The Power of Twisted Strings: A Portable Elbow CPM Machine with Twisted String Actuator

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1. Introduction

1.1 About our research

Recently, as the age of population is going high and brain related diseases' patients has increased, the number of patients who requires rehabilitation due to paralysis or reduced motion skills is increasing. Rehabilitation treatment is usually performed with a physical therapist or using CPM(Continuous passive Motion) devices.

Those CPM devices are actuators that connect and operate back and forth to the joint area such as elbows and knees for patients who lost their athletic ability. This activates their nerves and muscles associated with the joint action, and helps their rehabilitation. Since instrumental treatment is cheaper in terms of time and cost than conventional physical therapists, it has recently been introduced and used in many rehabilitation hospitals. However, the current CPM actuator is bulky and heavy, making it difficult to use in patients' homes. For these reasons, CPM actuators acts as a hassle for patients with difficulty in moving, and it is a big problem that it can be only used in hospitals, thus not leading to frequent rehabilitation treatment.

CPM actuators have large volumes and weights because they utilize electric motors, pneumatic and hydraulic actuators. For electric motors, large gear ratios result in a larger gear weight and volume, and for pneumatic and hydraulic actuators, additional devices such as compressors are required for operation, so that it leads to increase of weight and volume.

To solve these problems, our team thought that twisted string actuators could be an alternative. The twisted string method is an application of a conventional method using string to transmit power between certain distances. A twisted string actuator (TSA) is effective by transmitting forces in a simple physical method [1]. When string gets twisted by low torque, the cord contracts with a high linear force, which functions as a gear with a nonlinear ratio. TSA with a single strand of string can operate more accurately, and multiple strands of TSA have higher stiffness and shrink faster and more to produce greater power. These twisted driving mechanisms are light, quiet, flexible, and produce enough forces, which makes it suitable to use as exoskeletal systems. Glanluca Pali and their team applied a string-based driving system to robot hands which requires high concentration, and implemented it to enable robotic hands to perform various functions. These twisted string mechanisms have the advantage of enabling significant force transmission with less volume and weight [2]. However, even with the advantages of twisted string mechanisms, rapid gear ratio changes in mechanisms are known to severely degrade control performance, making it difficult to apply to muscular power assistance robots.

What our team considered was that CPM actuators are different from robots that require precise control, in that it repeatedly controls patient's arms at equidistant speed, so that it can be operated with a lower level of control than ordinary forms of robots. On the other hand, the benefits of applying twisted string actuator to a CPM are significant. It is expected that when circular trajectory is used, we will be able to produce portable rehabilitation device by reducing volume and weight innovatively.

1.2 Establishing Research Goals

These following research problems are established based on the problems of CPM actuators and the prior studies [1][2][3] of twisted string actuators.

1. Designing high-power and elastic circular twisted

string CPM actuator

2. Find the range that fulfills our theoretical model in experiment, and comparing it with real driving range -> Determine the predictability of movement of the actuator

3. Compare & Contrast the relationship between string twisted extent and Force Output / Measure Force Output

-> Check the suitability for rehabilitation equipment

2. Methods & Results

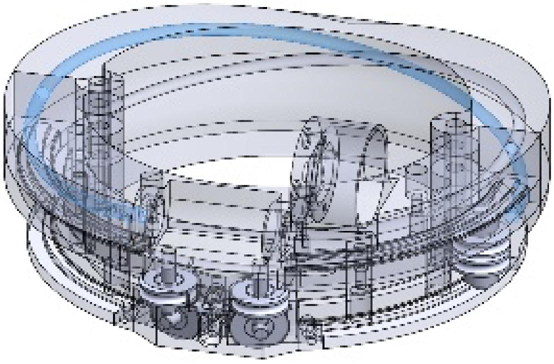
2.1 Research Methods

2.1.1. Design & Construction of Circular TSA

We made our twisted string actuator that could be used in elbow rehabilitation, like the following [Fig.1]

[Fig. 1] Wearing condition of CPM

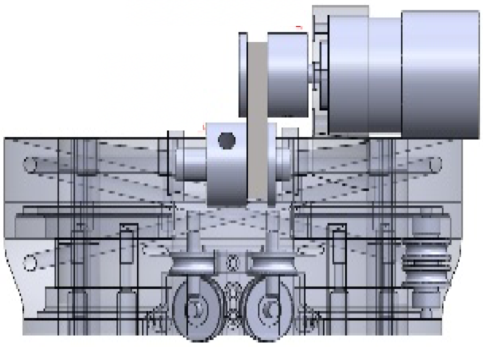
The designed CPM Actuator is as shown in [Fig.2]. When two or more strings of the twisted part gets wound by the motor, the string arranged in straight line starts to twist in spiral shape so that the drive part on the other side of the motor is operated.



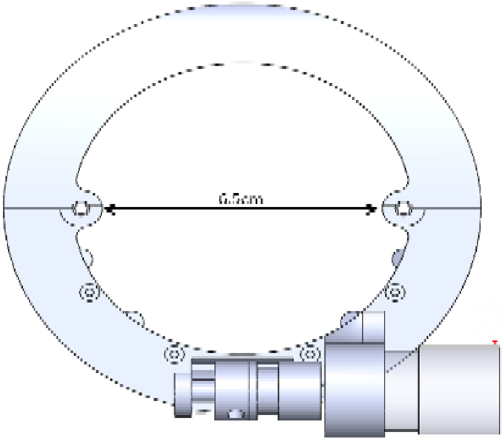
[Fig. 2] Appearance of the TSA CPM

Most of the previously developed types of TSA are designed to get twisted in straight line. These types have the disadvantage of requiring large volume and weight in the process of transmitting power in a linear arrangement of lines.

In this research, we adopted circular trajectory into TSA, in order to reduce the volume and weight. This structure winds the arm brace twice, and this allows the actuator to reduce its volume and weight drastically than linear forms. We found out that the string shrinks up to 75percent of its ordinary length, enabling it to transmit power.



[Fig. 3] Structure of motor and motor shaft



[Fig. 4] Upper structure of the TSA

In our model, the cord of the twisted string part penetrates the holes in the shaft of the motor, so that it is not directly connected to the instrument as shown in [Fig.3, 4].

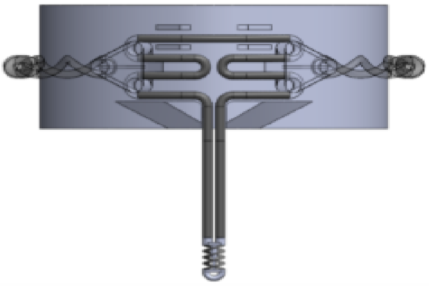
Also, as shown in [Fig.5,6], we designed the pulley system so that it can be pulled on both sides by a string, so that the force caused by the twisted cord itself could be dispersed to maintain its structural stability.

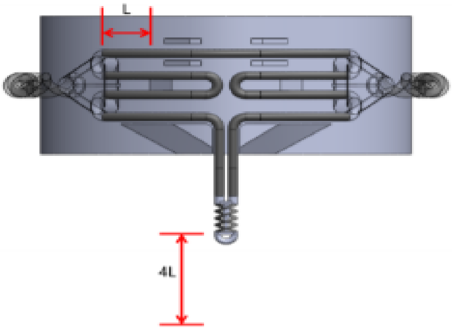
The string twist part is consisted of four strings, and the length of the string before the twisted condition is 55cm. This length is determined by considering the arm length of the average person. In our latest model, we used no.10 fishing line, which were considered suitable for rehabilitation treatment.

2.1.2. Design of the Pulley system

Due to the properties of TSA models, we found out that the operation range was short. Furthermore, our earlier models had difficulty due to the limitation of the length. We came up with a new method, by adopting pulley system in [Fig.5] and solved the problems. When the pulley connected to the string twist part is pulled to both sides by the wire twist mechanism, the wire connected to the outer drive gets pulled by the pulley and the CPM Actuator gets activated.

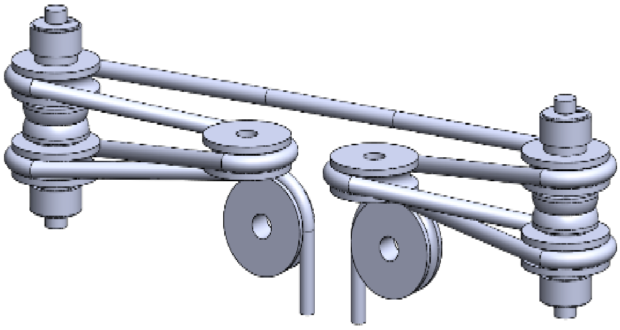
By this, the operating range and operating speed could be quadrupled. The actuator is an instrument that assists rehabilitation, so we thought that even if enough power is given, effective rehabilitation cannot be given if the operation range is small. We verified the range of operation of our model, which was 10.6cm, so that we concluded that it is sufficient enough raise an arm during rehabilitative training.





[Fig. 5] Pulley System of TSA

When we start to wound the strings using the motor, it begins to twist in a spiral shape, attracting the drive that is on the opposite side of the motor.



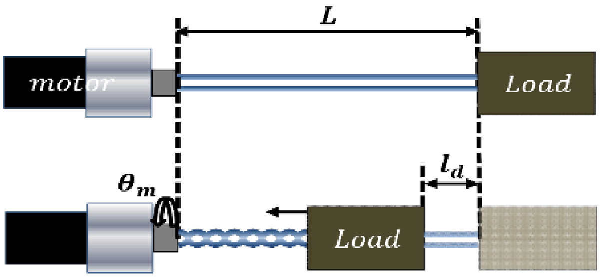
[Fig. 6] Pulley System

2.1.3. Theoretical verification of TSA

To find out if the TSA could be used for rehabilitation, we set up our theoretic driving mechanism model and verified it. We completed our driving mechanism following by physical relationship between the variables, and applied to our model analysis.

2.1.3.1. TSA Mechanism Model

As shown in [Fig.7], the TSA converts the motor's rotational motion into a linear motion to transfer the force.



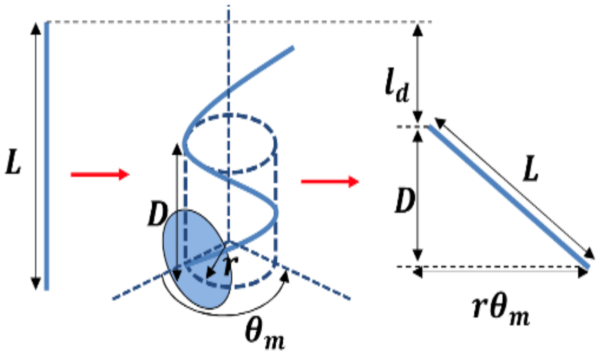
[Fig. 7] Force transmitting mechanism

Two strings connected to the load are twisted by the motor and this enables the transmission of power. This twisted string makes the spiral structure as [Fig.8]. Spiral structure can be simplified as right triangular shape. Base of the triangle is length of the circumference which covers the cylinder of a helix, and this circumference can be represented by $r\theta_m$ which is a multiplication of motor rotated angle(θ_m), and radius of the string(r). String shrinkage originated by string twist(D) and length of the string(L) can be expressed by equation (1) by pythagorean theorem.

$$l_d = L - \sqrt{L^2 - (r\theta)^2} \qquad (1)$$

Relationship between string twisted amount and length shrinkage l_d of our CPM actuator(r=2mm, L =0.5m) is expected as [Fig.9] by equation(1).

When we differentiate l_d of equation(1), we get achieve equation(2), and when we express reduction ratio ($J(\theta)$) with speed originated by the power source and output speed, we can get equation(3).

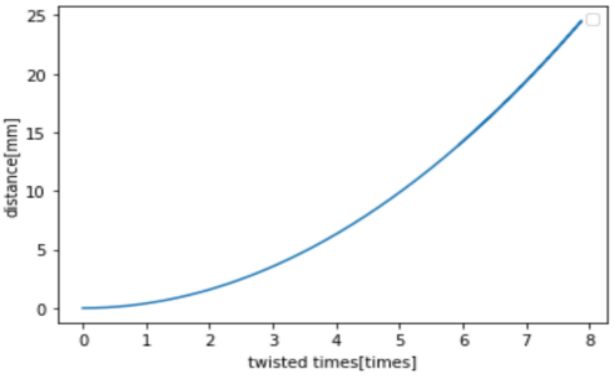


[Fig. 8.] Variables of the Equation

$$\dot{l_d} = \frac{r^2\theta}{\sqrt{L^2 - (r\theta)^2}}\dot{\theta} \qquad (2)$$

$$J(\theta) = \frac{\dot{l_d}}{\dot{\theta}} = \frac{r^2\theta}{\sqrt{L^2 - (r\theta)^2}} \qquad (3)$$

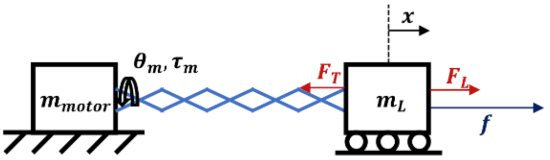
Differentiation of reduction ratio($J(\theta)$) can be expressed by equation(4).



[Fig. 9.] Theoretical relationship between twisted time and shrinkage length

$$\dot{J}(\theta) = \frac{r^2(L^2 - (r\theta)^2) + r^4\theta^2}{(L^2 - (r\theta)^2)^{3/2}} \qquad (4)$$

When we twist strings by CPM actuator as [Fig.10], the motor output force F_T and output force F_L working on actuator work on load m_L. We can express motor output force F_T with motor torque τ_m as equation(5).



[Fig. 10] Variables of TSA Mechanism [4]

$$\tau_m = K_t u - I_w \ddot{\theta}$$

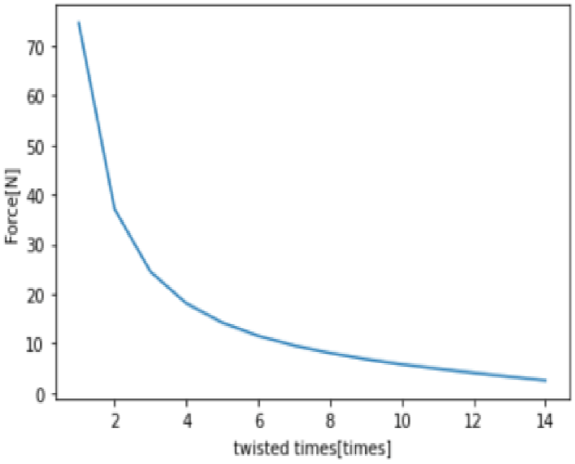
(K_t:Constant u:Current I_w:rotational inertia of string)

$$F_T = \frac{d\theta}{dl_d}\tau_m = \frac{d\theta/dt}{dl_d/dt}\tau_m = J^{-1}(\theta)\tau_m \qquad (5)$$

Because torque originated by rotational inertia of motor is negligible, we can express F_T as equation(6).

$$F_T = \frac{\sqrt{L^2 - (r\theta)^2}}{r^2\theta} K_t u \qquad (6)$$

During this research, when the current is 0.13A, τ_m is measured as $24.5 \times 10^{-3} N \cdot m$, so that K_t is 0.188. Therefore, theoretical F_T on the number of twisted times shows as [Fig.11].

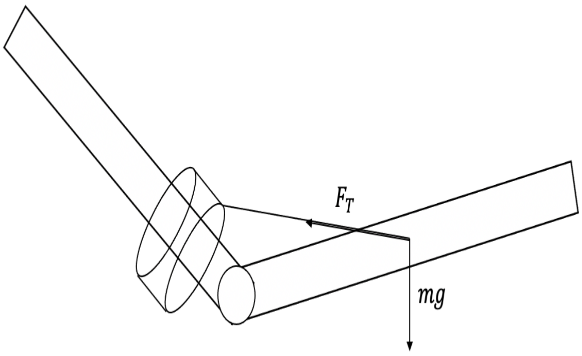


[Fig. 11] F_T followed by twisted time

According to the TSA mechanism model, the CPM actuator in this study was expected to be capable of exerting 70N of force in the early stages of drive, which is sufficient enough to lift the arm for rehabilitation.

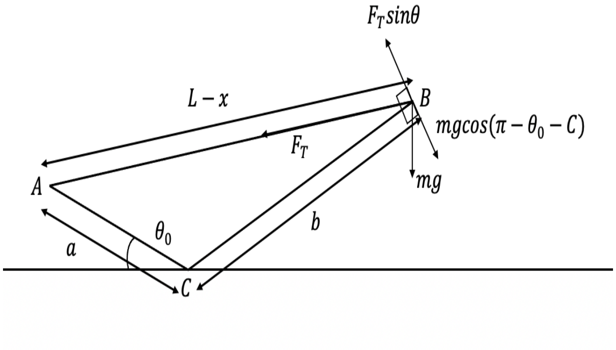
2.1.3.2. Input Current Mechanism of TSA for Constant Speed Rehabilitation

When we suppose constant speed motion so that the TSA can be used appropriately for CPM, F_T and F_L(gravitational force) should be in equilibrium.



[Fig. 12] Force acting on the arm

F_T that is necessary to move the actuator in constant speed can be expressed as the Freebody diagram in [Fig.13].



[Fig.13] Freebody diagram

When we solve the variables in [Fig.13] using equation (6), we can show the input current u as equation (7). In this case, angle B and C means the two respective angles of the triangle in [Fig.13].

$$F_T \sin B \times b = mg\cos(\pi - \theta_0 - C) \times b$$

$$F_T \sin B = -mg\cos(\theta_0 + c)$$

$$a^2 = (L-x)^2 + b^2 - 2(L-x)b\cos B$$

$$\cos B = \frac{(L-x)^2 + b^2 - a^2}{2(L-x)b}$$

$$(L-x)^2 = a^2 + b^2 - 2ab\cos C$$

$$\cos C = \frac{a^2 + b^2 - (L-x)^2}{2ab}$$

$$F_T = K_t u = -mg\frac{\cos(\theta_0 + C)}{\sin B}$$

$$\therefore u = -\frac{mg}{K_t}\frac{\cos(\theta_0 + C)}{\sin B} \quad (7)$$

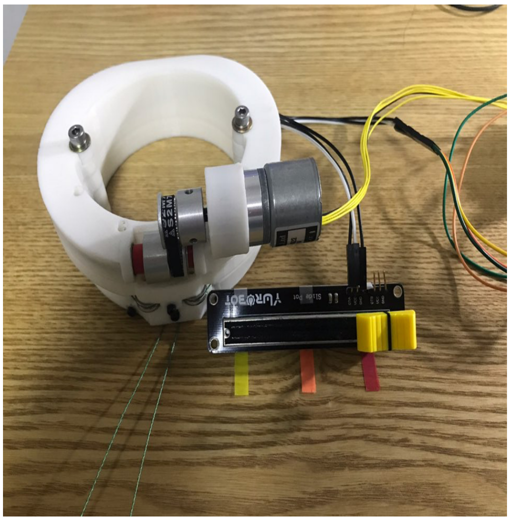
Using equation(7), we can calculate the necessary current needed followed by the angle between the arm and horizontal line during constant speed motion. Using this, we could supply appropriate electricity to the actuator.

Then, we verified our model that it could supply enough power to move adult men's arm in these following methods. Adult men's average forearm weight takes 2.52%[5], and the average weight of men is 62kg[6]. Based on this, we could calculate the arm weight is about 1.56kg. Using our mechanism, we adopted a=8cm, b=13cm, (L-x)=17cm, $\theta_0=45^\circ$ into [Fig.13], and calculated F_T =29.4N that is needed to move the arm brace in constant speed. As shown in [Fig.11], maximum output of our actuator was 70N, so we thought that our actuator could produce enough power for rehabilitation.

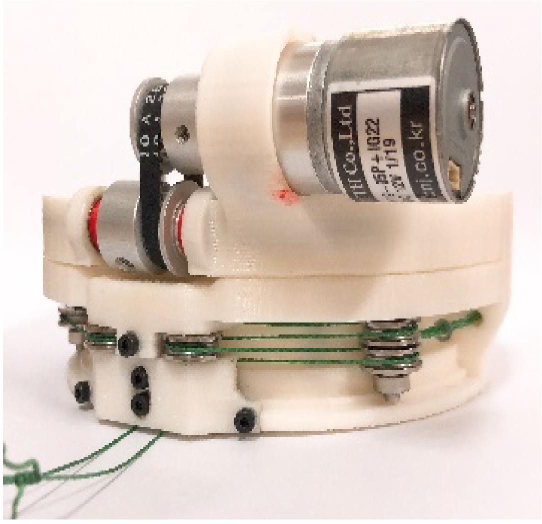
2.1.4. Design of the TSA Output Controller

Since our team focused on making patient-friendly TSA, we developed a controller for our actuator, so that the patient can control the strength of motion. Using (7), 2e designed the variable resistance that can control the current from 0.5mA up to 130mA shown in [Fig.14].

Our TSA, with which we confirmed possibility for rehabilitation device by Twisted String Mechanism theoretical model was built as [Fig. 15] via 3D printer.



[Fig. 14] Controller that enables to adjust the rehabilitation intensity of the TSA

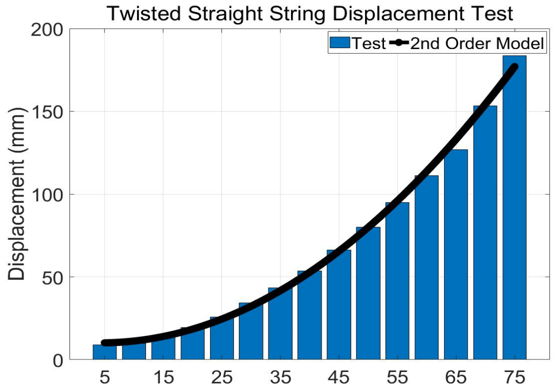


[Fig. 15] Circular trajectory TSA

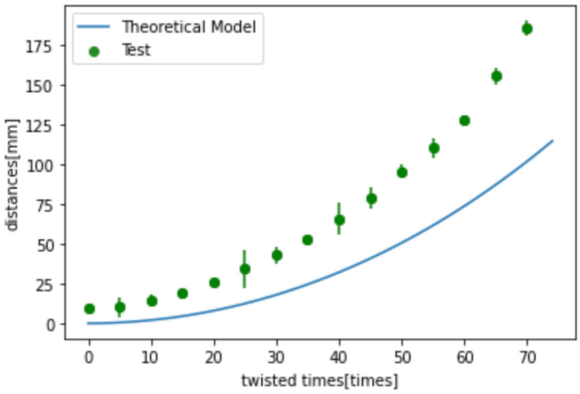
3. Research Results

3.1. Twisted String Displacement Test

These results about the relationship between the length and twist number were obtained when TSA was under load, keeping the string taut. The results are shown in [Fig. 16, 17].



[Fig. 16] The shrinkage length followed by the twist and Fitted model



[Fig. 17] Comparison between Experiment and Theoretical Values

The relationship between the twisted angle and the reduced length of the line was similar to the theoretical value. The range of patterns similar to theoretical values was up to 200mm. After 200mm, the data showed nonlinearity. Therefore, we determined that we should use 200mm range, so that we could theoretically predict the movement of the CPM TSA.

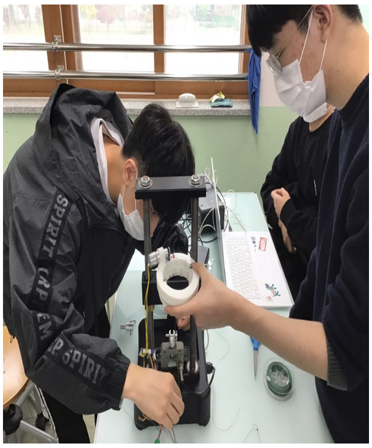
3.2. Spring Constant Test of TSA

Considering that the circular twisted string actuator would have elasticity due to tightening, we conducted experiment to determine the elasticity coefficient of each number of twists. In the experiment, we installed CPM TSA in the Materials Testing Machine to measure the elasticity coefficient of the twisted allowance as shown in [Fig.19].

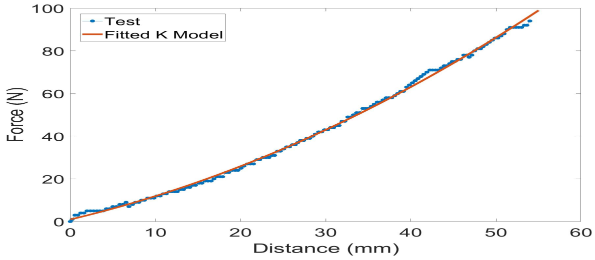
The results of the experiment are shown in [Table.1]. The test 1-4 results show that the elastomeric coefficient is measured at levels 7-10N/m. Furthermore, experiments show that if the shrinkage rate is greater than 51%, the TSA will result in nonlinear properties. This is about 25cm out of the total length 50cm. As previously seen in experiment, the modulus of elasticity also fits the theory within a range of about 25cm, confirming that it is predictable. Therefore, the foreseeable range requires the driver to be driven in categories within 51%. When the actuator was operated within 51% of the shrinkage rate, the experiment showed an average 15 times increase in power compared to the motor torque, which is expected to be suitable as a CPM driver

[Table 1] Spring constant values by the twist

	Test 1	Test 2	Test 3	Test 4
shrink rate (%)	6	18	33	71
Spring constant (N/m)	7.176	7.51	9.41	8.795



[Fig. 18] Spring Constant Experiment



[Fig. 19] Comparison between Experiment and Theoretical values of Elastic coefficient of TSA

3.3. TSA Pull test

As shown in [Fig. 17], we measured the length using Linear Potentiometer (SP2-12) and measured the power output using Load Cell (CDFCS-100) to calculate the power of the actuator according to the applied load. The measurement results are shown in [Table.2].

[Table 2] Power due to load on the actuator

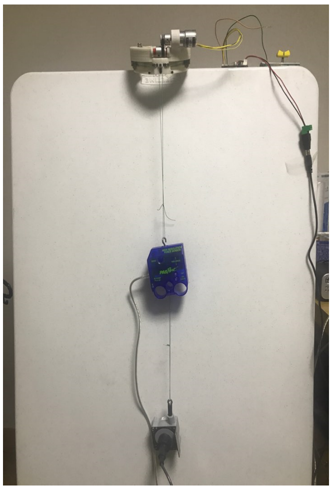
	Test 1	Test 2	Test 3	Test 4	Test 5
Speed(mm/s)	12.3	13.96	8.832	7.58	7.81
Force (N)	9.281	11.28	22.62	23.87	26.85
Power (J)	0.114	0.158	0.2	0.181	0.21

The results of Test 1 to 5 show that the speed of operation decreases as the load applied increases, but the CPM TSA developed in this research is suitable for high load work because the power of the actuator increases.

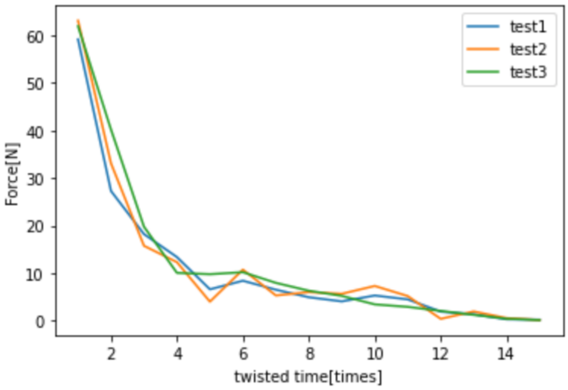
3.4. Output Force & Displacement Test

We used linear potentiometer in the circular actuator to calculate the shrinking length and load on the end of the actuator as the motor works.

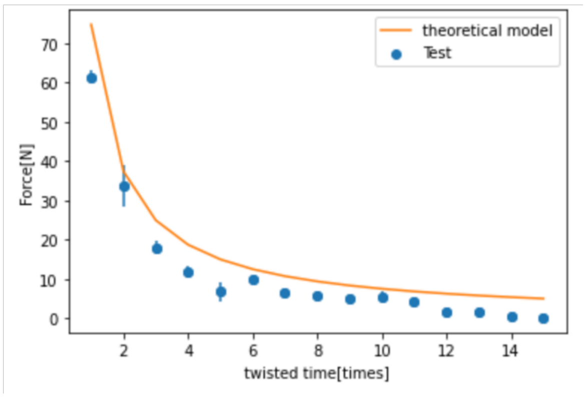
Measurements showed that the force of the TSA resulting from the twisted cord was shown in the graph [Fig.19]. As the string gets twisted, the force of the TSA decreased. The maximum force was 59.23N, 63.16N, and 61.98N, respectively as shown in [Fig. 21], showing the maximum output similar to the expected 70N. Therefore, it can be confirmed that the TSA exerts sufficient force to lift the arm beyond 32.6N. Through this, we determined that the designed model would be able to assist in actual rehabilitation.



[Fig. 20] Output Force & Displacement test



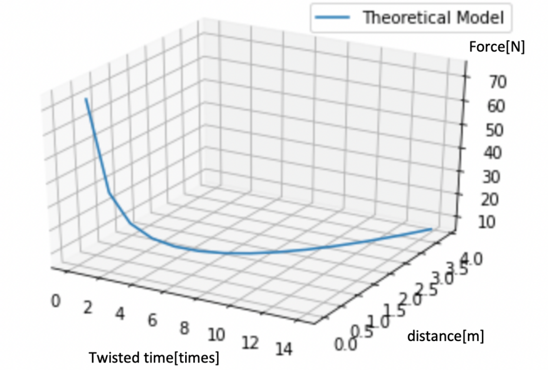
[Fig. 21] Force followed by twist



[Fig. 22] Force by the twisted string (Compare with Theory)

3.5. TSA's mechanism

We used Google Colab to plot the variables of TSA mechanism in three dimensions. We plotted the number of twist, the length which shrank, and the output force as [Fig. 23]. Aforementioned about the mechanism, the TSA CPM showed that the length reduced and the output decreased as the string twisted.



[Fig. 23] Twisted number(x axis), Shrinkage length(y axis), Output force(z axis)

4. Conclusion

4.1. Research Conclusion and Analysis

Using a TSA method, our team designed and constructed a circular TSA CPM, which can be worn on patient's arm.

In order to raise the arm using the twist of the cord, sufficient range of motion was required for the cord to retract. We applied Pulley System to increase range of operation, while consuming small volume. We found out that it will be possible to operate 10.6cm range to rehabilitate the patient's arm.

To verify the feasibility of utilizing the rehabilitation treatment of the TSA CPM, we developed a TSA mechanism model and confirmed it through experiments. It was predicted that the TSA designed through the model, could carry a force of up to 70N when the input current is 0.13A. This is sufficient to lift the patient's arm at equidistant speed, with the force required to move the arm at constant speed calculated to be 29.4N.

In addition, the load on the actuator depends on the angle between the ground and arm during action, and the input current to the actuator must be changed for each angle to move the arm at constant speed. Therefore, we developed TSA mechanism model through (7), and we are expecting that it could move the patient's arm in constant speed in every angle.

After constructing our model, we conducted experiments in order to measure shrinkage length according to the number of twists, and found out that the range up to 200mm showed the same result to the theoretical model. After 200mm, the experiment data showed nonlinearity. Also, we found that the string coefficient showed nonlinearity after shrinkage rate 33%, and collected the same experimental results from the two experiments. We concluded that TSA CPM has specific applicable range that depends on the characteristics of the strings used for the model. From these experimental suggestions, we concluded that we could expect operation range through the properties of TSA.

Our team's TSA could provide enough power to pull average men's arm brace in constant speed. Through the pull test, we found out that the experimental results followed the theoretical calculation. The theoretical power was calculated as 70N, and the test results showed 59.23N, 63.16N, 61.98N. Furthermore, as the load increases, the operation length decreased, but we found out that the power of TSA increased. Through this, we concluded that this actuator is suitable enough for high loaded work, thus can provide effective rehabilitation programs.

Therefore, our team concluded that the circular actuator with TSA mechanism developed through this study would be available as commercial CPM for elbow rehabilitation. We expected that this model would be very useful as it is very small and light compared to the conventional models, so that it allows patients to attach and detach easily. This shows possibility of developing to portable rehabilitation instrument, which means that patients themselves could get healed without spatial constraints

.4.2. Further Applications

From this research, we develop innovative form of CPM, and verified it's efficiency. Our team did not stoped at this, and thought of several applications for other genres.

4.2.1. Industrial Exoskeletons

Our CPM device supplies extra power, and the intensity can be controlled by the user. From this properties, our team thought that this device can be applied in industrial uses. There are many industrial sites that require hard labor, and the workers often gets injured. When we supply our CPM devices for the workers, they can have extra power, and their efficiency of the work will increase.

4.2.2. Heavy Equipments

In Korea, there is a traditional construction machine called 'Geojunggi', which were used to construct walls. The physical principles adopted in those equipment is about the distribution and transmission of power. In our device, we used pulley system and twisted string structure, and designed a new system of power distribution in circular trajectory. Appling these, our team thought that we could make new form of heavy equipments that can be used in many industrial sites.

4.3. Suggestion

Even though we designed revolutionary models, there were still limitations for our model. Throughout consistent experiments and innovation, we are looking forward to solving these problems. Also, we have to apply our actuators to patients, and see if it really helps them.

Our device can be made by installing two TSA CPM in our arm brace, using the pinpoint structure. This allows the TSA to bind in each direction. We think that the motion could be controlled by one motor, since the two sides of CPM can release and reverse while each sides are getting winded.

We also thought that applying devices to patients and receiving feedbacks from them necessary. The driving range and the output of the TSA are examined by theoretical model and several experiments, showing possibility for rehabilitation. When we adopt this device for patients, there might be unexpected situations. To decrease those risky moments, we are planning to supply these to patients and receive feedbacks about their experiences and rehabilitation outcomes.

Lastly, we are planning to find ways to vary the size of the actuator, so that diverse patients with different conditions can use our actuator. For this process, our team is planning to adopt various materials and sizes for the actuator.

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Photo References

[Fig. 1] -> Designed by us with Powerpoint

[Fig. 2~6] -> Screenshot from SOLIDWORKS(our 3D model)

[Fig. 7,8,10,12,13] -> Reference 4

[Fig. 14,15,18,20] -> Photo taken by us