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Basic Study for Drive Mechanism with Synthetic Fiber Rope
-Feasibility Study of a Tension Measurable High-Strength Synthetic Fiber Rope-

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***Abstract*— Lightweight and high-strength synthetic fiber ropes are widely used as components in tendon-driven manipulators. However, measuring their tension involves structural and electrical complexity, which makes it difficult to take measurements in the middle of the rope. Through a comparison of three commercially available conductive ropes, we confirmed that the organic conductive fiber Thunderon exhibits high linearity between rope tension and electrical resistance. However, Thunderon alone has a low breaking strength, making it insufficient for application in a tendon-driven manipulator that requires high tension. To improve the breaking strength, we prototyped a composite rope using the high-strength fiber Zylon as the jacket. Tensile tests showed that the breaking strength was improved by more than 25 times and that a stable electrical response was obtained even under high tension. By implementing this rope in a coupled tendon-driven manipulator, we demonstrated that tension changes along the rope could be detected through resistance changes. This method is expected to be a new approach that enables tension measurement in coupled tendon-driven manipulators.**

I. INTRODUCTION

In recent years, research on lightweight, high-strength, and highly flexible synthetic fiber ropes has advanced, and their application to tendon-driven mechanisms has become more active. Compared to stainless steel ropes, synthetic fiber ropes have a superior strength-to-weight ratio, offering advantages such as weight reduction. Their applications are diverse; for instance, Super Dragon, a 10-meter-long coupled tendon-driven manipulator developed in our laboratory, uses Dyneema, a synthetic fiber rope, for joint actuation [1]. CubiX, developed by Inoue et al. at the University of Tokyo, is a cable driven parallel robot that actively connects to environmental objects such as trees and pillars using drones, utilizing the environment as an external frame. For its ropes, the robot uses Vectran [2].

To precisely control these robots that use synthetic fiber ropes, it is essential to accurately measure the tension in the ropes. Tension measurement methods include using a pulley to infer tension from the force transmitted to it, or placing a force sensor at the end of the rope [3]. However, the former is structurally and electrically complex, while the latter is limited to the endpoints of the rope, making it impossible to measure tension in the middle of the rope. Other tension measurement methods face similar problems. This limitation is particularly problematic in coupled tendon-driven manipulators with long rope routings via numerous idler pulleys, such as Super Dragon [1]. In such systems, the tension measured at the base may not accurately reflect the actual tension in the middle or at the distal end of the rope. This discrepancy arises from tension losses due to friction across the many pulleys and the elasticity of the rope itself. Consequently, the rope may slacken, degrading control precision, or experience excessive localized tension, leading to a risk of breakage. Therefore, directly measuring the tension in the middle of the rope is essential for ensuring both system safety and precise control.

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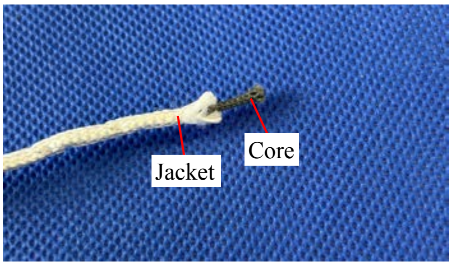


Fig. 1. Structure of the composite rope, consisting of a conductive core and a high-strength synthetic fiber jacket.

To address this issue, we propose a tension measurement method using conductive rope. Specifically, by using a conductive synthetic fiber rope, it may be possible to estimate the rope's tension through distribution over multiple idler pulleys from changes in its own electrical resistance. Zhang et al. proposed a method for estimating tension from the change in electrical resistance accompanying torsion in a Twisted String Actuator (TSA) using a conductive rope [4]. In their study, Al-Qaralleh and Chung proposed a method for measuring tension using the change in inductance of a steel wire rope [5]. Similar to these prior works, by focusing on the change in electrical resistance of a conductive fiber rope due to tension, we can estimate tension, enabling not only weight and wiring reduction, but also tension measurement along the rope.

Fig. 1 shows an overview of the developed rope. It is a composite rope with a core made of conductive rope and a jacket made of a high-strength synthetic fiber rope. Typically, the core bears the load while the jacket is used to improve properties such as abrasion resistance. A unique feature of our rope is that these roles are reversed.

The purpose of this study is to develop a lightweight and high-strength synthetic fiber rope and to propose and validate a new method for measuring tension from the change in the rope's own electrical resistance.

II. EVALUATION OF BASIC PROPERTIES OF CONDUCTIVE FIBER ROPES

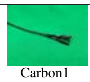
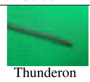
In this study, we aimed to evaluate the feasibility of using conductive fiber ropes as tension sensors. In recent years, conductive ropes, including those made from carbon fiber and organic conductive fibers, have been developed. We investigated the change in electrical resistance with respect to tension for three types of commercially available conductive fiber ropes (Carbon1, Carbon2, and Thunderon). Furthermore, Thunderon is an organic conductive fiber created by chemically bonding conductive copper sulfide to acrylic and nylon fibers. The specifications of the ropes used are shown in Table I. For Carbon1, a specific product number was not provided by the supplier (Beijing Jinglong Special Carbon Technology). The rope was ordered based on specifications as a 2 mm diameter, 6-strand braid carbon rope. Carbon2 is SILTEX Article 656. The Thunderon rope is model SS-20. Each rope had a diameter of 2 mm. The breaking strength is the average of three tensile tests conducted for each rope until breaking, using a tensile testing machine (AG-1, Shimadzu Corporation).

In the experiment to measure electrical resistance, a tensile testing machine (AGX-20kNVND, Shimadzu Corporation) was used to apply tension to the rope, and the electrical resistance at that time was measured with an impedance analyzer (IM3590, Hioki E.E. Corporation). To measure the resistance, electrodes were stably connected to the rope at two points 200 mm apart using a conductive adhesive (TK Paste CR-2800, Kaken-Tech). The experimental procedure involved repeatedly loading and unloading tension within a range that would not break the rope, and measuring the tension and resistance values during these cycles. This loading/unloading cycle was repeated 4-5 times. The resistance change rate $\Delta R/R$ was defined by the change amount ΔR from the reference resistance value R at the end of the first cycle.

Fig. 2 shows the relationship between tension and electrical resistance change rate for each conductive rope. The graphs were obtained by plotting the obtained measurement points and connecting them with lines in the order of measurement. Fig. 2(a) shows Carbon1, (b) shows Carbon2, and (c) shows Thunderon, respectively. For Carbon1, the resistance increased by a few percent as the tension increased, however with repeated cycles, the resistance value gradually shifted upwards, and the hysteresis was large. Carbon2 showed a non-linear behavior where resistance decreased with tension, and it lacked reproducibility. On the other hand, although Thunderon showed initial elongation due to plastic deformation in the first loading cycle, it exhibited stable behavior from the second cycle onwards. A maximum resistance increase of about 50% relative to the reference resistance value was confirmed as tension increased, and this change showed a certain degree of linearity. Furthermore, the hysteresis during loading and unloading was relatively small, and the reproducibility between cycles was high.

These results indicate that Carbon1 and Carbon2 have issues with stability for use as tension sensors. In contrast, Thunderon was shown to be a promising material for tension sensors. However, the breaking strength of Thunderon alone is very low at 0.11 kN, making it difficult to apply to tendon-driven manipulators like Super Dragon that require high tensions of 3 kN or more. This issue needs to be addressed.

TABLE I
SPECIFICATIONS OF EACH CONDUCTIVE FIBER ROPE

Name	Supplier	Electrical resistance [Ω/100mm]	Breaking strength [kN]	Structure
 Carbon1	Beijing Jinglong Special Carbon Technology	1.0	2.06	6 strand braid
 Carbon2	SILTEX	2.0	0.43	8 strand braid
 Thunderon	Nihon Sanmo Dyeing	2.2×10^2	0.11	7 strand braid

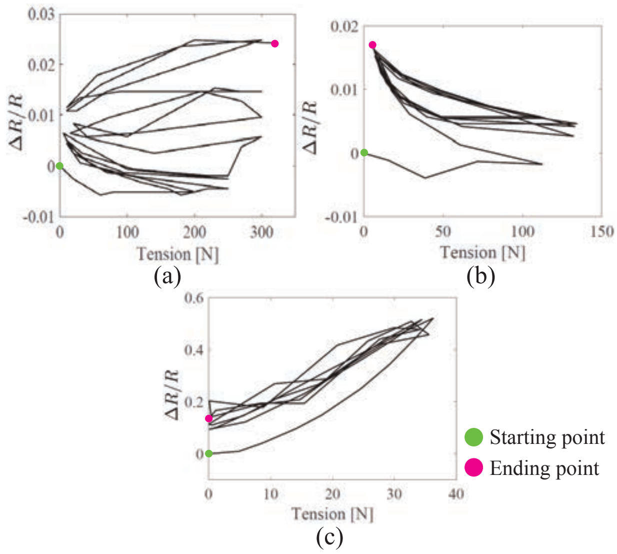


Fig. 2. Relationship between tension and electrical resistance change rate for each conductive fiber rope: (a) Carbon1, (b) Carbon2, (c) Thunderon

III. HIGH-STRENGTH CONDUCTIVE SYNTHETIC FIBER ROPE

In the previous section, the conductive fiber rope, Thunderon, was identified as a promising material for a tension sensor. However, it had the problem of low breaking strength (0.11 kN) on its own. Therefore, we manufactured two types of composite ropes with a conductive rope as the core and a high-strength fiber rope as the jacket, and investigated whether the breaking strength was increased. In general, to increase the strength using two fibers, the core is made of a high-strength rope, and the jacket provides auxiliary protection [6]. However, in this study, since Thunderon was already available as a braided rope, we opted for the reverse configuration (Thunderon as the core, high-strength fiber as the jacket) for ease of prototyping. The following two types of ropes were manufactured: (A) A rope with a conductive Thunderon

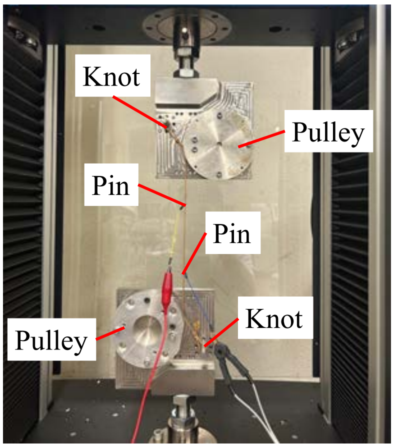


Fig. 3. Experimental setup for measuring the relationship between tension and electrical resistance.

core and a high-strength Vectran jacket. (B) A rope with a conductive Thunderon core and a high-strength Zylon jacket.

TABLE II
SPECIFICATIONS OF THE COMPOSITE ROPE

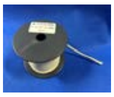
Name	Appearance	Core	Jacket	Rope Diameter [mm]
Rope(A)		Thunderon	Vectran	2.8
Rope(B)		Thunderon	Zylon	2.3

TABLE III
SPECIFICATIONS OF THE JACKET OF THE COMPOSITE ROPE

Name	Jacket	Manufacturer	Density [g/cm^3]	Composition
Rope(A)	Vectran (Polyarylate fiber)	KURARAY CO.,LTD	1.40	1670 dtex × 16 strand
Rope(B)	Zylon (PBO fiber)	TOYOBO MC Corporation	1.54	1110 dtex × 16 strand

The details of the two types of prototyped ropes are shown in Tables II and III. Tensile tests were conducted three times for each of the ropes (A) and (B) to obtain the average breaking strength. As a result, rope (A) showed a breaking strength of 3.14 kN, and rope (B) showed 3.56 kN. In both cases, a strength improvement of more than 25 times was confirmed compared to the 0.11 kN breaking strength of Thunderon alone.

IV. EXPERIMENT ON TENSION AND ELECTRICAL RESISTANCE RELATIONSHIP

In this section, we conducted an experiment to evaluate quantitatively the relationship between tension and electrical resistance in the composite rope manufactured in the previous section. The experimental setup is shown in Fig. 3. A tensile testing machine (AGX-20kNVND, Shimadzu Corporation) was used to apply tension. In the test, the rope was wrapped once around fixed pulleys with a diameter of 100 mm on the upper and lower rope fixtures, and the ends were fixed by forming a loop with the double figure-eight knot and hooking it onto a pin [7]. For measuring electrical resistance, two male jumper wires were inserted as electrodes, penetrating through the jacket to reach the core. The electrodes were placed between the upper and lower pulleys, with a distance of 100 mm between them. The electrical resistance of the rope in this section was measured using an impedance analyzer. The experiment was conducted for both ropes (A) and (B) from Section III. First, a tension of 1000 N was applied and held for 5 minutes. Then, the tension was unloaded to 50 N and then reloaded to 1000 N for about 5 minutes. The loading-unloading cycle from 50 N to 1000 N was repeated 6 times, and the tension and electrical resistance were measured at 50 N, 200 N, 400 N, 600 N, 800 N, and 1000 N during both loading and unloading.

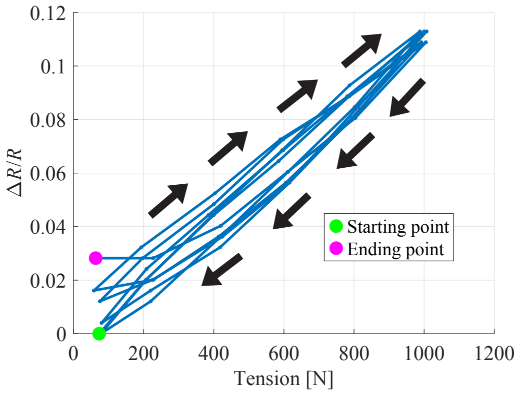


Fig. 4. Relationship between tension and the rate of change in electrical resistance for the rope with the Vectran jacket.

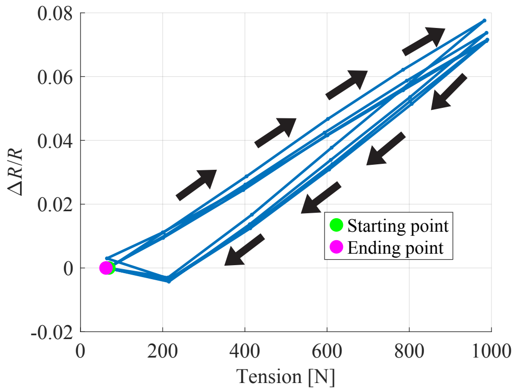


Fig. 5. Relationship between tension and rate of change in electrical resistance for the rope with the Zylon jacket.

The relationship between tension and the rate of change in electrical resistance for the ropes with the Vectran and Zylon jackets is shown in Fig. 4 and Fig. 5, respectively. The

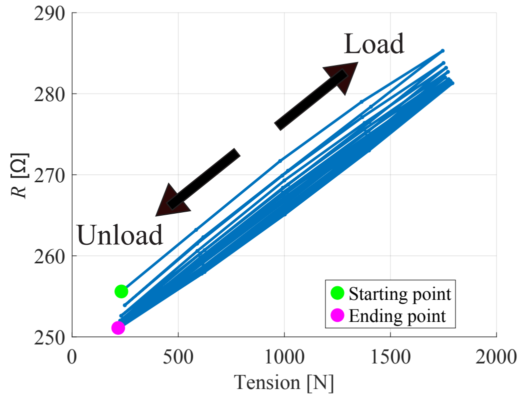


Fig. 6. Relationship between tension and electrical resistance for the Zylon-jacketed rope under high tension.

first cycle was excluded as the change in electrical resistance was unstable. For comparison, R is the electrical resistance value at the end of the first cycle, and $\triangle R$ is the change from R. The results showed that both ropes exhibited a relatively linear change in electrical resistance with respect to tension. The rope with the Vectran jacket showed a larger change in electrical resistance than the one with the Zylon jacket. This is likely because Vectran has lower stiffness than Zylon, which transfers a greater share of the load to the conductive core. While this increases the sensor's sensitivity, it reduces the core's long-term durability, making it less suitable for high-load applications. From these results and those of the previous section, the Zylon-jacketed rope was judged to be suitable for use in high-tension robot environments due to its small diameter, high breaking strength, and stable electrical response.

Following the comparative experiment between Vectran and Zylon, we further evaluated the stability of the electrical resistance of the more practical Zylon-jacketed rope under high-tension conditions. The experiment was conducted using the setup from Fig. 3 used in the previous section. Before starting the experiment, a maximum tension of 1800 N was applied to the rope and held for 10 minutes. The tension was then reduced to 200 N, which served as the starting point for the cycles. The tension was increased from 200 N to 1800 N and then decreased back to 200 N, repeating this cycle 10 times, with each cycle conducted over a period of 10 minutes. Tension and electrical resistance values were measured approximately every 400 N throughout the loading and unloading processes.

The results, as shown in Fig. 6, demonstrated that the observed relationship between tension and resistance had very high linearity over the entire evaluation range, with a coefficient of determination (R^2) calculated to be 0.97, proving that hysteresis was small. Furthermore, there was almost no variation in behavior between cycles, confirming high reproducibility. This stable electrical response under high tension suggests that it will function as a reliable tension sensor when applied to a robot.

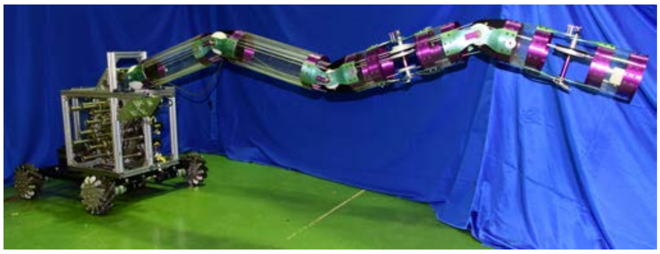


Fig. 7. External view of the robot arm "Mini 3D CT-Arm" used in the experiment.

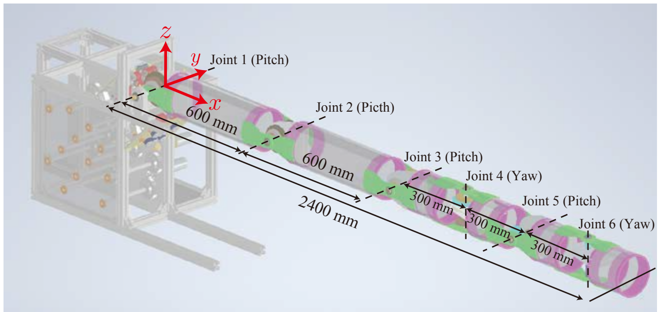


Fig. 8. Joint lengths of the Mini 3D CT-Arm.

V. TENSION MEASUREMENT ON THE MINI 3D CT-ARM

In this section, we implemented the developed Zylon-jacketed rope on a coupled tendon-driven manipulator, the "Mini 3D CT-Arm" to determine whether tension changes can be detected. A photo of the Mini 3D CT-Arm is shown in Fig. 7, and the length of each section is shown in Fig. 8. The arm of this robot uses a coupled tendon-driven mechanism, enabling motion in 3D space. The arm is 2.4 m long, has a total weight of 66.5 kg, and has 6 degrees of freedom. The joint configuration is as shown in Fig. 9, where the 1st, 2nd, 3rd, and 5th joints from the base rotate in the pitch direction, and the 4th and 6th joints rotate in the yaw direction. Each joint is driven by a synthetic fiber rope, and the arm is controlled by winding and unwinding the ropes with motors at the base. This design achieves a lightweight arm. For the control system, the joint angle is measured by a potentiometer mounted on each joint, and the required motor winding amount to achieve the target joint angle is calculated and subsequently controlled by a PI controller [8]. In this experiment, one of the two ropes extending to Joint 6 was replaced with the Zylon-jacketed rope (see Fig. 9). Then, two electrodes were inserted 50 mm apart between Joint1-2 on this rope, and another two electrodes were inserted between Joint5-6, allowing for the measurement of resistance between each pair of electrodes. In the experiment, the arm was held in a horizontal position, and the resistance between the electrodes at Joint1-2 and Joint5-6 was measured using an impedance analyzer. Next, a loading cycle was performed by sequentially increasing the payload attached to the arm's tip from 0 kg to 1 kg, and then 2 kg, followed by decreasing it back to 1 kg and 0 kg. The electrical resistance at both locations was recorded at each stage. This cycle was repeated a total of

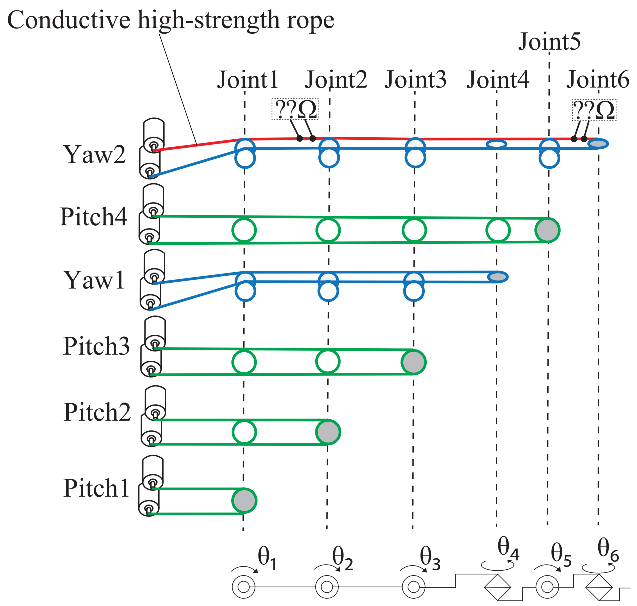


Fig. 9. Schematic of the tendon-driven mechanism of the Mini 3D CT-Arm.

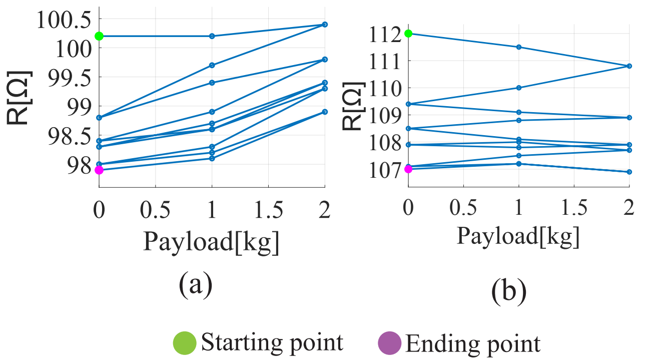


Fig. 10. Relationship between the payload at the robot arm's tip and the rope's electrical resistance. (a) resistance between electrodes at Joint1-2. (b) resistance between electrodes at Joint5-6.

5 times, with resistance measurements taken each time. Fig. 10 shows the plotted relationship between the weight value and the resistance. Here, we supplement the justification for this experimental setup. In this experiment, the resistance of the tendon (Yaw2), which drives the yaw joint (Joint 6), was measured while varying the vertical payload. As shown in the schematic (Fig. 9), this single Yaw2 tendon is routed through idler pulleys on the intermediate joints J1, J2, J3, and J5. These specific intermediate joints are all pitch joints. Due to this coupled routing, the Yaw2 tendon also acts on these pitch joints, and these joints (J1, J2, J3, J5) are precisely the ones that receive the pitching moment from the vertical payload.

Consequently, when a load is applied, the resulting pitching moment on these pitch joints is mechanically distributed (shared) with the Yaw2 tendon. This setup is therefore valid for detecting the load change. Fig. 10(a) shows the relationship between payload and resistance between electrodes at Joint1-2, and Fig. 10(b) shows the same for Joint5-6. Fig. 10(a) shows the resistance values stayed within a 3 Ω range. Also, a phenomenon was observed where the resistance increased when weight was added and decreased when it was removed during the cycle. Fig. 10(b) shows the resistance values stayed within a 6 Ω range. However, in this case, no change in resistance was observed when the payload was varied.

VI. DISCUSSION

In this section, based on the experimental results up to the previous section, especially the results from implementing the developed conductive rope on a tendon-driven manipulator, we discuss the effectiveness of this method and its feasibility and challenges for practical application.

First, a significant achievement of this study is that we were able to detect the tension change caused by the payload variation at the robot arm's tip as a change in electrical resistance in the middle of the rope using the developed conductive synthetic fiber rope. Particularly between Joint1-2, which is close to the arm's base, a correlation was observed where the resistance increased as the payload was increased and decreased as the payload was reduced. This suggests that the conductive synthetic fiber rope used in this study can function as a tension sensor in a coupled tendon-driven manipulator.

On the other hand, this study also brought new issues to light. According to conventional static analysis, the tension measured in the single rope we tested should theoretically be the same between Joint1-2 and Joint5-6 at the arm's tip. However, the experimental results differed greatly between the two, with no clear resistance change observed at the arm's tip even when the payload was varied. Further investigation is needed to determine whether this is due to the attenuation of tension transmission through numerous passive pulleys or an issue with the measurement method itself.

Using a pseudoinverse matrix, we determined a tension distribution that minimizes the sum (norm) of all rope tensions [9]. The results of this simulation predicted that the change in tension when the payload increased from 0 kg to 2 kg would be a relatively small value of about 40 N. This prediction could partially explain why no change was observed at the tip. That is, it is conceivable that this small tension change was dampened by static friction in the numerous pulleys leading to the arm's tip and did not sufficiently reach the sensor section. However, this simulation is merely one solution for the tension distribution, and it is uncertain whether the tension distribution assumed by the model's premise is actually being realized by the current control system. To clarify this tension distribution, it will be essential in the future to replace all the ropes of the robot with the conductive rope developed this time and directly measure the tension distribution of the entire system.

Although the experimental results of this study leave issues to be further verified, such as the reproducibility of measurements, they suggest feasibility for the practical application to some extent. By monitoring the electrical resistance of the rope, it is expected that applications such as detecting excessive tension that could lead to breakage in advance and reducing the tension can be demonstrated.

VII. CONCLUSION

In this study, to address the conventional challenge of difficulty in measuring tension over multiple idler pulleys, we proposed a new tension measurement method utilizing changes in electrical resistance. First, through a comparative experiment of three commercially available conductive ropes, we confirmed that the organic conductive fiber Thunderon, exhibits a highly linear response to tension. However, while this Thunderon showed suitability as a tension sensor, its very low breaking strength (0.11 kN) when used alone presented a challenge for application in robot arms requiring high tension. To improve the breaking strength, we prototyped a composite rope using high-strength fiber, Zylon, as the jacket and, through tensile testing, achieved a breaking strength improvement of more than 25 times.

Furthermore, evaluation of the relationship between tension and electrical resistance showed high linearity and reproducibility even under high tension up to 1800 N. We also implemented this rope on a coupled tendon-driven manipulator, the "Mini 3D CT-Arm," and confirmed that tension changes corresponding to payload changes at the tip could be detected as changes in electrical resistance in the middle of the rope.

These results suggest that the conductive composite rope enables measurement of tension distribution along the entire rope. This approach could eliminate the need for external force sensors and pulley mechanisms traditionally required for tension measurement.

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