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Design of a Passive Brake Mechanism for Tendon Driven Devices

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Tendon driven mechanism is one of the most popular mechanism for transmitting force and power from a distance. The energy efficiency of a tendon driven system can be improved if it can maintain actuation force while it is not moving without mechanical work. This could be achieved by a brake; a brake without an additional actuator is preferred for the compactness of the whole system. We present a novel passive brake mechanism, a capstan brake, which consists of a capstan and two one-way clutches. The friction between the capstan and the cable amplifies a small resisting force (originated from an inactive motor) to gain enough brake force. Because no additional actuator is involved, generation of the brake force does not consume energy. Also, the one-way clutches enable the capstan to rotate in the winding direction. Therefore, the brake force is exerted only when it is needed, and the performance of the whole device does not decrease owing to the use of the capstan brake. The performance of the proposed brake mechanism has been evaluated through several tests. The results show that the amount of the maximum brake force for the test condition is more than 55 N (and can be further increased by increasing the number of windings), and that the force loss from the brake is negligible.

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1. Introduction

Recently, tendon driven mechanisms have been adapted to many bio-mechanical robots and medical robots. The advantages of using tendon driven mechanisms are as follows. First, the actuators do not need to be placed at each joint since the tendons can transmit force from a distance. Second, various designs can be realized because the tendons are flexible. These advantages encourage engineers to make portable devices with the tendon driven mechanism.

Generally, the energy efficiency of an electric motor is relatively higher than other types of actuators.[1] However, because a small electric motor, which is typically adapted to portable cable driven devices, is back-drivable,[1] it dissipates energy to maintain tension. In this case, the energy efficiency of the motor is zero. Such a 'zero energy efficiency area' needs to be minimized. For example, while grabbing an object with a robotic hand,[2] the actuating motor moves the finger and the robotic hand operates within the 'normal energy efficiency area' before the finger reaches the object. However, once the finger touches the object, the motor still needs to apply the torque to maintain the position. As a result, energy dissipates even though the motor does not generate mechanical work.[3]

The passive brake mechanism provides a solution for this issue. In the same example mentioned above, after the finger touches the object and sufficient amount of torque is applied, the passive brake can be activated to make the motor non-back-drivable and maintain the tension of the tendon. Several mechanisms were developed in the past to make actuators non-back-drivable.[3] Worm gear pairs and lead-screws were employed to earn non-back-drivability.[4,5] High reduction ratio transmission was used to achieve non-back-drivability.[1,6] The third mechanism employed a customized clutch.[3,7]

In this paper, we propose a novel type of passive brake mechanism for cable driven devices to get non-back-drivability. The mechanism can be constructed with a cylinder (we call it capstan), two one-way clutches, and frames to fix them. Since the proposed mechanism does not use any gears, non-back-drivability can be achieved without a decrease in speed and efficiency drop between the gears. Compared to the passive brake made of a customized one-way clutch,[3,7] the proposed system is simple and can be made using off-the-shelf one-way clutches. This system uses a small hold-force originating from a turned-off motor, as a source of brake force. This force is amplified by the capstan to get a large brake force. Also, a one-way clutch is used to enable the brake force to be applied only in the desired direction. In the following sections, the structure and the operating principle of the mechanism is explained, and the performance of the brake is validated with a test platform. The results show that the brake force when the motor is turned off is large enough and that the brake does not affect the system when the motor is turned on.

2. Mechanism and its Analysis

2.1 Description of a capstan brake

The desired function of our brake mechanism is to maintain the tension of the cable even with the motor turned off. To achieve this, the brake mechanism should be activated when the motor is turned off. In addition, to prevent loss of efficiency and to facilitate smooth operation of the whole system, the brake should not exert a resistive force when the motor winds or unwinds the cable. The functions mentioned above can easily be fulfilled by an active brake. However, an active brake requires an additional actuator, which makes the whole system bulky. Therefore, we propose a novel passive brake mechanism satisfying these functions without any additional actuator, called “capstan brake”. The schematic drawing is shown in Fig. 1.

The capstan brake is basically a capstan with a one-way clutch that can rotate only in one direction. The cable coming out of the motor is wound around the capstan brake before being connected with an external load.

The capstan brake operates as follows. When the motor is turned off, the capstan brake is passively activated to resist the external force. The source of the brake force is “motor resisting force ($F_{mot,0}$)”, which is defined as the amount of force an inactive motor can endure. $F_{mot,0}$ is amplified by the friction between the capstan brake and the cable wound around it, and this produces a brake force. When the motor is turned on to pull the cable, the one-way clutch enables the capstan to rotate in the winding direction. Because the free rotating torque of the one-way clutch is negligible, only a small amount of the winding force is lost. Finally, when the motor is turned on to release the cable, the cable becomes loose from the capstan brake. Therefore, even though the capstan does not rotate in the unwinding direction, the cable releases.

2.1.1 Braking operation

When the motor is turned off and an external force tries to unwind the cable, $F_{mot,0}$ is amplified by the friction between the capstan and the cable. The capstan equation describes the amplification ratio of $F_{mot,0}$. Fig. 2 shows the relation.

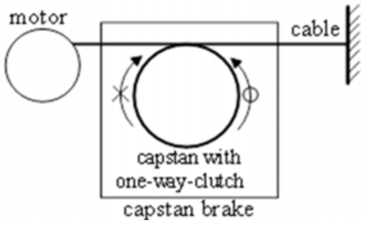

Fig. 1 Schematic drawing of the capstan brake. A brake force is only produced when the external force tries to unwind the cable

According to the capstan equation, the ratio of the load-force to the hold-force is proportional to the exponential of the friction coefficient times the contact angle between the cable and the contact surface. The classical form of the capstan equation is

$$F_{load} = F_{hold} e^{\mu_s \phi} \qquad (1)$$

Even though there are several modified versions of the capstan equation considering various properties of the cable,[8,9] the classical capstan equation is used for the analysis of our device for simplicity.

Fig. 3 shows the forces for the braking operation. $F_{mot,0}$ is the motor resisting force, F_{ext} is external force to release the motor, and $F_{friction}$ is friction force between the capstan and the cable. According to the classical capstan equation, the condition for the passive brake to work is

$$F_{ext} \le F_{mot,0} e^{\mu_s \phi} \qquad (2)$$

Maximum brake force is $F_{mot,0}e^{\mu_s \phi}$ according to (2). If F_{ext} is lower than the maximum brake force, the cable will not be unwound.

2.1.2 Winding operation

Fig. 4 shows the forces for the winding operation. F_{mot} is the force applied by the motor and F_{loss} is the force required to rotate the capstan. When the motor winds the cable, a capstan rotates freely and does not provide brake force. The force equilibrium is

$$F_{ext} = F_{mot} - F_{loss} \qquad (3)$$

Fig. 2 Forces of the cable on the capstan with a contact angle of pi. In this figure, F_{hold} is amplified to resist F_{load}

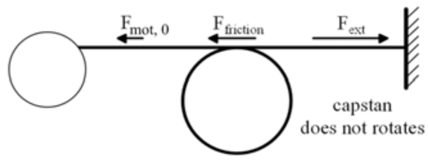

Fig. 3 Schematic of braking condition

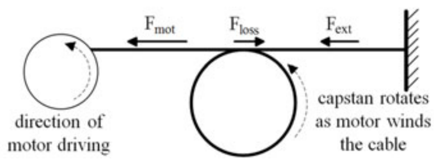

Fig. 4 Schematic of winding condition

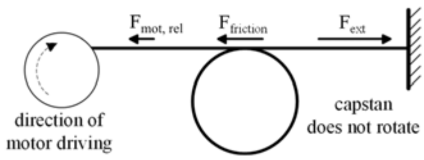

Fig. 5 Schematic of releasing condition

As illustrated, a small amount of force (F_{loss}) is required to rotate the capstan. Therefore, the external force (F_{ext}) is smaller than the original force provided by the motor (F_{mot}). F_{loss} is negligible because free rotating torque of a one-way clutch is negligible.

2.1.3 Releasing operation

Fig. 5 shows the forces for the releasing operation. $F_{mot,rel}$ is the force applied by the motor when the motor unwinds the cable. Because the capstan with one-way clutches does not rotate in the releasing direction, one might think that the friction between the cable and the capstan prevents the external force (F_{ext}) from releasing the cable.

However, when the motor unwinds the cable, $F_{mot,rel}$ becomes nearly zero. Therefore, even though $F_{mot,rel}$ is amplified by the capstan, the minimum amount of F_{ext} required to unwind the cable is small. The force relationship to release the cable is given by (4). If F_{ext} is higher than $F_{mot,rel}e^{\mu_s\phi}$, the cable can be unwound without difficulty.

$$F_{ext} > F_{mot,rel}e^{\mu_s\phi} \tag{4}$$

2.1.4 The assembly of the capstan brake

The assembly of the capstan brake is shown in Fig. 6. The spooler, for winding the cable, is connected to the motor. The capstan is installed parallel to the motor with two one-way clutches, which enable the capstan to rotate only in the winding direction. As mentioned in the introduction, this system is simple and can be made using off-the-shelf one-way clutches.

2.2 Test Platform

To estimate the performance of the brake, we built a test platform that can measure the tension of the cables. It consists of a motor, a capstan brake and two load cells. The material used to make the capstan is aluminum with a diameter of 21 mm, and two One-way clutches (manufactured by Origin Electric Co. LTD., Japan) were used to enable the capstan to rotate only in the winding direction. A 0.5-mm-diameter Ti cable, coated with nylon, was used for the experiment. The picture of the test platform is shown in Fig. 7.

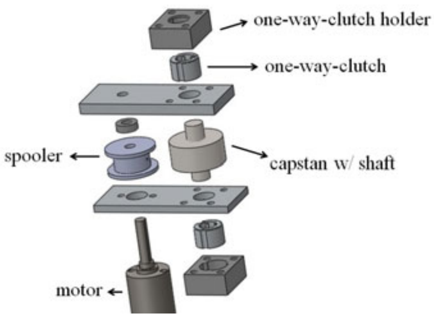

Fig. 6 Assembly of the brake

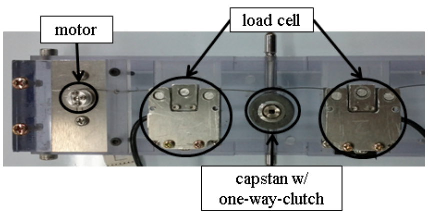

Fig. 7 Overview of the test platform. It consists of a prototype capstan brake and two load cells for measuring the tension

3. Test results and discussion

The performance of the capstan brake was evaluated in three aspects. The amount of friction loss when the motor winds the cable, the minimum external force needed to release the cable, and the maximum brake force.

3.1 Friction loss when the motor winds the cable

In the previous section, the amount of friction loss (F_{loss}) required to rotate the capstan was expected to be negligible. To verify the prediction, the tension between the capstan and the motor (F_{mot}), and the tension between the external load and the capstan (F_{ext}) were measured. F_{loss} equals the difference between F_{mot} and F_{ext}. The results are shown in Fig. 8.

According to the results, the amount of F_{loss} is negligible in comparison with the amount of F_{mot}. Also, the amount of F_{loss} is nearly constant regardless of the number of windings. Therefore, it is verified that the maximum amount of the winding force does not decrease because of the capstan brake.

3.2 Releasing the cable

Theoretically, the minimum amount of the tension on the motor side becomes zero when a cable is sufficiently untightened. However, because of material properties such as the mass and the rigidity of the cable, the tension does not decrease to absolute zero in reality. Since the capstan cannot rotate in the unwinding direction, the remaining tension ($F_{mot,rel}$) is amplified, and an external force (F_{ext}) higher than $F_{mot,rel}e^{\mu_s\phi}$ becomes necessary to unwind the cable. The minimum F_{ext} to release the cable, $F_{mot,rel}e^{\mu_s\phi}$, is measured. The result is shown in Table 1.

According to the result, the amount of required F_{ext} is low. However, higher F_{ext} allows the device to operate more smoothly. Therefore, the number of windings and friction coefficient should be carefully adjusted to prevent jamming.

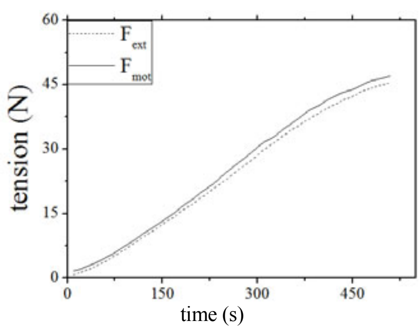

Fig. 8 F_{eff} and F_{mot} are measured. The gap between them is F_{loss}

Table 1 Required external force to release the cable

# of windings	1	2	3	4
The minimum F_{ext}	0.32 N	0.44 N	0.68 N	1.60 N

3.3 Braking and maintaining the tension

To verify the performance of the passive brake, we conducted the braking operation for varying conditions, according to the amount of target tension (F_{target}). First, the motor winds the cable until the motor side tension (F_{mot}) and external force (F_{ext}) reaches F_{target}. As soon as F_{target} is reached, the motor is turned off. Then, F_{mot} decreases to $F_{mot,0}$. Test has been conducted for different number of windings. The results are shown in Fig. 9.

According to the results, when F_{target} is less than the maximum available brake force before the motor is turned off, the decrease in F_{ext} is negligible. Otherwise, F_{ext} decreases until it reaches maximum braking force. Also, it is noticeable that the maximum braking force increases as the number of windings increases.

4. Conclusion

In this paper, we have presented a novel passive brake using capstan. Basically, its purpose is to provide better energy management for the back-drivable actuator used in a tendon driven device.

The experiments show the following: First, it is capable of delivering enough brake force. Moreover, its operating range can be adjusted by simply changing the number of windings. Therefore, the brake can be adapted to various devices. Second, the mechanism does not reduce the maximum winding force and mechanical work. According to the test result, lower than 2 N is required to rotate the capstan. Third, releasing the cable will not be an issue if the proper external force is present. Furthermore, because the structure of the capstan brake is simple and it is made using off-the-shelf parts, it is easy to produce. The maximum brake force of the current mechanisms is about 55 N, which is suitable for a tendon driven wearable robotic hand,[10] which is the target application of the device. The maximum brake force can be increased by increasing the number of windings. However, since it also increases the external force required to release the cable, it lowers the controllability of the device as well. Although the range of the force is limited by the available release force, the simplicity of the mechanism makes it an attractive choice as a supplement for tendon driven mechanisms.

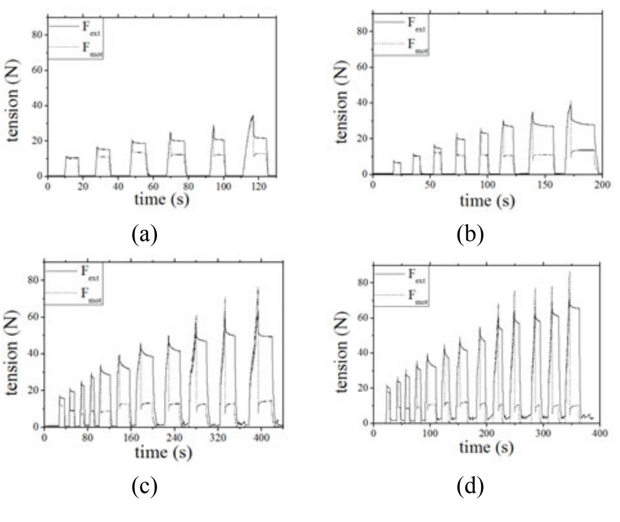

Fig. 9 Performance of the brake examined according to various values of F_{target}. The number of windings is (a) one, (b) two, (c) three, and (d) four

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REFERENCES

1. Pons, J. L., Rocon, E., Ceres, R., Reynaerts, D., Saro, B., Levin, S., and Van Moorleghem, W., "The MANUS-HAND dextrous robotics upper limb prosthesis: mechanical and manipulation aspects," Autonomous Robots, Vol. 16, No. 2, pp. 143-163, 2004.
2. Kim, E.-H., Lee, S.-W., and Lee, Y.-K., "A Dexterous Robot Hand with a Bio-mimetic Mechanism," Int. J. Precis. Eng. Manuf., Vol. 12, No. 2, pp. 227-235, 2011.
3. Controzzi, M., Cipriani, C., and Carrozza, M. C., "Miniaturized non-back-drivable mechanism for robotic applications," Mechanism and Machine Theory, Vol. 45, No. 10, pp. 1395-1406, 2010.
4. Light, C. M. and Chappell, P. H., "Development of a lightweight and adaptable multiple-axis hand prosthesis," Medical Engineering & Physics, Vol. 22, pp. 679-684, 2000.
5. Carrozza, M. C., Cappiello, G., Micera, S., Edin, B. B., Beccai, L., and Cipriani, C., "Design of a cybernetic hand for perception and action," Biological Cybernetics, Vol. 95, No. 6, pp. 629-644, 2006.
6. Kyberd, P. J., Evans, M., and te Winkel, S., "An intelligent anthropomorphic hand, with automatic grasp," Robotica, Vol. 16, No. 5, pp. 531-536, 1998.
7. Chu, J.-U., Jeong, D.-H., Youn, I., Choi, K., and Lee, Y.-J., "Myoelectric Hand Prosthesis with Novel Adaptive Grasping and Self-locking," Int. J. Precis. Eng. Manuf., Vol. 12, No. 6, pp. 1095-1103, 2011.
8. Jung, J. H., Pan, N., and Kang, T. J., "Capstan equation including bending rigidity and non-linear frictional behavior," Mechanism and Machine Theory, Vol. 43, No. 6, pp. 661-675, 2008.
9. Howell, H. G., "The General Case of Friction of a String Round a Cylinder," Journal of the Textile Institute, Vol. 44, No. 8-9, pp. 359-362, 1953.
10. In, H., Cho, K.-J., Kim, K., and Lee, B., "Jointless Structure and Under-Actuation Mechanism for Compact Hand Exoskeleton," IEEE International Conference on Rehabilitation Robotics (ICORR), pp. 1-6, 2011.