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Bidirectional Elbow Exoskeleton Based on Twisted-String Actuators

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***Abstract*— In this paper, a bidirectional elbow exoskeleton device based on rotational twisted string actuators is proposed. A novel actuation mechanism incorporating antagonistic motors is proposed and its kinematic model is presented along with its experimental evaluation. Two antagonistic actuation mechanisms provide the motion of the forearm link in both directions thus allowing to position the forearm precisely even in the presence of such disturbances as friction, external forces, and at different positions of the upper arm link. In addition, we propose a method to control the antagonistic exoskeleton based on the actuators kinematics. The developed twisted strings-driven elbow exoskeleton can be effectively used in a variety of haptics, teleoperation, and rehabilitation applications.**

***Index Terms*— New Actuators for Robotics; Tendon/Wire Mechanism; Joint/Mechanism.**

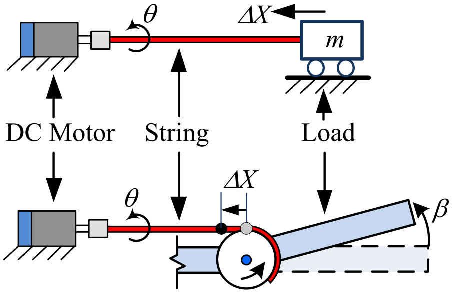

Fig. 1. Translational and rotational twisted string actuators

I. INTRODUCTION

Exoskeletons are robotic systems worn by a person in such a way that the physical interface leads to a direct transfer of mechanical power between the human and environment. Their applications include rehabilitation and physiotherapy, human assistance, power amplification, haptic interaction with virtual environments, and teleoperation.

In recent years, a significant progress in the field has been made, with the development of the exoskeletons for lower-limb support [1], upper-limb support [3], and hand support applications [4]. However, such systems are not widely used due to several fundamental challenges in their implementation, which include big weight, large size, low mobility, and mechanical complexity. The above mentioned restrictions are mainly caused by the limitations of the available actuators. Therefore, there is a need in lightweight, compact, compliant and inexpensive actuators which can serve as drives for exoskeleton systems.

One of the promising actuation technologies which satisfies the above mentioned requirements is twisted string actuation. Recently, twisted string actuators (TSAs) were a subject of several research works, where their characteristics along with advantages and disadvantages were described. TSAs were used to design actuation systems, robot joints and robotic fingers [5], [6], [8], [9], [10]. Twisted strings were recognized as effective actuators due to their negligibly small weight, high gear ratio, compliance, low noise level and cost.

Actuators based on twisting of the strings operate on well-known principle: When being twisted by a relatively low torque, the string (or several strings connected in parallel) contracts producing high linear force (Fig. 1). Thus, the string acts as a gear with a nonlinear gear ratio. Using several strings in a TSA results in higher endurance and positioning velocity of the actuator at the cost of higher motor torque required for operation.

A kinematic model of a single string can be applied in case when multiple strings are used, since the model considers a single string or a batch of strings to be a cylinder of a uniform diameter [2], [6]. In order to use twisted strings to actuate a rotational joint, a single RTSA (rotational twisted string actuator) module was developed and implemented in an elbow exoskeleton [7]. The basic working principle of the RTSA is as follows: When a bundle of strings is twisted, it contracts and unwinds a part of itself, wrapped around the pulley, which results in the rotational motion of the pulley. For more details on the RTSAs, please see [7].

This paper extends a unidirectional RTSA-based exoskeleton to a bidirectional one and introduces a way to control it by using the kinematics of the device. Two RTSAs are employed at each side of the pulley, which is coaxial to the elbow joint, in an antagonistic manner. This antagonistic connection of two twisted string actuators makes the control challenging since the actuators may interfere each other's motion if not controlled precisely. Moreover, a highly nonlinear nature of the gear ratio of the twisted string actuators makes the control even more complicated. To the best of our knowledge, no such systems have been designed and analyzed to date.

The paper is organized as follows. In Section II, we describe the mechanical structure of the proposed exoskeleton device. In Section III, the kinematics of the device is derived, while Section IV is dedicated to the control algorithm. Section V presents experimental evaluation of the proposed kinematics, and the existing issues are summarized in Section VI. The paper is concluded by Section VII.

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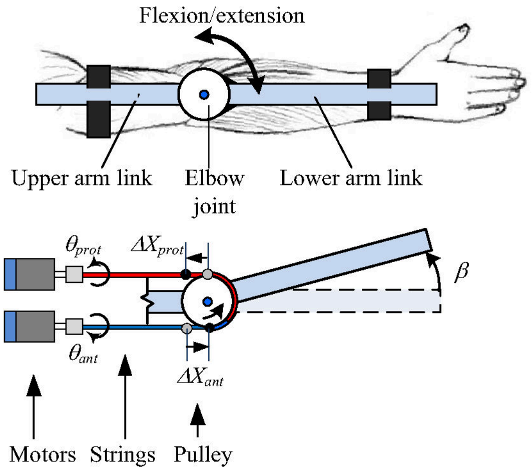

Fig. 2. Kinematic structure of the proposed elbow exoskeleton

II. BIDIRECTIONAL ELBOW EXOSKELETON

In this Section, a concept of a bidirectional actuation of a rotational joint based on the RTSA is proposed for the implementation of the elbow exoskeleton. A simple anthropomorphic design of the exoskeleton arm was chosen, in which two mechanically connected links corresponding to the upper arm and the forearm were connected by a rotational joint coaxial with the human elbow joint, as shown in Fig. 2. A pulley was rigidly attached to the forearm link coaxially with a rotational joint. The motion of the forearm link is realized by the rotation of the pulley.

In order to perform controllable motion of the pulley in both directions, two RTSA modules were used (Fig. 3). The upper motor moves the elbow in the upward direction and is hereinafter referred to as a protagonist motor, with its counterpart being referred to as an antagonist motor. Both motors are installed at the shoulder side. Strings were connected to the motor shaft at one end and to the pulley on the other end. When the exoskeleton is fully extended, the string of antagonist RTSA is fully twisted and contracted, while the string of protagonist RTSA is fully untwisted, with its contraction being equal to zero. When the flexion motion is required, the motor of the protagonist RTSA starts to rotate and twist the protagonist string. At the same time, the motor of antagonist RTSA starts to rotate to untwist the antagonist string. In case of extension motion of the elbow, actuators actions are reversed. Thus, the protagonist and antagonist actuators mimic the functions of human bicep and triceps muscles.

Therefore, a precise kinematic model is required in order to facilitate control of the proposed antagonistic exoskeleton, since the two RTSAs can affect each other during twisting process, for instance, if one RTSA contracts faster than other one extends. In order to avoid such undesirable interference between the actuators, the kinematics model of the bidirectional RTSA was derived and evaluated.

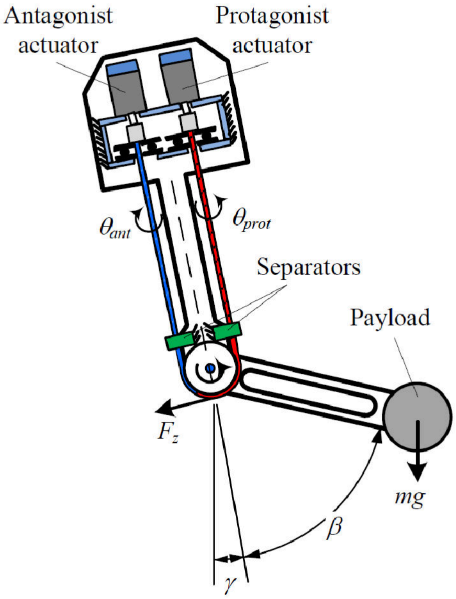

Fig. 3. Detailed prototype elbow exoskeleton structure

III. KINEMATICS

In this Section, a kinematics models of the protagonist and antagonist RTSAs are presented. It is extremely important to have an accurate kinematics in order to control two RTSAs at the same time.

If the purpose of the exoskeleton is to lift a certain weight against the gravity, as depicted in Fig. 3, only one actuator (the protagonist) is required to provide desired lifting force and position. It is possible to use only one actuator at a time while the other one is fully released, but in case when it is required to switch the direction of motion, it will take some time to twist the string so that the idle actuator can start operating. Moreover, if a disturbance acts in the direction of the motion, e.g. the human muscle force, the exoskeleton will not be able to counter this disturbance with a single actuator. In order to cope with the above mentioned issues, the two actuators may be used in such a manner that one (protagonist) provides the required position and force while the other one (antagonist) follows the protagonist.

In order to derive kinematic relations, we consider a set of strings as a uniform cylinder of a radius r and a length L with a stiffness constant K (Fig. 4). In this work, radius, length and stiffness of protagonist and antagonist strings were considered equal, although in general they may vary. By stiffness constant of the strings we mean an axial stiffness coefficient of the strings. Once being twisted, the strings form a cylinder of a bigger radius, inside which each separate string has a form of spiral. In this case, the axial stiffness of the string remains constant, while the overall stiffness of the cylinder formed by the strings decreases since the string acts as a spring with variable stiffness. The stiffness of the cylinder decreases with the increase of angle of twisting θ.

The mathematical model of the RTSA is based on a geometrical model of a cross-section of the strings during

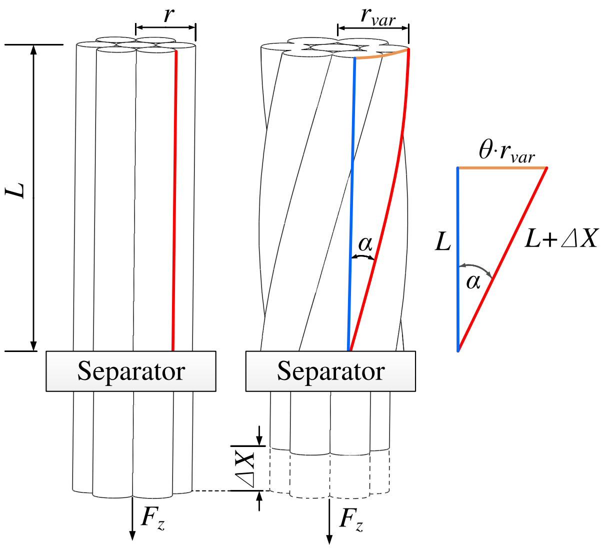

Fig. 4. Kinematic structure of the proposed elbow exoskeleton

twisting (Fig. 4). A separator part allows for the twisting of only the part of the string between the motor and the separator itself. Thus, the string wraps around the pulley in the untwisted state, which allows the pulley to return to its initial position. A more detailed description of the model and separators can be found in [7]. In this work we derive kinematics of two RTSA actuators, assuming that those do not interfere with each other during twisting process. This means that if one actuator follows the desired command, it does not affect another actuator's kinematics. In such case, when being twisted on angle θ, a string of an RTSA module will contract for some length ΔX, and the relation between this contraction and the angle of twisting can be described as follows:

$$\Delta X = \sqrt{L^2+\theta^2 r_{var}^2} - L - \frac{F_z}{K} \tag{1}$$

where r_{var} is a radius of a cylinder formed by twisted string. The radius r_{var} increases (the bundle of strings becomes thicker) as the angle of twisting θ increases:

$$r_{var} = r \cdot \sqrt{\frac{L+\Delta X}{L}} \tag{2}$$

A detailed study on variable radius of the string is presented in [2]. F_z is the force applied at the end of the string (at the point of connection with a pulley). When the elbow is mounted vertically, as shown in Fig. 2, the force F_z can be found as

$$F_z = \frac{mg\sin(\beta+\gamma)}{r_{pul}} \cdot L_{arm} \tag{3}$$

where L_{arm} is the length of the forearm link, r_{pul} is the pulley radius, m is the weight of the applied load, g is the gravity constant, β is the angle between the upper and lower links and γ is the angle between vertical axis and the upper arm link.

In order to set up and control a bidirectional RTSA-based exoskeleton, we should know the value of the required angle of twisting at the moment when the strings of the antagonist actuator are fully twisted and angle β is equal to zero. The required initial angle of twisting for the antagonist string $\theta_{ant} = \theta_{max}$ can be found as follows:

$$\theta_{max} = \frac{1}{r_{var}} \cdot \sqrt{\left(\Delta X_{max} + \frac{F_z}{K} + L\right)^2 - L^2} \tag{4}$$

where

$$\Delta X = r_{pul} \cdot \beta \tag{5}$$

The maximum contraction is therefore $\Delta X_{max} = r_{pul} \cdot \beta_{max}$, where β_{max} is the maximum possible elbow angle.

As we mentioned earlier, we consider that two actuators can follow the desired trajectory without interference. Therefore, the relation between desired angle of the exoskeleton β and the angle of twisting θ can be derived in terms of the protagonist RTSA only:

$$\beta_{i+1} = \frac{\sqrt{L^2+\theta_i^2 r_{var}^2} - L}{r_{pul}} - \frac{mgL_{arm}\sin(\beta_i+\gamma)}{Kr_{pul}^2} \tag{6}$$

where the subscripts 'i' and '$i+1$' denote the present and next data points, respectively.

The angle θ_{prot} of the protagonist RTSA which is required to lift the load of mass m at the angle β can be found as follows:

$$\theta_{prot} = \frac{1}{r_{var}} \cdot \sqrt{\left(L + \beta r_{pul} + \frac{F_z}{K}\right)^2 - L^2} \tag{7}$$

The angle θ_{ant} of the antagonist RTSA which is required to lift the load of mass m at the angle β can be found as follows:

$$\theta_{ant} = \frac{1}{r_{var}} \cdot \sqrt{\left(L + \Delta X_{max} - \beta r_{pul} + \frac{F_z}{K}\right)^2 - L^2} \tag{8}$$

In the equations above, the term F_z/K enters the models of both protagonist and antagonist actuators but serves a different purpose. If the force F_z is applied, strings of one RTSA will extend while some slack will appear on the strings of the second RTSA. In this case both actuators will need to increase the contraction of the string, which will make the first actuator return to its desired position and remove the slack for the other actuator.

The developed kinematic model (6) was experimentally evaluated, while the relations (7) and (8) were used by control algorithm.

IV. CONTROL ALGORITHM

In this Section, a control sequence of the proposed exoskeleton is presented.

It may seem that the most straightforward way to operate the proposed bidirectional exoskeleton would be to control two actuators independently from each other, based solely on the desired angle β. However, the actuators may contract at different rates due to the nonlinear nature of the RTSA's

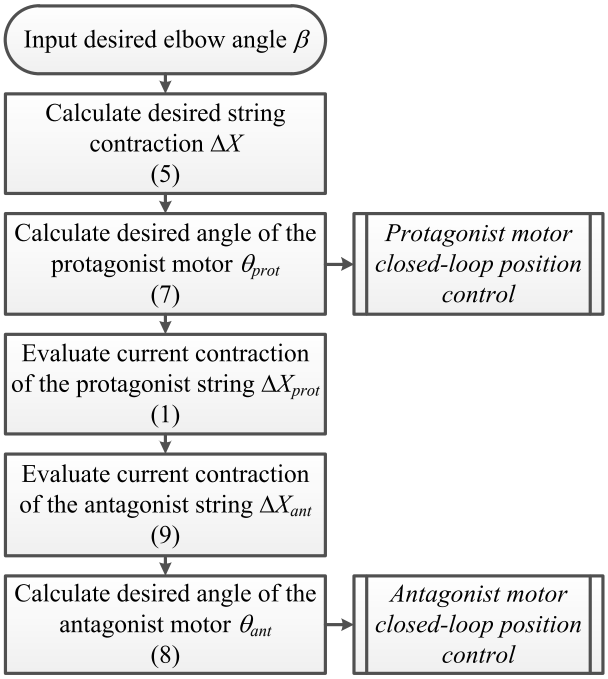

Fig. 5. Control algorithm flowchart

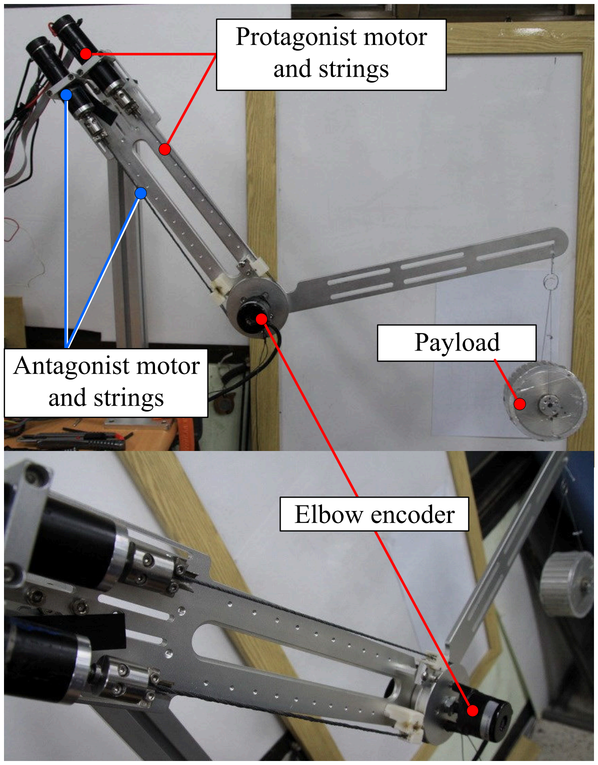

Fig. 6. Prototype of the bidirectional exoskeleton

gear ratio. Therefore, the velocity of both actuators should be controlled precisely, as the actuators may affect each other while twisting. A study on the velocity control of a linear TSA system was presented in [2], however it showed that the velocity control of TSAs is less accurate then position control. Therefore, a position control algorithm for the RTSA is proposed in this paper.

After the desired elbow angle β is given by the operator, control software calculates the contraction of the protagonist strings ΔX required to rotate the elbow. Next, control system finds the angle of the protagonist motor θ_{prot} which is required to provide the necessary linear contraction of the strings. After the desired motor angle is obtained, the protagonist motor is being moved for the angle θ_{prot} by a closed-loop feedback control system with PD-controller.

Since the prototype exoskeleton also incorporates an antagonist actuator and strings, it is required to operate the antagonist motor in such a way what it follows the protagonist motor without any interference. Therefore, at every time instance the antagonist motor must provide exactly same contraction of the string with that of the protagonist motor, but in the opposite direction. Thus, we assume that the following equality holds:

$$\Delta X_{ant} + \Delta X_{prot} = \Delta X_{max} \tag{9}$$

where the terms represent the contraction of the protagonist and antagonist strings and the maximum string contraction, respectively. After required antagonist contraction ΔX_{ant} is calculated, the desired antagonist motor angle θ_{ant} is evaluated according to (8). Next, the motor is being driven to the desired angle using a closed-loop PD-controller, just like it is done in case of the protagonist RTSA. The proposed control algorithm can be summarized as shown in Fig. 5.

V. EXPERIMENTAL EVALUATION

A. Experimental Setup

A prototype of the twisted strings-driven exoskeleton was designed as described in the previous Section and is shown in Fig. 6. The prototype was composed of two aluminum links, connected at a rotational joint, a pulley, plastic separator, a DC motor (Maxon RE-35 with a 2000-CPT encoder and a spur gearhead, gear ratio $n = 18$), an optical 1000-CPT encoder (Kwangwoo) measuring the elbow angle, and 6 Vectran strings (Kuraray Co., Ltd.) used in parallel. The shaft of the motor was aligned with the upper-arm link, and the strings were connected to the shaft of the gear at one end and to the pulley at the other. During experiments, the work load (various objects with known masses) was connected to the end of the forearm link, as shown in Fig. 6. The strings were aligned with the rotation axis of the motor.

The total weight of the system including sensors was 2.2 kg, however, it can be significantly reduced by choosing lighter motors and sensors and manufacturing the links using a lighter material, e.g. carbon. The lengths of the forearm and upper arm links were 0.41 m and 0.39 m, respectively. The radius of the pulley was chosen to be $r_{pul} = 0.04$ m. The strings used in the prototype had the twisted length (distance between the motor and the separator) $L = 0.25$ m, and the

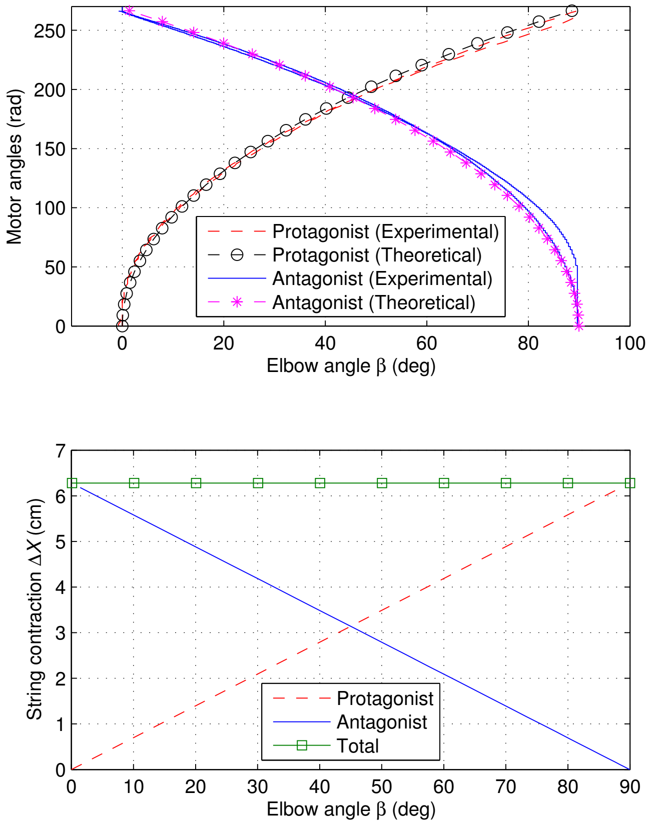

Fig. 7. Experimental and theoretical values of two motor angles as a function of angle β (top); experimental protagonist and antagonist strings contractions (bottom)

initial radius of a single string was $r = 0.36 \cdot 10^{-3}$ m. Such a configuration is capable of carrying a workload of at least 10 kg and can be used in such applications as haptics, rehabilitation, power amplification, etc. The exoskeleton can be further customized depending on the design purpose, for instance, for rehabilitation applications the maximum power and weight can be reduced.

B. Experimental Evaluation of Kinematics

We conducted several experiments in order to verify the developed mathematical model (6).

At first, the elbow was mounted in the horizontal plane in order to eliminate the influence of any external forces such as gravity. The theoretical and experimental values of the elbow angle with respect to the angles of the protagonist and antagonist motors are shown in Fig. 7, top. It can be observed that the elbow follows the developed kinematic model well. A hysteresis in the behavior of the antagonist actuator can be observed for the large values of the elbow angle ($\beta > 75°$). At such large values of the elbow angle, a small change in the angle of the almost fully twisted and contracted protagonist actuator causes large change in the string contraction which the antagonist actuator is supposed to compensate for, but since the latter is nearly completely untwisted, it needs to rotate a lot to remove the slack. This can be improved by decreasing the rotational speed of the protagonist RTSA for large values of elbow angle, and we are planning to address this issue in our future works.

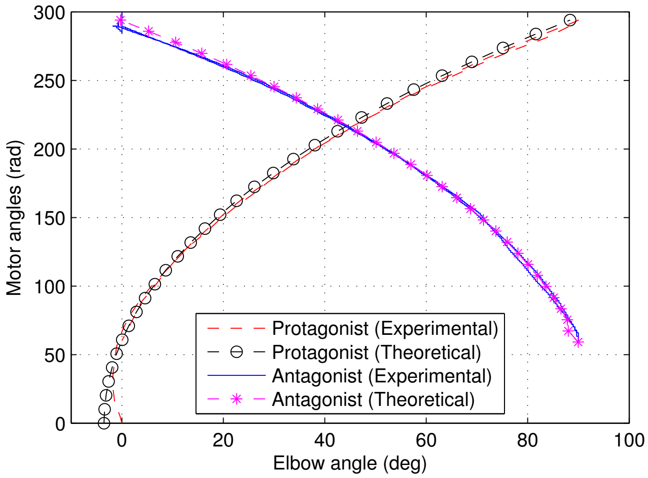

Fig. 8. Experimental and theoretical values of two motor angles as a function of angle β for the load of 1 kg

It can be observed on Fig. 7, bottom, that the experimental contractions of the protagonist and antagonist strings follow the developed control law (9), with the total contraction always equal 2π cm, as can be obtained from (4) for the chosen pulley radius of $r_{pul} = 4$ cm and $\beta = 90°$. The experimental data prove that the two actuators were not affecting each other during the twisting process.

In addition, we conducted the experiments when the elbow was positioned vertically, as shown in Fig. 3, with a 1 kg payload attached to it. The results are presented in Fig. 8. It can be noted on the figure that the presence of external force due weight caused the initial elbow angle to become negative (area in the lower-left in Fig. 8), and therefore the protagonist actuator was forced to rotate by approximately 60 radians in order to compensate for this initial deflection. Consequently, this initial angle, and not zero, became the minimum angle for the antagonist RTSA, which started operation at the maximum angle of approximately 290 radians and untwisted to 60 radians in the course of elbow motion from 0 to 90 degrees.

Based on the experimental results, we can conclude that the developed mathematical model of the RTSA-based exoskeleton can be effectively used for design and control of such systems.

VI. DISCUSSION

During the experiments it was observed that the angles of the protagonist and antagonist actuators were related as shown in Figure 9. It can be derived from (7) and (8) that:

$$\theta_{ant}^2 + \theta_{prot}^2 = \theta_{max}^2 + A + B \tag{10}$$

where

$$A = 2\frac{1}{r_{var}^2}\Delta X\left(\Delta X - \Delta X_{max}\right) \tag{11}$$

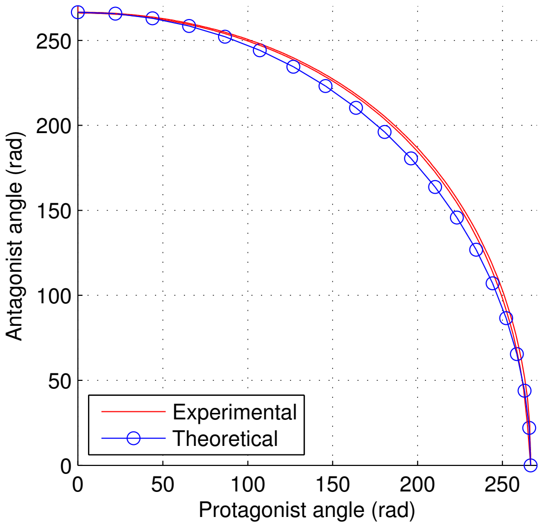

Fig. 9. Experimental and theoretical angles of the protagonist and antagonist actuators

$$B = 2\frac{1}{r_{var}^2}\frac{F_z}{K}\left(\frac{F_z}{K} + 2L + 2\Delta X_{max}\right) \tag{12}$$

The term A is negligibly small in comparison to the term θ_{max}^2. The B term enters the equation when the external load force F_z is applied, and this term does not depend on contraction of the string. Therefore, equation (10) can be used for control of the proposed elbow exoskeleton, and the approximation $\theta_{ant}^2 + \theta_{prot}^2 \approx \theta_{max}^2$ neglecting the terms A and B can be used when no external load force is applied.

The model (10) is plotted in Fig. 9 together with experimental data in case when no gravity or external load forces were acting on the exoskeleton ($F_z = 0$). It can be noted that this model matched the experimental results fairly well, with the maximum error being around 5 %. This suggests that the value of either protagonist or antagonist twisting angle can be calculated based on the current angle of its counterpart and the maximum angle of contraction θ_{max} known in advance, thus eliminating the need to calculate the values of current strings contraction. Therefore, a simplified version of the proposed control algorithm may be designed in order to operate the exoskeleton, although a certain difference between the model (10) and experimental data may cause an increased fatigue of the strings and lead to their faster rupture.

VII. CONCLUSION AND FUTURE WORKS

In this paper, we proposed an bidirectional elbow exoskeleton based on two antagonistic twisted string actuators. A kinematic model of antagonistic actuation mechanisms was developed and experimentally verified. A control algorithm based on the proposed kinematic model was developed and implemented in the elbow exoskeleton prototype. Such control algorithm allowed to operate the exoskeleton with high accuracy without any interference between the antagonistic actuators.

In the future, we plan to focus on two main areas: stiffness control and human intention detection. The present structure of the device incorporating two antagonistic actuators allows to change the stiffness of elbow posture. In this case the actuators will affect each other during twisting process. For instance, over-twisting of one actuator will generate excessive tension forces on the strings which will drive the other actuator away from its desired position. In such case a more advanced kinematic model of the RTSA must be developed.

Another important advantage of the developed twisted strings-based exoskeleton is that the device is compliant due to the properties of the strings. This allows the user to bend the elbow during the operation, which can be used as a source of the human input. Therefore, a human intention detection algorithm can be introduced in order to facilitate controllable online operation of the exoskeleton device, which is another subject of our future investigation.

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