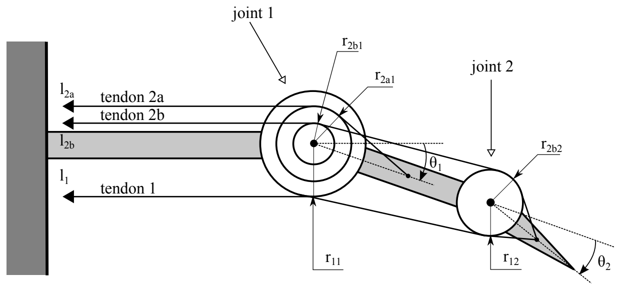


Fig. 2. Model of the proposed robotic finger regarding the branching tendon in the proposed robotic finger as independent two tendons.

where l_i is each tendon displacement, and the tendon Jacobian matrix is given as:

$$\boldsymbol{P} = \begin{bmatrix} -r_{11} & -r_{12} \\ r_{2b1} & r_{2b2} \\ r_{2a1} & 0 \end{bmatrix}, \tag{5}$$

where r_{ij} is a moment arm between each tendon and each joint, and its subscript indicates the corresponding joint and tendon. Note that the positive rotation is in a counterclockwise direction in the figure and positive displacement of the tendon is in a pulling direction. In order to apply any desired torque to each joint, the system has to be tendon controllable depending on elements of the matrix $\boldsymbol{P}$[10]. We assume that $\boldsymbol{P}$ is satisfied the condition to be tendon controllable.

We consider the kinematics in the case that the manipulator has a branching tendon as Fig. 1 based on the expression described above. The branching tendon is sometimes used to realize the underactuated manipulator[5]. Sawada and Ozawa[13] proposed a generalized control method for tendon-driven mechanism with branching tendons. Shirafuji et al.[9] has been proposed that the tendon-driven manipulator with branching tendons can be controlled as a manipulator with less DoFs than original DoFs virtually under the assumption that the branching tendon has no elasticity. It is caused by the geometric constraint of the branching tendon which generate coordinated motion of the joints. In addition, they implied that the system can be released arbitrarily from this coupled motion by adjusting the bias tensile force. We apply the method proposed by Shirafuji et al.[9] to the proposed robotic finger, and derive the condition to keep the coupled motion.

Shirafuji et al.[9] use a virtual tendon Jacobian matrix $\boldsymbol{P}_v$ to represent the relation between tendons include branching tendons and coupled joints. First, we derive this matrix of the proposed robotic finger. Equation (4) can be divided as follows:

$$\dot{l}_1 = \boldsymbol{P}_1 \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}, \tag{6}$$

$$\begin{bmatrix} \dot{l}_{2a} \\ \dot{l}_{2b} \end{bmatrix} = \boldsymbol{P}_2 \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}, \tag{7}$$

where $\boldsymbol{P}_1$ and $\boldsymbol{P}_2$ are the corresponding submatrices given as:

$$\boldsymbol{P}_1 = \begin{bmatrix} -r_{11} & -r_{12} \end{bmatrix} \ \boldsymbol{P}_2 = \begin{bmatrix} r_{2b1} & r_{2b2} \\ r_{2a1} & 0 \end{bmatrix}. \tag{8}$$

If there is no slacked tendon, the tendon displacement velocities of two tendons branched from tendon 1 has to be same because they are connected at the same point. Therefore, $\dot{l}_{2a} = \dot{l}_{2b} = \dot{l}_2$ and (7) can be rewritten as:

$$\dot{l}_2 \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \boldsymbol{P}_2 \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}. \tag{9}$$

The joint angler velocity is derived using the inverse of $\boldsymbol{P}_1$ as:

$$\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \dot{l}_2 \boldsymbol{P}_2^{-1} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \frac{\dot{l}_2}{r_{2a1}} \begin{bmatrix} 1 \\ \frac{r_{2a1} - r_{2b1}}{r_{2b2}} \end{bmatrix}. \tag{10}$$

During the coupled motion under the assuming there is no slack, it can be seen that the relation between each joint angular velocity is described as:

$$\dot{\theta}_1 : \dot{\theta}_2 = 1 : \frac{r_{2a1} - r_{2b1}}{r_{2b2}}. \tag{11}$$

The condition not to cause slackness to tendons will hereinafter be described in detail. We define a virtual angle θ_v to represent the angle of coupled joints as $\dot{\theta}_v = \dot{l}_2$. Substituting (10) into (4), we obtain the follows:

$$\begin{bmatrix} \dot{l}_1 \\ \dot{l}_{2b} \\ \dot{l}_{2a} \end{bmatrix} = \begin{bmatrix} \boldsymbol{P}_1 \\ \boldsymbol{P}_2 \end{bmatrix} \dot{l}_2 \boldsymbol{P}_2^{-1} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \begin{bmatrix} \boldsymbol{P}_1 \boldsymbol{P}_2^{-1} \begin{bmatrix} 1 \\ 1 \end{bmatrix} \\ 1 \\ 1 \end{bmatrix} \dot{\theta}_v. \tag{12}$$

From the fact that $\dot{l}_{2a} = \dot{l}_{2b} = \dot{l}_2$ when there is no slack, (12) can be rewritten as:

$$\begin{bmatrix} \dot{l}_1 \\ \dot{l}_2 \end{bmatrix} = \begin{bmatrix} \boldsymbol{P}_1 \boldsymbol{P}_2^{-1} \begin{bmatrix} 1 \\ 1 \end{bmatrix} \\ 1 \end{bmatrix} \dot{\theta}_v. \tag{13}$$

This align can be regarded as the relation between the joint angular velocities and the tendon displacement velocity of the tendon-driven manipulator with one-DoF and two tendons. In this case, the tendon Jacobian matrix of the system is described as:

$$\boldsymbol{P}_v = \begin{bmatrix} \boldsymbol{P}_1 \boldsymbol{P}_2^{-1} \begin{bmatrix} 1 \\ 1 \end{bmatrix} \\ 1 \end{bmatrix}, \tag{14}$$

and we call $\boldsymbol{P}_v$ as virtual tendon Jacobian matrix. Second, we apply this matrix to (2). Multiplying both sides of (2) by $(\boldsymbol{P}_2^{-1}[1\ 1]^T)^T$, we obtain the follows:

$$\begin{bmatrix} 1\ 1 \end{bmatrix} \boldsymbol{P}_2^{-T} \boldsymbol{\tau} = -\begin{bmatrix} 1\ 1 \end{bmatrix} \boldsymbol{P}_2^{-T} \boldsymbol{P}^T \boldsymbol{f} = -\boldsymbol{P}_v \begin{bmatrix} f_1 \\ f_{2a} + f_{2b} \end{bmatrix}, \tag{15}$$

where f_i is each tensile force and $f_{2a} + f_{2b}$ is equivalent to the tensile force of the branching tendon f_2. Furthermore, defining virtual torque vector as:

$$\tau_v = \begin{bmatrix} 1\ 1 \end{bmatrix} \boldsymbol{P}_2^{-T} \boldsymbol{\tau}, \tag{16}$$

we can control the proposed robotic finger regarding as the tendon-driven manipulator with one-DoF and two tendons virtually under the assuming that there is no slack of tendon.

We assumed that there is no slack of tendon in the above discussion, but the coupled motion is lost when one of the divided tendons is slack. This slack is caused by forces applied to the robotic finger, include external force generated by the contact with the environment and inertial force during its motion. The proposed robotic finger has a branching tendon, and there are two states of tendons when slackness is occurred as shown Fig. 3. These states can be used when we wish to control the robotic finger without the coupled motion of joints (e.g. we wish to manipulate the grasped object using with the end link of the robotic finger). Finally, therefore, we derive the condition that one of the tendons divided from the branching tendon become slack when torques are applied to the joints as a result of the external force applied to the fingertip as shown in Fig. 4. We consider the planar motion, and given the external force vector $\boldsymbol{F}$ which is applied to the tip of robotic finger, the relation between the external force and joint torques can be represented as:

$$\boldsymbol{\tau} = \boldsymbol{J}^T \boldsymbol{F}, \tag{17}$$

where $\boldsymbol{J}$ is a Jacobian matrix representing the relation between velocity of the contact point in each direction and each joint angular velocity. Assuming the frictionless point contact, the external force vector can be described as $\boldsymbol{F} = [0\ F]^T$, and (17) can be written as:

$$\boldsymbol{\tau} = \begin{bmatrix} L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2) \\ L_2 \cos(\theta_1 + \theta_2) \end{bmatrix} F, \tag{18}$$

where L_1 is the length of the link between the joints and L_2 is the distance between the contact point and joint 2. The slack of each tendon is occurred when

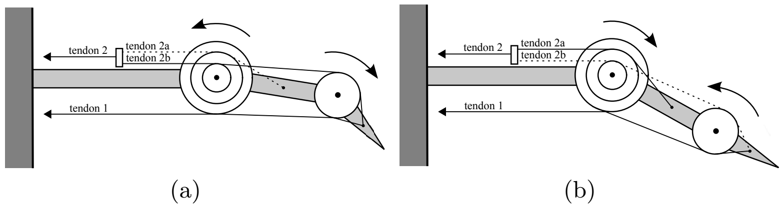


Fig. 3. States of the tendons when one of them is slack. The slacked tendon is illustrated as a dotted line. (a) The state when tendon 2a is slack. (b) The state when tendon 2b is slack.

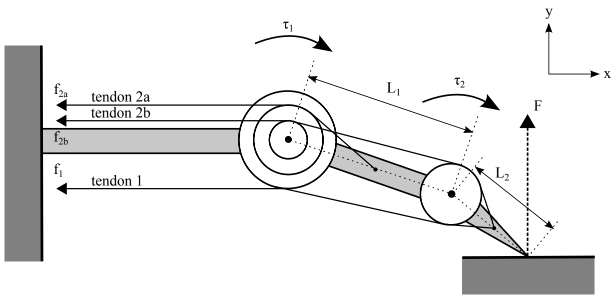


Fig. 4. Model of the equilibrium of force resulting from a contact with the environment.

its tensile force becomes negative because a tendon can not exert a pushing force. Therefore, substituting (18) into (3), we obtain the follows:

$$\begin{bmatrix} f_1 \\ f_{2b} \\ f_{2a} \end{bmatrix} = -\boldsymbol{P}^{+} \begin{bmatrix} L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2) \\ L_2 \cos(\theta_1 + \theta_2) \end{bmatrix} F + \boldsymbol{f}_b, \tag{19}$$

where we regard the branching tendon as independent tendons as shown Fig. 4. When one of f_{2b} and f_{2a} become negative for given the external force F and the bias force vector $\boldsymbol{f_b}$, the state of tendons change to the state such as Fig. 3, and this is the condition to nullify the coupled motion. We use these derived relations in this section to develop the robotic finger and validate the state transition of the tendons caused by the slack of tendon in the following section.

3 Development of Robotic Finger

We produced a robotic finger with the non-elastic branching tendon and developed a two-fingered gripper. Each finger has three links and two joints with five pulleys, and is driven by flexion/extension wires.

Movement of the joints is determined by the applied torque, and the torque is function of a moment arm of each tendon. Therefore, the moment arm is

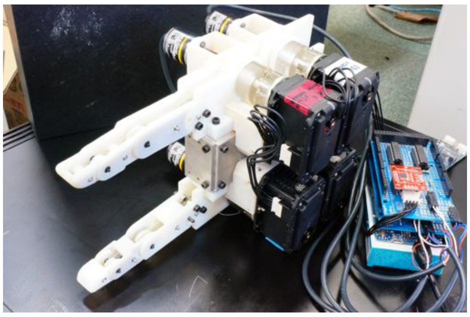


Fig. 5. Photo of the robot hand that has two underactuated fingers with branching tendon

an important factor to design the movement of the joint. The finger is driven by branching extensor tendon and flexor tendon, which is a simple model of a human finger. The actual moment arms for the rovotic finger are decided as follows: $r_{11} = 7$, $r_{12} = 4$, $r_{2b1} = 3$, $r_{2b2} = 4$, $r_{2a} = 5$(units are [mm]), taking the real parameters into account[14, 15]. Although the moment arm r_{2b1} is a nonlinear function of PIP joint angle according to Leijnse et al. [14], we set it as a constant value for simplicity. The diameter of the pulleys are designed depending on the real moment arms. Link length is also designed to imitated a real human. The length between joint 1 and joint 2 is 30.5[mm] and the length between joint 2 and fingertip is 22[mm].

Fig. 5 shows exterior of the finger system. Each tendon is driven by a servo motor(Dynamixel MX-64R), and rotation angle of a base pulley which winds the tendon is measured by a rotary encoders(OMRON E6A2-CW3C). Tendon displacement can be calculated by this angle. Pulses from the encoder are counted by a counter IC(NEC μPD 4702C). The finger is controlled by Arduino DUE. Arduino reads the values of the counter from digital input ports and sends out the commands for the motors by a Serial port.

Tensile force $\boldsymbol{f}$ and tendon displacement velocity $\dot{\boldsymbol{l}}$ are controlled by winding tendon wire by the base pulley. Base pulleys are not directly connected to servo motors, but driven by linear-torsion springs which are placed between servo motors and base pulleys. Torque exerted by the spring can be calculated by subtracting displacement of the base pulley from that of spring; therefore, for controlling the tensile force of a tendon, we have to control the spring displacement. We adopted springs whose spring constant is 5.17N/mm. A rotary encoder which measures angle of base pulley is directly connected to a shaft of the pulley.

Angular position and fingertip force can be controlled unless the tendons do not slack. The control is discrete system and micro computer on Arduino repeats the chain of calculation. The angular position control uses PID which calculates the desired spring torque from an position error of a joint. And current torque of spring is fed back to target torque. In addition, bias force is added tendon

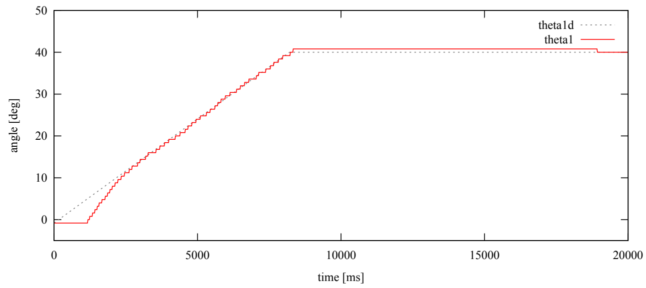


Fig. 6. Time response of joint angle 1 when the target is a ramp input. Desired angle changes from 0 to 40 degrees in about 8[s].It has certain time delay.

tensile force realizing target torque. Restricting finger movement on horizontal plane, gravity compensation is not included in the system. When not needing position control, finger can move with only feedback control of spring torque, giving the value of joint torque which exerts target fingertip forces.

Fig. 6 shows tracking performance of the developed system. We can see delay of initial response in the graph. This may be caused by rotational friction of joints on not the shaft but the surface of finger frame. In this time, we didn't sufficiently configure each gain constant because position control is not main focus in this research. If we had to improve responsibility, we can configure gain.

4 Validation of Tendon Slack

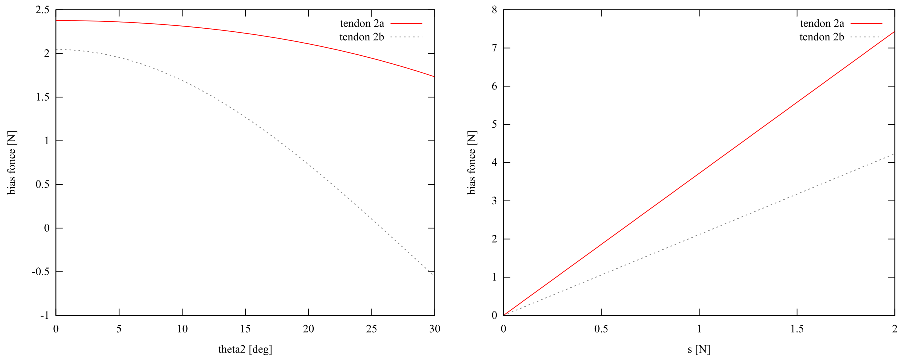
Depending on the bias tensile force of tendons and force exerted to the fingertip, one of the branched tendons may slack. We derived the slacking condition in Chapter 2. In this chapter, we will validate it in the real environment.

When tensile force of tendon 2a or that of 2b in (19) is zero, the tendon slacks. Substituting real parameters of the robot hand to (19), we can get

$$\begin{bmatrix} f_1 \\ f_{2b} \\ f_{2a} \end{bmatrix} = \begin{bmatrix} 0.0606L_1 \cos 2\theta_2 + 0.1098L_2 \cos 3\theta_2 \\ 0.0606L_1 \cos 2\theta_2 - 0.1402L_2 \cos 3\theta_2 \\ -0.1515L_1 \cos 2\theta_2 + 0.0387L_2 \cos 3\theta_2 \end{bmatrix} F + \begin{bmatrix} 1 \\ 1 \\ 0.8 \end{bmatrix} f_b, \qquad (20)$$

where f_b is a bias tensile force variable. From (20), we can derive f_b to make f_{2a} or f_{2b} zero by a function of F and θ_2. Fig. 7 shows the bias force f_b to keep f_{2a} and f_{2b} positive.

As figure shown, on the developed finger, the value of f_b which make f_{2a} to zero is larger than that of f_{2b} in any θ_2, F. Therefore, f_{2a} fall to zero and tendon 2a loosen before f_{2b} do, while gradually lowering f_b. In order to make tendon 2b slack, we have to change moment arms which defined the values of the matrix $\boldsymbol{P}$. This change need to produce new pulleys because the moment arms represented by the diameter of pulleys on joints.



(a) Limit of f_b against θ_2 when $F = 0.6$ (b) Limit of f_b against F when $\theta_2 = 15°$

Fig. 7. Limit value of f_b to keep f_{2a} or f_{2b} positive

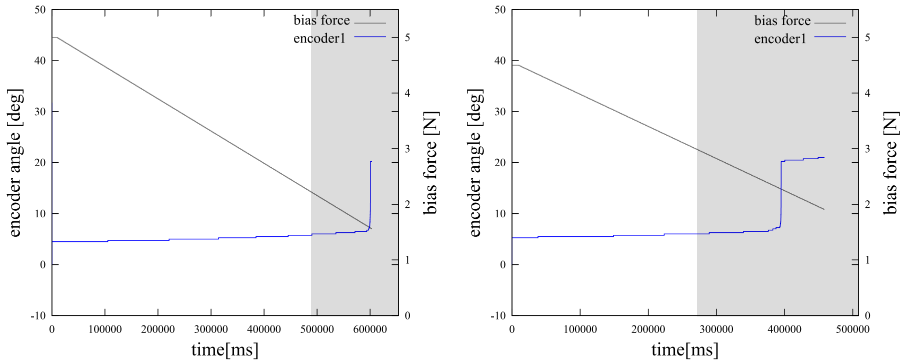
We conducted experiments to validate the slacking condition (20). The bias force f_b to loosen the tendon depends on a joint angle and fingertip force. For experimentally finding f_b to slack a tendon,

1. large f_b is applied to keep joint coupling,
2. the finger is actuated to generate a certain fingertip force F and
3. is brought into contact with low-friction board with a certain joint 2 angle θ_2,
4. f_b is decreased gradually, and finally
5. we find f_b to loosen tendon 2a.

Since the ratio of bias force between tendon 1 and tendon 2 is 1 : 1.8, bias force cannot generate the joint torques and finger doesn't move. However, practically, the finger actually moves when we set this ratio. This is caused by various factor such as difficulty to set initial displacement of torsion spring to zero. Then, before starting experiment, we stabilized finger with some bias force at the point where finger is extended in a straight line. We use the ratio of tendon 2 tensile force to tendon 1 in this time as the ratio of bias force.

The result obtained by actuation of finger using $\theta_2 = 15°$ as joint angle and $F = 0.6, 0.8$ as fingertip force is shown in Fig. 8. In addition, an example of finger movement in the experiment is shown in Fig. 9. In Fig. 8, "bias force" represents the value of f_b in (20) and this is bias force of tendon 1. "encoder angle" represents the angle displacement of the drive shaft measured by the rotary encoder which drive tendon 2. The area painted gray is which mathematically tensile force of tendon 2a is minus. As graph shows, tendon 2a get slack and finger movement causes increase of the value of the encoder after bias tensile force f_b fall short of the limit to keep tendon 2a's tensile force positive. It is verified that the slack of one of the branching tendon is caused by the value of bias tensile force.

The value which practically finger movement started is smaller than the calculated value for loosening tendon 2a. We can consider that the main reason



(a) $F = 0.6$ (b) $F = 0.8$

Fig. 8. Result of experiment$\theta_2 = 15°$

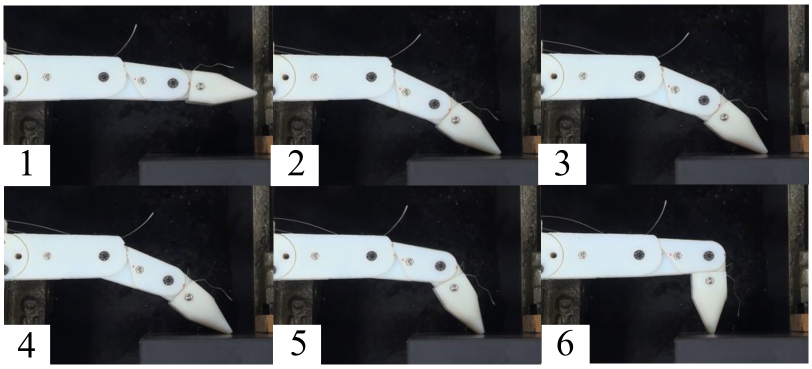


Fig. 9. Example of finger movement in the experiment. After the bias tensile force f_b fall short of the limit, figer move.

of this gap is the factor we ignored in the derivation of the condition to loosen tendon or the real environment. As the main factor we disregarded, we mention the sliding friction between the fingertip and the board and the rolling friction on the joints. If we notes the effect of these friction, finger's shape change need not only slack of tendon but also large force enough to get over the frictions. Then, finger movement come later than tendon relax. In the experiment, we could observe loosening tendon shortly before finger slided. Hence, when we control the finger, it is needed to consider these derived from dynamics of the robot. Moreover, the difficulty to adjust the ratio of bias tensile force possibly affect the difference. This ratio changes and is not clearly decided because of joint friction and setting initial position of torsion spring. We need to reduce the effect of these problem with improvement of robotic finger.

In addition, the measurement error on link lengths and joint angles also affects. For example, if a shorter length than that of the real finger uses, the value of bias tensile force to loosen tendon is calculated larger than the actual. At the same time, the actual fingertip force is smaller than expected because the joint torque to exert the requested force is calculated smaller. The smaller fingertip force, the smaller the value necessary for slacking off tendon. Therefore, the shorter measured length than the actual, the larger the difference between calculated and real bias tensile force to loosen branch.

5 Conclusion

We presented our two joint robotic finger which has branching tendon. First, we produced and actuated the finger system with position and tensile force control. Second, we found the condition to loosen branched tendon in the situation like that the finger exert a vertical force at the fingertip against a plane surface. We validated this condition of bias tensile force using the developed finger system. As a result, there is some gap between the calculation and the value to make the tendon slacken which is observed in the experiment. Though, we could expect the reasons about this difference as like above discussion and intentionally loosen the branch. This result can be an indication to actuate fingers of a gripper having a branching tendon with slack of branches.

In this paper, we can't deal with a gripper with the developed finger. We need to consider and investigate about a grasping tactics, a control of a gripper, and so on. It is expected that non-elastic branching tendon mechanism become a notable factor on the field of robotic, especially anthropomorphic hand. In the future, further study about this mechanism is required.

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