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Development of Drum CVT for a Wire-Driven Robot Hand

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***Abstract*— We propose a load sensitive Continuously Variable Transmission (CVT) for a wire-driven robot hand "Drum CVT", and aims at achieving efficient finger motions by mechanically changing the reduction rate of the drive: fast finger motion with low load (i.e., low drive at fast motion) and slow finger motion with high load (i.e., high drive at slow motion). We developed two material types of Drum CVT: the deflection-type (using nylon) and the torsion-type (using metal). Both types are investigated in both theoretical and actual models, and demonstrated their performance. Eventually, we revealed those characteristics, and indicated the usage of each Drum-CVT.**

I. INTRODUCTION

ROBOT hands are used for multiple purposes (i.e., industrial robots [3,4], medical robots [6], and prosthetic applications), and their usages require different design specifications: the numbers of degrees of freedom (DOF), size, weight, drive, and speed.

Especially for prosthetic applications, robot hands should be the mimics of human hands with regards to their appearance and performance, and they have technological difficulties to achieve such design specifications with the conventional design policy: that is, one motor directly actuates one joint. One of the major solutions is wire-driven mechanism. The mechanism realizes location-free actuation using wires, and the actuation part keeps light weight because the part does not have the weight of actuators. Thereby, many prosthetic hands achieve light weight on the fingers in human-hand size. However, their mobile requirement limits weight of actuators and, moreover, the design condition limits drive and speed of actuators. Thus, it is necessary to design mechanisms that enhance speed and drive of joints. Therefore, we aim at enhancing finger motions mechanically, and propose the Drum CVT (Continuously Variable Transmission) mechanism. Then, we verify its performance on theoretical and actual models.

II. DESIGN OF DRUM CVT

A. Conventional CVT

CVT is a mechanism that continuously and variably trades off between speed and force in its actuation. For example, Takagi [3] developed a link-mechanism CVT, which reduction rate is determined with the distance between a point to apply force and an actuation source. Therefore, it is necessary to reveal desire speeds and desire forces at specific motion ranges (e.g., fast motion and low drive at 0 to 90 [deg], and slow motion and high derive at 90 to 180 [deg]). However, the relationships between the ranges and the performances (i.e., speed and force) are fixed. As another example, Hirose [2] developed a load-sensitive CVT "X-screw", which has springs in the structure, and passively change its reduction rate with the degree of its load. However, the screw structure limits it motion range and does not suitable for rotational motions.

B. Proposal Drum CVT

We aims at developing a CVT for the wire-driven robot hand (Fig.1) [1]. For enhancing the performance, we focus on the following finger conditions: the finger moves fast when it gets a light load; the finger move slow when it gets a heavy load. Thus, we target a load sensitive CVT, which satisfies the above conditions, and propose a Drum CVT as shown in Fig.2 and 3. Fig.2 shows the basic structure. It consists of a RC servo motor, two discs, a shaft, a spring, a frame, and strings. One disc is attached to the axis of the RC servo, and the frame is attached to the outer box of the RC servo. The shaft is fixed with a hole of the disc and a hole of the frame. There are a spring and another disc on the shaft, and two discs are connected with strings as shown in Fig.3. This Drum CVT works as follows: when the wire gets no load, the circle on the cross section of the strings keeps max diameter and pull the wire at the fastest speed. Meanwhile, when the wire gets a load, the diameter of the circle will be smaller and pull the wire at slower speed. But, the wire traction force will increase. Then, the reduction rate (i.e., trade off between speed and force) is tuned with the coefficient of the spring.

Moreover, we propose two types of Drum CVT. (1) Deflection-type Drum CVT: the discs are connected with soft strings so that the soft string is deflected when the wire gets a load in Fig.2a. (2) Torsion-Type Drum CVT: two discs are connected with soft strings covered and aluminum tubes are on

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the strings. So, the strings do not deflect but the drum itself get torsion as shown in Fig.2b.

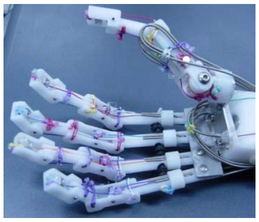


Fig. 1. The wire-driven robot hand [1].

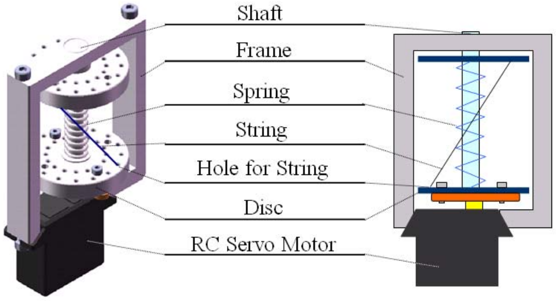


Fig. 2. A basic drum structure for Drum CVT.

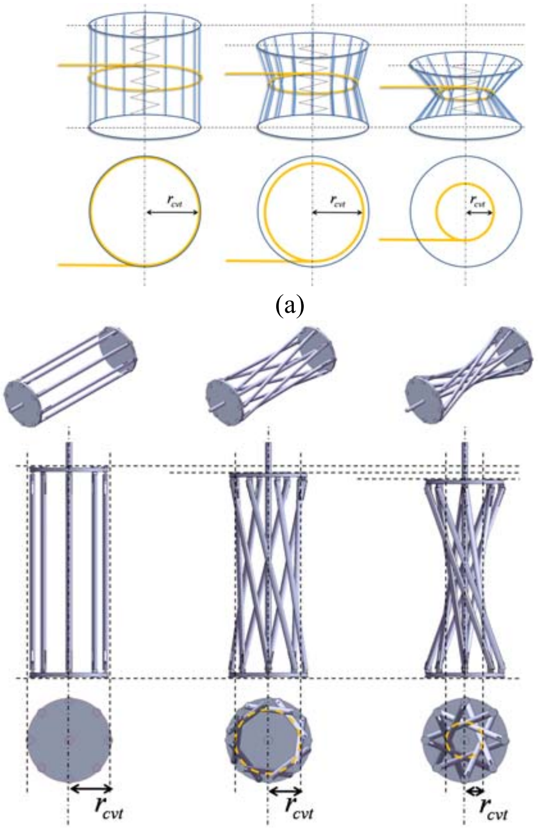


Fig. 3. Two types of Drum CVT (left: initial condition, center: middle condition, right: end condition). (a) Deflection-Type Drum CVT is made of the basic drum structure with nylon lines. (b) Torsion-Type Drum CVT is made of the basic drum structure with nylon lines and aluminum tubes.

Thus, the kind of two-disc connection also determines the reduction rate. Therefore in this paper, we investigates on the performance of Drum CVTs, which made of two different disc connections and three different springs.

III. THEORETICAL MODELS

Two proposed Drum-CVTs are modeled, and their reduction rates are investigated theoretically.

A. Deflection-Type Drum CVT

The theoretical model of Deflection-Type Drum CVT is shown in Fig.4. It consists of two discs, a string, a circular arc string, and a wire. The edges of the spring are connected to the center of discs, and the edges of the circular arc string are connected to the left edge of the discs. The wire is horizontally attached to the center of the circular arc string.

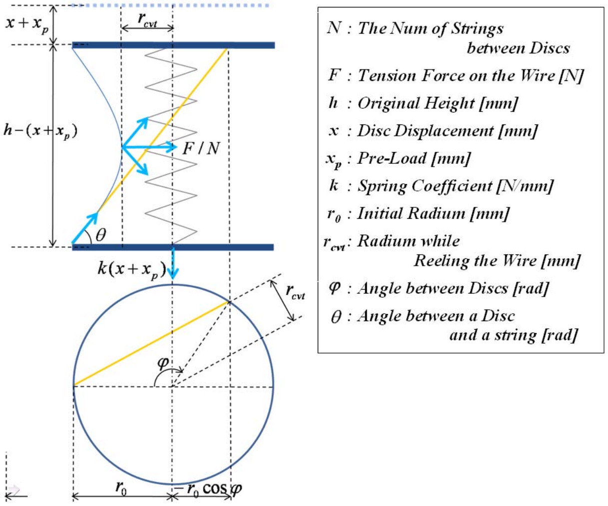


Fig. 4. The theoretical model of Dflection-type Drum CVT.

In this model, the more the wire tension F increases, the sharper the angle θ gets and the more the disc displacement x gets corresponding the coefficient of the spring k. The reduction rate $r_{cvt}$of the theoretical model is geometrically calculated with Equation (1) to (6).

$$\frac{F\sin\theta}{2\cos\theta} = k(x + x_p) \tag{1}$$

$$r_{cvt} = r_0\cos(\frac{\varphi}{2}) \tag{2}$$

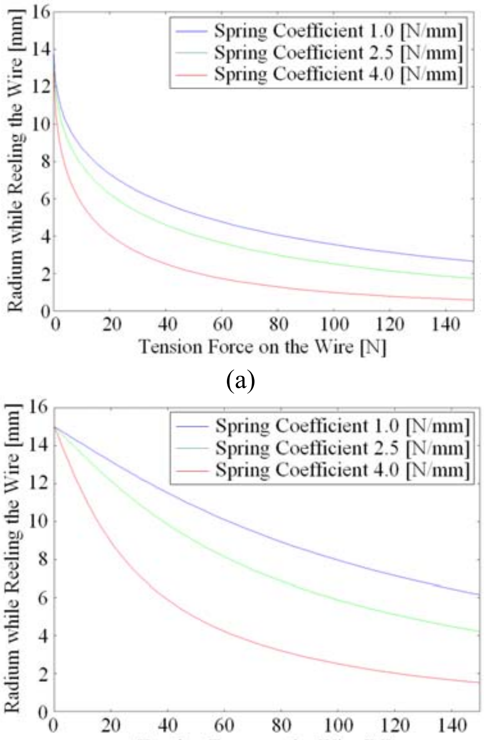
$$h^2 = (h - x)^2 + \{2r_0\sin(\frac{\varphi}{2})\}^2 \tag{3}$$

$$\tan\theta = \frac{h - x}{r_0(1 - \cos\varphi)} \tag{4}$$

$$F = \frac{2kr_0(1-\cos\varphi)(x_p + h - \sqrt{h^2 - \{2r_0\sin(\frac{\varphi}{2})\}^2})}{\sqrt{h^2 - \{2r_0\sin(\frac{\varphi}{2})\}^2}} \tag{5}$$

$$r_{cvt} = r_0\cos(\frac{\varphi}{2}) \tag{6}$$

The theoretical results are shown in Fig.5: it displays the radium r_0 corresponds to the wire tension force at three spring coefficients (i.e., 1.0[N/mm], 2.5[N/mm], and 4.0[N/mm]).



(a)

(b)

Fig. 5. Theoretical results of Deflection-type Drum CVT. (Common setting: h=30[mm], r_0 =15[mm]). (a) Pre-load x_p=0[mm]. (b) Pre-load: x_p=20[mm].

B. *Torsion-Type Drum CVT*

The theoretical model of Torsion-Type Drum CVT is shown in Fig.5. It consists of two discs, a string, two same-length straight-line strings, and a wire. The edges of the spring are connected to the center of discs. One edge of each straight-line string is connected to the right edge of each disc, and the other edge of each straight-line string is connected together. The wire is horizontally attached to the connection of the straight-line strings.

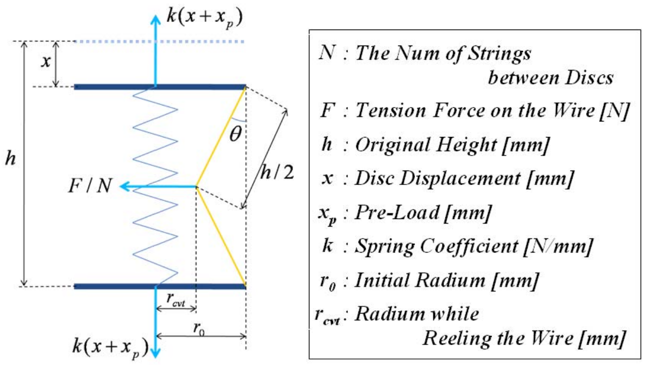
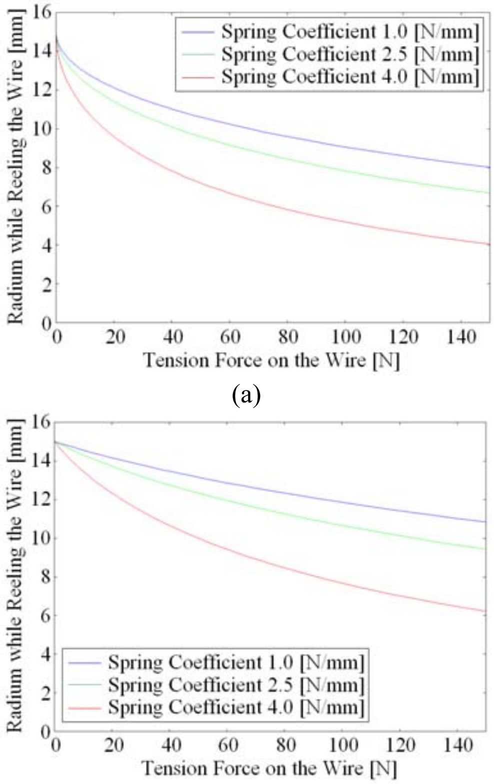


Fig. 6. The theoretical model of Torsion-type Drum CVT.



(a)

(b)

Fig. 7. Theoretical results of Torsion-type Drum CVT. (Common setting: h=30[mm], r_0 =15[mm]). (a) Pre-load x_p=0[mm]. (b) Pre-load: x_p=20[mm].

The reduction rate $r_{cvt}$of the theoretical model is geometrically calculated with Equation (7) to (10) as the previous section.

$$\frac{\cos\theta}{2\sin\theta}F = k(x + x_p) \tag{7}$$

$$\sin\theta = \frac{2(r_0 - r_{cvt})}{h} \tag{8}$$

$$x = h(1-\cos\theta)$$

$$F = \frac{2k\{x_p + h(1-\cos\theta)\}\sin\theta}{\cos\theta} \tag{9}$$

$$r_{cvt} = r_0 - \frac{h\sin\theta}{2} \tag{10}$$

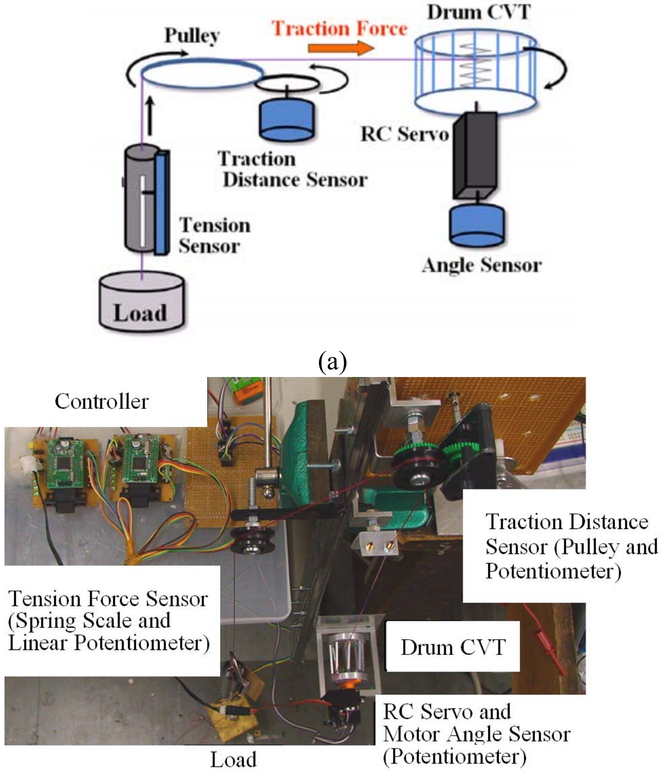
The theoretical results are shown in Fig.7: it also displays the radium r_0 corresponds to the wire tension force at three spring coefficients (i.e., 1.0[N/mm], 2.5[N/mm], and 4.0[N/mm]).

C. *Discussion*

The reduction rate range and characteristic of each CVT determines its performance. As the results, the widest range of the torsion-type is the radium 5 to 14 [mm] at the pre-load x_p=0[mm] and the spring coefficient 4.0 [N/mm]. Meanwhile, the widest range of the deflection-type is 2 to 15 [mm] at the pre-load x_p=20[mm] and the spring coefficient 4.0 [N/mm]. In summary, the deflection-type realizes the wider range of CVT. However, the characteristic is drastic change in low load and smooth change in high load. Therefore, it might be difficult to control the motion.

IV. EXPERIMENTS WITH REAL DRUM CVTS

We developed actual Drum-CVTs and investigated the reduction rates with the following experimental setups.



(a)

(b)

Fig. 8. The experimental setup. (a) Conceptual diagram. (b) Appearance.

A. *Experimental Setups*

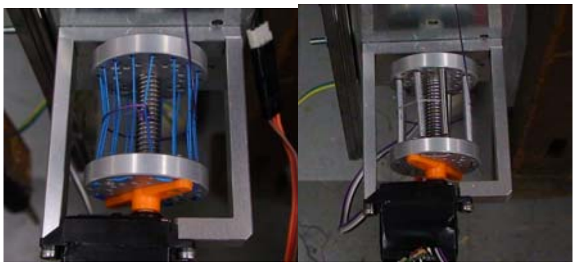
Fig. 8 shows the experimental setups. There are three sensors: the rotational potentiometer, which is connected to the RC servo motor observes the angle transition of the motor axis; the rotational potentiometer, which is connected to the pulley, observes the wire traction distance; the liner potentiometer, which is connected to the spring scale, observes the wire tension. The reduction rates are calculated with those sensor values.

For the experiments, we prepared 18 different material combinations as listed in Table I: two types of strings (Fig.9); three types of spring; three loads. That is, we record 18 runs to compare analyze their performance. At each run, the RC servo with Drum CVT pull the load up for 2 seconds, stop for 1 second, and pull the load down for 2 seconds.

TABLE I

EXPERIMENTAL SETUPS FOR 12 DIFFERENT TRIALS

Parts	Experimental Setting
Type of String	Nylon Line (Deflection Type) / Steel Line & Aluminum Tubes (Torsion Type)
Spring Coefficient	1.0 [N/mm] / 2.5 [N/mm] / 4.0 [N/mm]
Load	0.12 [kg] / 1.3 [kg] / 3.2 [kg]



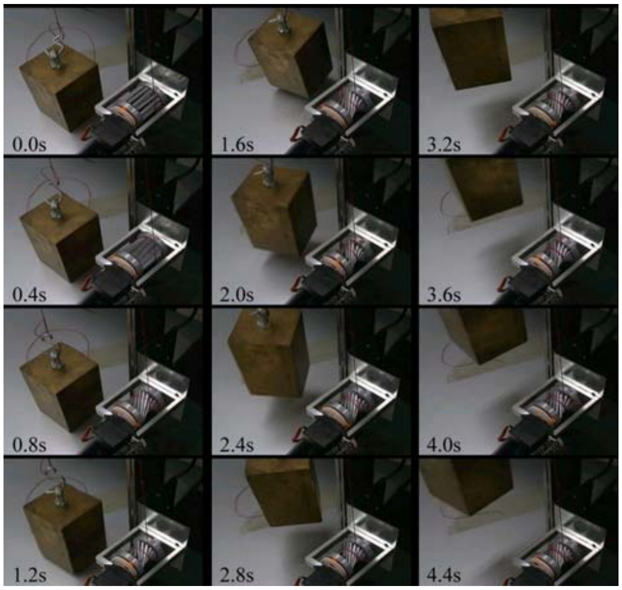
(a) (b)

Fig. 9. Appearances of Two Drum CVT. (a) The deflection-type. (b) The torsion-type.

B. *Results*

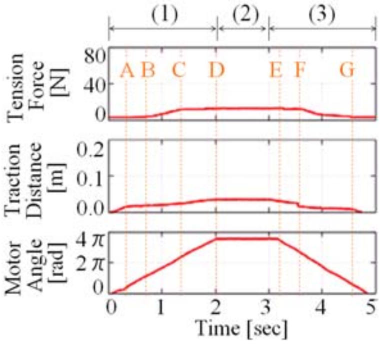
Fig.10 shows the experimental scenes: both types change the radium of the circle that is made of reeling the wire corresponding to their load. We have done 18 different runs. However, we only show two represent results in Fig.11: the transition of three sensor values (i.e., top: the wire tension force, middle: the wire traction distance, bottom: the motor angle). In Fig.11, the numbers (1) to (3) indicate the time ranges of three different motor control, and the alphabets A to G represent the time points of remarkable changes. Then, Table II explains those details. Here, we assume that the radium while reeling the wire is equivalent to the reduction rate, and discuss the results.

(a)

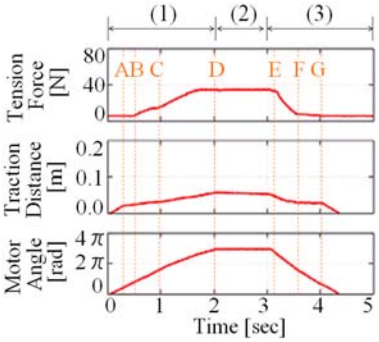


(b)

Fig. 10. Performance scenes of Drum CVTs. (a) The deflection-type. (b) The torsion-type.



(a)



(b)

Fig. 11. Results: transitions of wire tension force, traction distance, and motor angle. (a) The deflection-type (Load: 0.12[kg], Spring Coefficient: 4.0[N/mm]). (b) The torsion-type (Load: 3.2[kg], Spring Coefficient: 2.5[N/mm]).

TABLE II
LABEL INDICATION FOR FIG.10

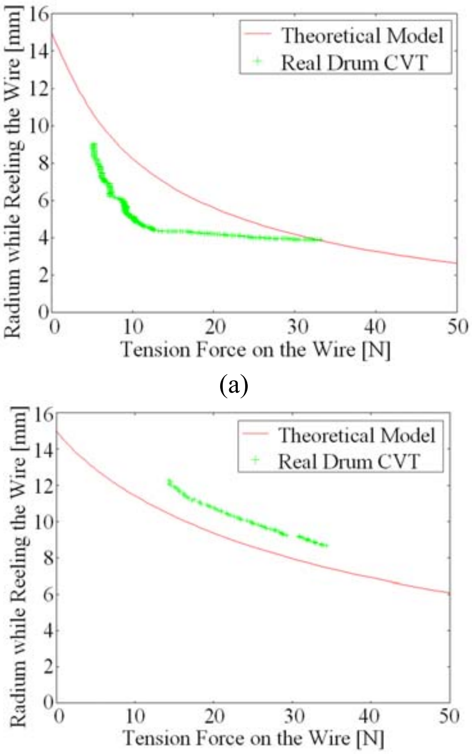
Label	Content
(1)	Pulling up the load.
(2)	Stop pulling the load.
(3)	Pulling down the load.
A	The time that the wire gets tension.
B	The load lands off the ground.
C	The time that the radium of the Drum CVT starts changing.
D	The time that the RC servo stops rotating for pulling down the load.
E	The time that the RC servo starts rotating for pulling up the load.
F	The time that the load lands on the ground.
G	The time that the wire lost its tension.

C. Compare-Analysis: Theoretical and Actual Drum-CVTs

Fig.12 shows the representative comparison between theoretical models and actual model of two types of Drum CVTs. The graph indicates the transitions of the radium in the string cross section (i.e., reduction rate) corresponding to the wire tension force.

D. Discussion

Fig.12 indicates the range reduction rates: the radium range of the torsion-type is 8 to 13 [mm]; the radium range of the deflection-type is 4 to 9 [mm]. Both have almost same width



(a)

(b)

Fig. 12. Compare-analysis between performances of the theoretical models and the actual Drum CVTs. (a) The deflection-type. (b) The torsion-type.

ranges, however, the deflection-type dramatically changes in lower load (i.e., wire tension force less than 12 [N]) and does not change in higher load (i.e., wire tension force more than 12 [N]). Meanwhile, the torsion-type constantly changes its reduction rate, which is relatively proportional to the load. Moreover, the comparisons between the theoretical and actual results illustrate: the deflection-type has differences in the slope angle of the lines; the torsion-type shows similar slope angles. It seems that, the deflection-type is made of soft strings and, therefore, it dramatically changes to the limit at the beginning and keep constant. Meanwhile, the torsion-type is made of aluminum tubes so that it stable changes its radium. Thereby, it is easy to control position with the torsion-type.

Table III lists the motion performance of two Drum-CVT. It shows that the deflection-type realize higher max drive force and reduction rate than the torsion-type. It is because that the torsion-type is made of aluminum tubes so that the minimum radium is wider than the minimum radium of the deflection-type. Thus, the deflection-type moves fast in lower load than the specific value which is determined with its spring coefficient. Then, it gets highest force and slowest speed in higher load.

As summary, we confirmed that both models achieved the desire performances (i.e., fast motion in lower load and slow motion in higher load). Then, for their controllability, it is better to apply the torsion-type because the reduction rate constantly changes and enable to control position precisely. Meanwhile, the deflection-type is useful for clearly dividing a variable transmission part and a constant transmission part: that is, fast motion in no load and, once it gets load, it moves at constant speed and high drive. Thus, either the deflection-type or the torsion-type should be applied by its design policy.

TABLE III
SUMMARY OF PERFORMANCE COMPARISON

	Deflection Type	Torsion Type
Optimal Spring Coefficient	Lower (k<0.1[N/mm])	Higher
Rise Time to Start Changing Reduction Rate	1.2 [sec]	0.5 to 0.8 [sec]
Max Drive Force	63[N]	42 [N]
Reduction Rate	1.0 to 3.0	1.0 to 2.0

V. CONCLUSION

We developed a load sensitive Continuously Variable Transmission for a wire-driven robot hand: “Drum CVT”. The purpose is to achieve mechanical trade-off between speed and force on the finger motions: that is, fast motion with low load and slow motion with high load. Then, we developed two types of Drum CVT: the deflection type is made of metal bars and the torsion type is made of nylon strings. We conducted theoretical and actual experiments for investigation of optimal springs and connection strings, which are suitable for our desire performance. As results, both models achieved the desire performances. Finally, we concluded that each Drum-CVT has own characteristics and achieves different controllability of the finger motion.

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