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입는 외골격 로봇을 위한 선형화된 출력을 갖는 회전형 줄꼬임 기반 구동기

Rotational Twisted String Actuator with Linearized Output for a Wearable Exoskeleton

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Abstract: Early wearable robotic devices were big, powerful and manipulator-like. Recently, various applications of wearable robotics have shown a greater demand for lower weight and compliancy. One approach to achieve these objectives is the use of novel actuators such as twisted string actuators. These actuator are very light, quiet, mechanically simple and compliant. Therefore, they can drastically decrease the weight and size of robotic systems such as exoskeletons. However, one drawback of this actuator is its nonlinear transmission ratio, which is established as a ratio between the angle of twisting of the strings and their resulting contraction. In this paper, we propose a transmission mechanism with rotational motion as the output incorporating a twisted string actuator (TSA). The designed mechanism allows the linearization of the relationships between the input and output displacements and forces of a TSA. The proposed design has been validated theoretically and through a set of computer simulations. A detailed analysis of the performance of the proposed mechanism is presented in this paper along with a design guideline.

Keywords: exoskeleton, twisting stings, wearable robotics, twisting strings actuators

I. INTRODUCTION

Recent advances in medical science have considerably increased the life expectancy. As a result the percentage of world's population over the age of 60 has also been increasing. According to world health organization estimates, this percentage will rise up from about 11% to 22% by 2050 [10]. This increase imposes a large burden of care to treat the health risks associated with aging. Robotic solutions can help tackle these issues and enable the elderly to regain their agility and strength in limb movements. Additionally, robotic systems can also be applied to assist in military endeavors-allowing soldiers to carry more and walk further [15, 16]. Moreover, there is ever more need of robotic assistance for soldiers who have suffered amputations.

One of the robotic assistance solution is exoskeleton systems that provide dexterity, natural mobility, and sense of touch to missing or paralyzed limbs. For example, Kiguchi et al. [12] developed an assisting system for shoulder movements with 2 degree of freedom (DOF). Sulzer et al. [13] designed an end-effector-based elbow assisting system providing one degree of freedom for physical therapy. Rosati et al. [14] developed a 5 DOF assisting system for both elbow and shoulder movements. Carignan et al. [11] developed a 5 DOF prototype for assisting shoulder, elbow and forearm movements.

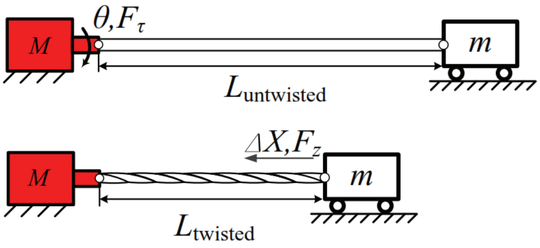

그림 1. 줄꼬임 기반 구동기의 작동 원리.
Fig. 1. Working principle of a twisted string actuator.

One of intrinsic design requisite for a wearable exoskeleton is the mobile nature of the system since the exoskeleton systems have to worn by the operator. Therefore, a light weight and dexterous system is needed. There are many ways to make a wearable robotic system lighter, where one of them is an implementation of lightweight actuators and power transmission systems.

Twisted string actuator is a compliant, light, and mechanically simple actuator module. The operation of twisted string actuation (TSA) systems is based on the following principle: the twisting of a string (or several of them in parallel) results in the length reduction of the mentioned string. Therefore, when having the string attached to an electrical motor at one end and to a load on the other, the rotation imposed to the string by the motor will reduce the length of the string, resulting in the translational motion of the load (Fig. 1). This approach allows realizing compact, light, cheap, and quiet actuators with high (though nonlinear) gear ratio.

In recent years, the use of twisted strings-based actuation systems has attracted considerable research efforts. An actuator composed of two parallel strings was described by Suzuki et al. in [8], who proposed the use of pairs of antagonistic actuators of this

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type to control the stiffness of the links composing robotic hands and mobile robots. Wurtz, Palli et al. [3,9] presented a kinetostatic model of a twisted strings-based transmission system and developed a sliding control algorithm for double twisted string actuators implemented in robotic hands, while Sonoda et al. [2,7] designed a robotic finger based on a twisted string actuator, which also employed the mathematical model of a twisted string for control. In our previous works, we improved conventional mathematical model of a twisted string actuators by introducing variable stiffness and variable radius models which sufficiently increased the models accuracy [1,6]. Lastly, a bidirectional elbow exoskeleton, actuated by antagonistic twisted string actuators was developed [4].

The main contribution of this paper is design of a novel TSA mechanism which has a linear relationship between the input angle of twisting and the output angular displacement of a joint. The proposed module can be useful for such applications, where weight and size are the crucial parameters, for example for actuating bidirectional joints of lightweight and mobile exoskeletons. Our approach reduces the number of motors required to actuate a bidirectional joint driven by TSAs. Thereby reducing the weight, cost and required energy for the overall system.

Even though a lot of work was done in order to study twisted string actuators and develop better mathematical model, the nonlinear relationship between the strings contraction and angle of twisting was never addressed. Fig. 2, highlights the nonlinear relation between the angle of twisting and the resulting contraction of the strings. Since TSA can generate a force only in one direction, two independently controlled motors were always needed in order to develop a bidirectional linear or rotational joint. One of the main objectives of this research is to reduce the number of motors, required to actuate such joint, to one. This issue is address in current work.

The rest of the paper is organized as follows. Section II outlines the main concept of our approach, and in Section III, kinematics of the designed system is described. Section IV is dedicated to the experimental evaluation of the new design. In section V, a detailed design guide is given for the new approach. Section VI, proposes an antagonistic setup for future work, while Section VII concludes the paper.

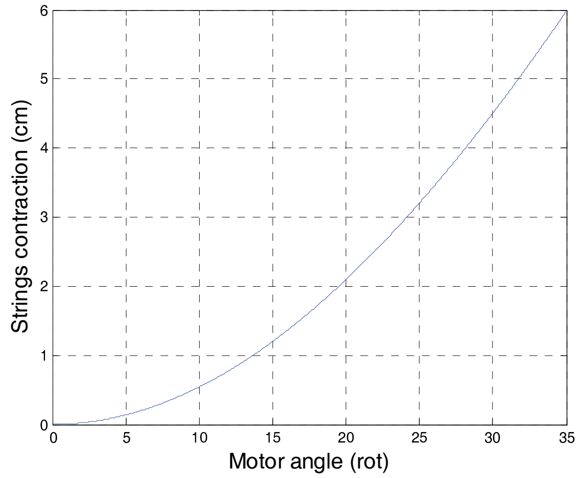


그림 2. 풀리 기반의 구조에서 모터 회전각과 조인트 각의 비선형적 관계.

Fig. 2. Nonlinear Relationship between motor twisting angle and the joint angle using a pulley based mechanism.

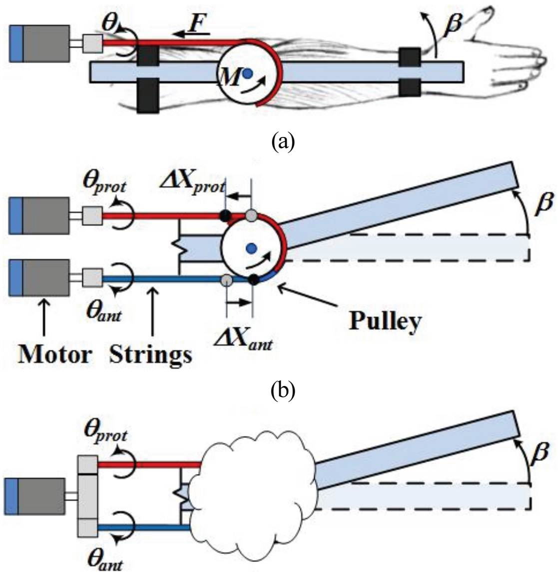
II. LINEARIZED TWISTED STRING ACTUATOR

In this section, we explain the basic idea of the proposed linearized rotational twisted string actuator.

In our previous work, we designed an elbow exoskeleton based on twisting string actuator by attaching one end of the string to a rotational pulley (Fig. 3(a)), [4]. The mentioned pulley converted linear displacement into the rotational motion, required for the elbow to function.

Since the pulley of a constant radius behaves like a linear gear and the twisted string actuator represents a nonlinear gear, it results in a nonlinear relation between the angle of twisting θ and elbow angle β. A sample relationship between elbow angle and the motor angle is shown in Fig. 2. It is noticeable that the relationship is highly nonlinear.

In Fig. 3(b), a bidirectional joint actuated by two TSA actuators is shown. In this case, protagonist strings and antagonist strings are connected to the same conventional pulley in order to create a bidirectional rotational motion. Such configuration of the wearable exoskeleton system is not ideal since an extra motor for every intended degree of freedom imparts additional weight and complicates the control. However, it is not possible to use a single motor in a conventional TSA mechanism to operate a bidirectional joint. Such setup will not be operational if both strings are connected to the same motor, due to nonlinear nature of the twisting process.



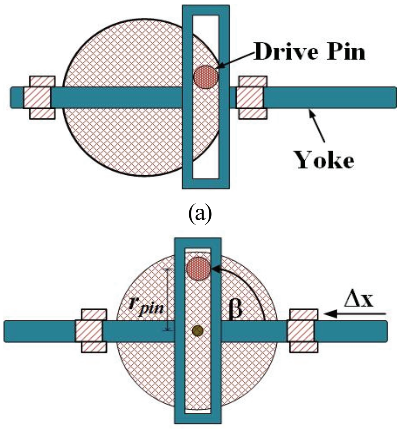
(a)

(b)

(c)

그림 3. 회전형 줄꼬임 구동기에 의해 움직이는 팔꿈치 조인트(a); 두 개 모터를 사용한 TSA에 의해 움직이는 양방향 회전형 조인트(b); 단일 모터를 기반으로 한 회전 조인트 디자인(c).

Fig. 3. Elbow joint driven by rotational twisted string actuator (a); a schematic representation of a bidirectional revolute joint powered by TSA using two motors (b); Single motor based design (c).



(a)

(b)

그림 4. 요크 핀 메커니즘의 작동 원리.

Fig. 4. Working principle of a yoke pin mechanism.

In order to reduce the number of TSAs required to actuate a single bidirectional joint and achieve a linear relationship between joint angle β and angle of twisting θ, a novel TSA mechanism with an additional non-linear gear is required. In such mechanism, the said gear must be designed in such a way that it provides a non-linear transmission that would cancel out the innate nonlinear behavior of the TSA itself (Fig. 3(c)).

The idea for the proposed mechanism was inspired from the yoke and pin mechanism. Fig. 4 presents a typical yoke and drive pin setup, where yoke drives a circular disk. The only contact point between the yoke and the disk is the pin. The yoke provides a linear motion which causes angular displacement of the disk. As a result, a linear motion of the yoke along the horizontal axis creates a circular motion of the pin about its center of rotation. In order to use the idea of pin and yoke mechanism to cancel out the nonlinearity posed by the TSA, the yoke's shape has to be modified.

Fig. 6 shows the modified yoke where the mechanism works as follows: the motor twists the strings which act like a nonlinear gear and contract, thereby pulling the yoke. Nonlinear displacement of the yoke is subsequently converted to the angular motion of the drive pin and consequently to the link's motion. Since the strings and yoke cancel out each other's nonlinearities, it enables the design to behave like a linear transmission system incorporating twisted strings. As a result, we achieve a linear relation between the angle of twisting θ and angular displacement of the joint β.

The instructions on required yoke shape design and the evaluation of the proposed system are presented in the following sections.

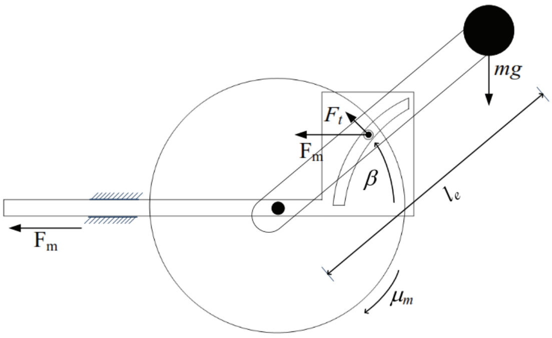


그림 6. 수정된 요크의 기구학.

Fig. 6. Kinematics of modified yoke.

III. PULLEY KINEMATICS

In this section we present equations describing the desired shape of the proposed yoke. Also, we provide a relation between the attached workload and motor torque that is required to care it.

1. Position Analysis

For a conventional setup of yoke and pin shown in Fig. 5, the coordinates of the pin can be derived through the angle of rotation β and distance from the center of rotation to the pin r_{pin} as follows:

$$x_{pin} = r_{pin} \cos \beta \tag{1}$$

$$y_{pin} = r_{pin} \sin \beta \tag{2}$$

$$x_{pin} = \Delta x \tag{3}$$

where, the terms x_{pin} and y_{pin} denote the pin's coordinates, and variable Δx represents displacement of the yoke. In our case, twisting string actuator provides a linear displacement of the yoke. The conventional model of such non-linear displacement was verified in [5] and can be used if an applied angle of twisting θ is known.

$$dx = \sqrt{L^2 - r^2\theta^2} \tag{4}$$

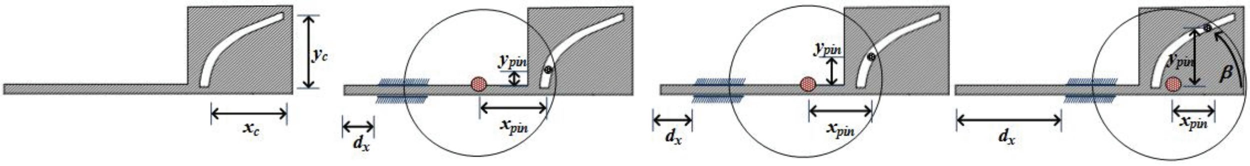
where d_x is the displacement caused by the contraction of the strings, L is the initial length of the strings, r is the radius of the strings, and θ is the rotation angle applied by the motor.

The following equations describe the required profile of the yoke curve:

$$x_c = d_x^{\max} - dx - r_{pin} \cos \beta \tag{5}$$

$$y_c = r_{pin} \sin \beta \tag{6}$$

where $d_x^{\max}$ is the maximum contraction of the strings and depends on the maximum desired angle of twisting $\theta_{\max}$.



(a) (b) (c) (d)

그림 5. 수정된 요크의 2D모델링 (a), 수정된 메커니즘의 표현 (b,c,d).

Fig. 5. The resulting modified yoke (a), two different states of an adopted mechanism (b,c,d).

As a result, by solving equations (5)-(6), we can generate the desired shape of the pulley which will linearize the relation between the applied angle of motor rotations θ and resulting angle of joint displacement β.

2. Force analysis

In order to investigate how the motor torque is transferred to the joint through two nonlinear gears (TSA and pin-yoke system), we need to perform force analysis of the developed design.

Considering a mass applied at the end of the link, as shown in Fig. 8, the total moment μ_m acting on the joint as a result of gravity can be described as

$$\mu_m = mgl_e \cos\beta \tag{7}$$

where m is the mass of the object, g is gravity constant, l_e is the length of the link.

Therefore, the tangential force F_t acting on the pin caused by the external load is given by:

$$F_t = \frac{mgl_e cos\beta}{r_{pin}} \tag{8}$$

The force F_m, which TSA applies on the yoke and, consequently, on the pin can found through the relation with tangential force F_t

$$F_m = \frac{F_t}{Sin\beta} \tag{9}$$

The torque required by the motor to provide a pulling force F_m by means of a TSA can be derived by using equation (13) in [9].

$$\tau_m = \frac{F_m \theta r^2}{\sqrt{L^2 - \theta r^2}} \tag{10}$$

substituting equations (8) and (9) into (10) yields

$$\tau_m = \frac{mgl_e \cos\beta(\theta r^2)}{r_{pin} \sin\beta\sqrt{L^2 - \theta r^2}} \tag{11}$$

As a result, equation (11) describes the relation between required motor torque and applied workload and can be used in order to choose an appropriate motor for the setup. The proposed kinematics has been evaluated and the results are presented in the following section.

IV. KINEMATICS EVALUATION

In the current section we explain the procedure and method of the kinematics evaluation. As a result, we present the graphs showing linear relation between input and output displacements and moments.

The curved profile of the yoke was generated according to equations. For the kinematic evaluation, elbow joint model was used. The experimental evaluation was conducted in SolidWorks Premium 2014 using motion analysis toolkit. Fig. 7 shows the model used for the experiments.

Following parameters were selected for the simulation:

- The length of the strings L was taken to be 0.25 m
- Three strings of combined radius of 0.8 mm were used
- The pin was at 2 cm distance from center of rotation
- The maximum displacement of the yoke was designed to be 40 mm
- Steel was selected as the part's material

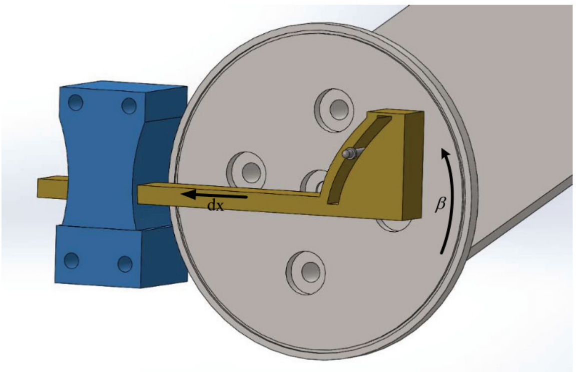


그림 7. 개발된 구동기의 3D 모델.

Fig. 7. A SolidWorks model of the developed actuator.

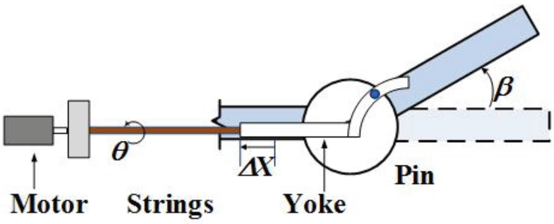


그림 8. 감속기 메커니즘에 기반한 회전형 TSA 모델.

Fig. 8. Schematic representation of a rotational TSA based transmission mechanism.

The following procedure was performed in order to evaluate proposed kinematics:

- As the part of SolidWorks motion analysis toolkit, the linear motor was applying a desired displacement profile on the yoke part. A function of yoke's displacement was modelling a behavior of TSA and was calculated by equation (4).
- Once the yoke applied the motion on the rotational pulley, the change of the joint angle β was measured by an angular sensor tool, attached at the pin.
- In order to verify equation (11), the reaction moment sensor tool was used to measure a moment between the rotational pulley and attached link.

Fig. 9 shows the simulation results of the joint angular displacement β versus motor angle θ. For easier visualization a straight line was plotted. The overall RMS error for angle β from 10° to 90° was calculated to be 0.0336 degrees. It can be seen that the proposed TSA mechanism provides a linear relation between the angle of motor rotation θ and angle of joint displacement β. The analysis of input-output moment's relation was also performed.

Fig. 10 shows the relation between the output moments μm and the required input motor torque τ_m. As the result of the strings contraction, the applied motor torque τ_m produces linear pulling force F_m. After being transferred through the yoke and pin mechanism, pulling force F_m creates a tangential force F_t, which in its turn generates an output moment μ_m. In the performed simulation, the applied motor torque was calculated by using the parameters of the modeled TSA. It can be noted that input-output moment's relationship is also linearized by the proposed yoke design.

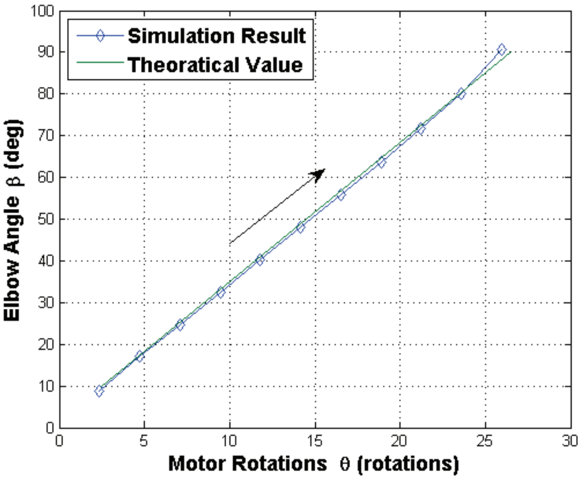


그림 9. 입력 모터 각 θ와 출력 각의 변화 β 와의 관계.

Fig. 9. Relationship between the input motor angle θ and output angle of displacement β.

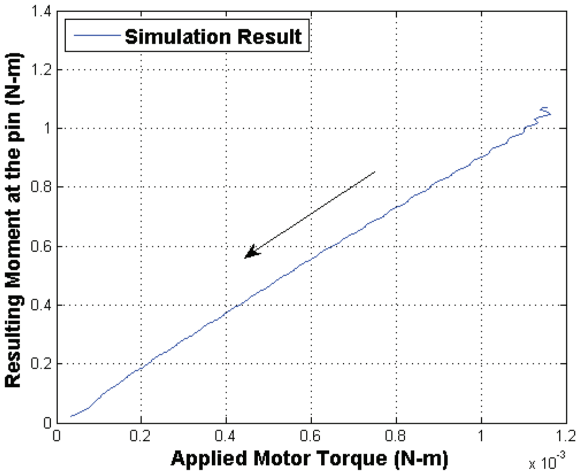


그림 10. 입력 모터 토크 τ_m 과 출력 모멘트 μ_m 의 관계.

Fig. 10. Relationship between the input motor torque τ_m and output and output moment μ_m.

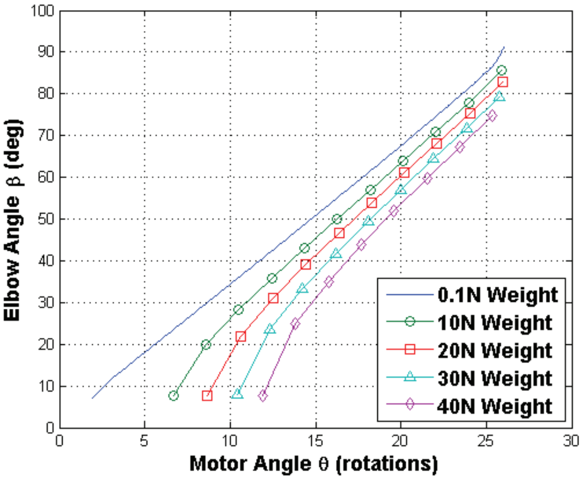


그림 11. 각 하중별 입력 모터 각 θ과 출력 각 β 의 관계.

Fig. 11. Evaluation of the mechanism under different load values.

표 1. 적용된 하중에 따른 선형오차.

Table 1. Deviation from linearity as a function of applied load.

Load (N)	10	20	30	40
RMS error (deg)	3.17	4.59	5.36	5.94

In the very start of the motion, when the joint angle β is small, the motor produces highest torque. This is due to the fact that, when the value of elbow angle β is close to zero, the denominator in (11) is minimal, which leads to high required motor torque.

In another simulation scenario, we studied how the variation of the applied workload will affect the performance of the mechanism. Since the shape of the proposed yoke was generated with no consideration of the applied workload, it is important to verify how the linearized behavior of the system gets affected, when the various workloads are being applied. For this purpose, different sets of load forces varying from 0.1 N to 40 N were applied. At the same time, the new function modelling the contraction of TSA was imported in order to provide a nonlinear displacement of the Yoke. The results of the simulation are presented in Fig. 11.

When a force is applied along the strings, they get extended and angle β decreases as the result of such extension. Therefore, in order to bring the link back to its initial position, the motor needs to be rotated by additional angle θ. This effect can be observed by the behavior of curves on Fig. 11 as they are shifted to the right and start from a higher value of motor angle with increase in applied load. With the increase in angle of twisting, the elbow angle β continues to increase in a nearly-linear fashion. However, a deviation from linear behavior still can be observed. It should be specifically noted that this deviation is maximal for small values of joint angle β which corresponds to nearly horizontal position of the link. In this case gravity has the biggest effect on the force extending the strings, as described by model (11). Once the link reaches the proximity of 20°, the relationships become nearly linear for all load cases.

To quantize the deviation observed under various loads, RMS errors between simulated curves and corresponding ideal linear relationships are summarized in Table 1. Even though a certain deviation from linear behavior was observed, it can be neglected due to the intrinsic compliancy of twisted strings. If two proposed mechanisms are actuated as a pair by single motor in a bidirectional joint, the interference between the strings can be considered negligible.

As a result we can say that the proposed kinematics can be used in order to design and control linearized twisted string actuators. The following section provides a guidelines on how to design such systems.

V. DESIGN GUIDE

This section presents a guideline on design of a linearized TSA-based rotational joint. The procedure is as follows:

- Choose the length of the strings L. This is usually constrained by maximum physically available distance between the motor and the joint.
- Choose the strings radius r. Several strings may be used in parallel. The increase of radius will result in the increase of output speed and required motor torque.
- Estimate maximum workload force that will be applied at

the joint and evaluate the force it generates on the pin using (8).
- Choose r_{pin} according to the material strength and the moment calculated in previous step.
- Calculate the maximum twisting angle θ max required to rotate the joint. The parameter θ max depends on the motor speed characteristics and the desired speed of the joint.
- Calculate the maximum linear displacement dmax of the yoke by using (4) and θ max calculated in previous step
- Find required motor torque using model (10)
- Calculate the coordinates of the required yoke profile using (5) and (6).

VI. DISCUSSION AND FUTURE WORK

The concept of the earlier proposed mechanism can be extended to make a TSA-based bidirectional actuator utilizing a single motor. Fig. 12 shows a conceptual drawing for such a setup. Two sets of strings are attached to corresponding yokes, and both yokes are designed using the proposed protagonist kinematic model (5)-(6). Therefore, the link is driven by two yokes attached to the same pin, whereas the protagonist and antagonist strings are actuated by a single motor via a gear. The assembly is such that rotation of motor in one direction causes the protagonist strings to contract and antagonist strings to extend, and vice versa. In such system, the opposing strings will not affect each other's work, since the linear displacements of both yokes are linearized relatively to the angular displacement of the pin. Such mechanism can be implemented in various exoskeleton systems and lightweight robotics applications.

As a future work, we are planning to do the following:
- Manufacture proposed unidirectional linearized rotational joint and evaluate its performance experimentally.

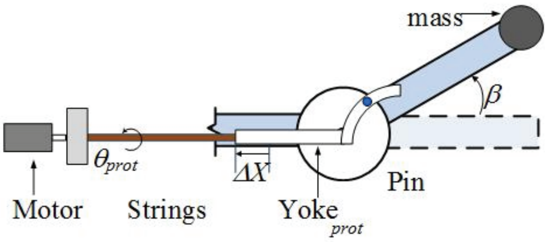


그림 12. 감속기 메커니즘에 기반한 회전형 TSA 모델.

Fig. 12. Schematic representation of a rotational TSA based transmission mechanism.

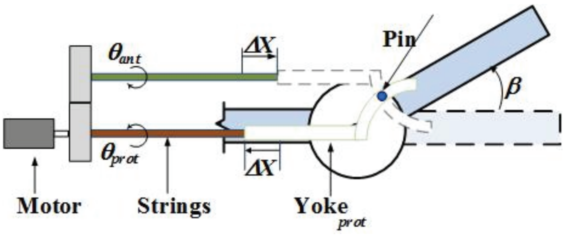


그림 13. 제안한 메커니즘을 이용한 양방향 조인트의 작동 원리.

Fig. 13. Working principle of a conceptual bidirectional joint using proposed mechanism.

- Develop and test the proposed bidirectional joint shown in Fig. 13.
- Develop a lightweight and wearable elbow exoskeleton actuated by the proposed systems.

This paper explores the possibility of linearization of a TSA-based rotational joint mechanism. The TSA are already considered light weight and quiet. Further linearization of the gear ratio, by introducing a mechanically passive component, reduces computing requirements and reduces the number of motors needed for bi-directional actuation. Therefore its implementation is beneficial in certain robotics applications where the weight and size of the actuators are crucial such as wearable exoskeletons for human assistant and rehabilitation. In this work, we proposed a rotational TSA-based transmission mechanism whose output displacement and moment are linearized in relation to input angle and torque. A design process of such mechanism was described in details, and its feasibility was explored through software simulations. In addition, guidelines on design of such mechanisms were presented which may help engineers in development of such modules. The proposed linearized TSA-based actuator can be also used as a part of a bidirectional joint. Possible applications of the developed actuator include wearable exoskeletons, lightweight manipulators, and mobile robots.

REFERENCES

[1] I. Gaponov, D. Popov, and J.-H. Ryu, "Twisted string actuation systems: A study of the mathematical model and a comparison of twisted strings," *Mechatronics, IEEE/ASME Transactions on*, vol. 19, no. 4, pp. 1331-1342, Aug. 2014.

[2] I. Godler and T. Sonoda, "Performance evaluation of twisted strings driven robotic finger," *Proc. of Ubiquitous Robots and Ambient Intelligence (URAI)*, pp. 542-547, Nov. 2011.

[3] G. Palli, C. Natale, C. May, C. Melchiorri, and T. Wurtz, "Modeling and control of the twisted string actuation system," *Mechatronics, IEEE/ASME Transactions on*, vol. 18, no. 2, pp. 664-673, Apr. 2013.

[4] D. Popov, I. Gaponov, and J. Ryu, "A preliminary study on a twisted strings-based elbow exoskeleton," *Proc. of World Haptics Conference (WHC)*, pp. 479-484, Apr. 2013.

[5] D. Popov, I. Gaponov, and J.-H. Ryu, "A study on twisted string actuation systems: Mathematical model and its experimental evaluation," *Proc. of Intelligent Robots and Systems (IROS)*, pp. 1245-1250, Oct. 2012.

[6] D. Popov, I. Gaponov, and J.-H. Ryu, "Towards variable stiffness control of antagonistic twisted string actuators," *Proc. of Intelligent Robots and Systems (IROS)*, pp. 2789-2794 Sep. 2014.

[7] T. Sonoda and I. Godler, "Multi-fingered robotic hand employing strings transmission named twist drive," *Proc. of Intelligent Robots and Systems (IROS)*, pp. 2733-2738, Oct. 2010.

[8] M. Suzuki and T. Mayaliara, "A method of real- time coordination of redundant muscles for multi-dof robot joints," *Proc. of SICE*, pp. 1064-1069, Sep. 2007.

[9] T. WuÌˊLrtz, C. May, B. Holz, C. Natale, G. Palli, and C. Melchiorri, "The twisted string actuation system: Modeling and control," *Proc. of Advanced Intelligent Mechatronics (AIM)*, pp.

1215-1220, Jul. 2010.

[10] World Health Organization. (2014, September 30). Facts about ageing. [Online] Available: http://www.who.int/ageing/about/facts/en/

[11] C. Carignan, J. Tang, S. Roderick, and M. Naylor, "A configuration-space approach to controlling a rehabilitation arm exoskeleton," *Proc. of Rehabilitation Robotics (ICORR)*, pp. 179-187, Jun. 2007.

[12] K. Kiguchi, K. Iwami, M. Yasuda, K. Watanabe, and T. Fukuda, "An exoskeletal robot for human shoulder joint motion assist," *Mechatronics, IEEE/ASME Transactions on*, vol. 8, no. 1, pp. 125-135, Mar. 2003.

[13] J. Sulzer, M. Peshkin, and J. Patton, "Design of a mobile, inexpensive device for upper extremity rehabilitation at home," *Proc. of Rehabilitation Robotics (ICORR)*, pp. 933-937, Jun. 2007.

[14] G. Rosati, P. Gallina, S. Masiero, and A. Rossi, "Design of a new 5 d.o.f. wire-based robot for rehabilitation," *Proc. of Rehabilitation Robotics (ICORR)*, pp. 430-433, Jun. 2005.

[15] H.-C. Kim and C.-Y. Lee, "Analysis on the kinematics and dynamics of human arm movement toward upper limb exoskeleton robot control part 2: combination of kinematic and dynamic constraints," *Journal of Institute of Control, Robotics and Systems (in Korean)*, vol. 20, no. 8, pp. 875-881, 2014.

[16] H.-D. Lee and C.-S. Han, "Technical trend of the lower limb exoskeleton system for the performance enhancement," *Journal of Institute of Control, Robotics and Systems (in Korean)*, vol. 20, no. 3, pp. 364-371, 2014.

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