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Repetitive Twisting Durability of Synthetic Fiber Ropes

Shinya Sadachika[1], Masahito Kanekiyo[1], Hiroyuki Nabae[1], and Gen Endo[1]

***Abstract*— Synthetic fiber ropes are widely used for robots because of their advantages such as lightweight, high tensile strength and flexibility. However, there is limited information on the physical properties of synthetic fiber ropes when used for robots. This study focuses on repetitive twisting of synthetic fiber ropes and provides information for selecting them for robots based on durability. To this end, we conducted repetitive twisting experiments on five types of ropes made from different fibers; we revealed that Dyneema has higher durability against repetitive twisting than the other ropes when a single rope is twisted. In addition, we conducted experiments on Dyneema by applying torsion to two ropes in parallel like a twisted string actuator. The result indicated that two Dyneema ropes in parallel have higher durability than a single rope; however, we revealed that the the tensile strength decreases sharply with an increase in the angle of twist.**

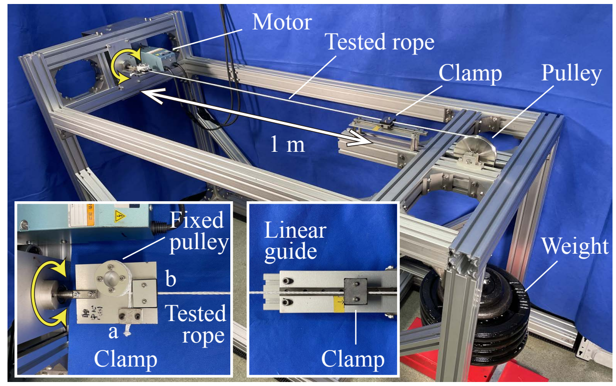

Fig. 1: Test apparatus used for repetitive twisting test.

I. Introduction

Synthetic fiber ropes are used in many fields because of their advantages such as being lightweight and more flexibile than stainless steel ropes. Ultrahigh molecular weight polyethylene (UHPE) fiber ropes, poly para phenylene benzobisoxazole (PBO) fiber ropes, and para-aramid fiber rope are $1/8$ to $1/5$ the density of stainless steel wire ropes. Thus, the ends of these ropes can be fixed with a knot as they are easy to bend and twist. Synthetic fiber ropes with higher tensile strengths compared to those of metal ropes have also been developed; therefore, they are used as hoist ropes for cranes [1][2] and mooring ropes for ships [3].

Parallel-wire robots, tendon-driven robots, and robots using twisted string actuators (TSA) are some applications that exploit the features of synthetic fiber ropes. In parallel-wire robots [4][5][6], these ropes are used as cables in winches that constitute the robot; in tendon-driven robots [7][8][9], torque is generated at the joints by pulling these rope; and in robot with TSA [10][11][12][13], a pair of these ropes is twisted by a motor to generate a contraction force to operate the robot. Thus, synthetic fiber ropes can be widely used for robots by exploiting their characteristics.

However, there is limited information on the physical properties of synthetic fiber ropes in selecting them as robot-drive systems. Especially when considering their application to robots driven by TSA taking advantage of the flexibility of synthetic fiber ropes, it is necessary to evaluate them against twisting and select an appropriate rope based on this evaluation.

Earlier studies that investigated the twisting of synthetic fiber ropes are insufficient information for rope selection due to limited experimental conditions. Davis et al. [14][15] showed that breaking strength decreases with an increase in the angle of twist; however, their results are not suitable for robots subjected to repetitive twisting because they only examined the breaking strength under static twisting. Further, the ropes used in their study were $\phi 18$ mm marine ropes, and thus, their results may not be directly applicable to ropes with smaller diameters. Usman et al. [16] used two types of Dyneema ropes and showed that the number of repetitions that leads to the rope breaking decreases exponentially under applied tension; further, the number of repetitions that leads to breaking increases in proportion to the number of ropes. However, Usman et al. did not discuss the change of tensile strength as a function of the angle of twist or rope type, which is critical for selecting ropes to use in robotic applications. Igor et al. [17] geometrically modeled twisted rope and compared the model and experimental results to propose a design method based on the length of TSA contraction and allowable angle of twist; however, braided ropes are not modeled extensively due to the complexity of the ropes themselves. Thus, the experiments investigating strength change in the rope under repetitive conditions and high tensile force are needed for application to robots when examining the twisting of thin synthetic fiber ropes. However, there is insufficient information about such experiments.

Therefore, in this study, we investigated the reduction in the tensile strength of synthetic fiber ropes under repetitive twisting by using the test apparatus shown in Fig. 1 and provide information for selecting them for robots based on durability. To this end, we conducted experiments to examine

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TABLE I: Experimental conditions for repetitive twisting

Tension [N]	Number of repetitions $\times 10^3$	Twisted length [m]	Angle of twist [deg/100 mm]	Twisting speed [deg/s]
490	7, 14, 35, 70	1	360, 720, 1440, 2880	540

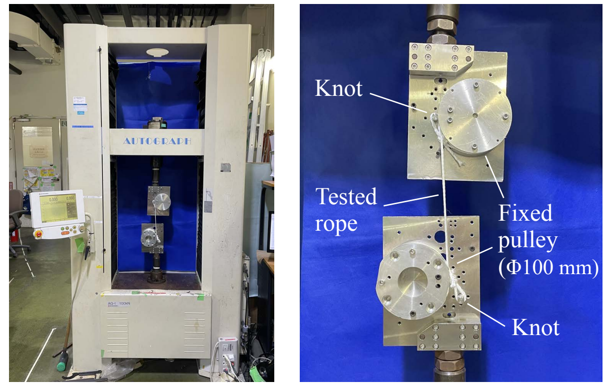
the effects of the number of repetitions, rope diameter, and rope type on the tensile strength of a single rope. Then, we performed experiments to determine the effects of the number of repetitions and angle of twist on the strength of two ropes in a twisted string actuator-like configuration. Finally, we will compare the results of these tests to illustrate the advantages and disadvantages of the tested ropes.

II. Test apparatus and experimental condition

Fig. 1 shows the test apparatus used for the repetitive twisting test. In this apparatus, one end of the tested rope is fixed to a flat plate connected to a single-shaft motor (YAMAHA, R5-3L-SR1-X05-N-B), and the other is tied to a weight via a passive pulley. The end of the rope connected to the motor is fixed as shown in the lower left part of Fig. 1. The rope is wound around a fixed pulley several times, and the end is secured with the clamp shown at a; the rope is secured with the clamp shown at b. The clamp at b holds the rope in place so that the axis of rotation of the motor aligns with the rope, which can help ensure that only pure shaft rotation is applied to the rope. Further, the rope can be twisted repeatedly by applying tension and then turning the motor forward and backward. The rope is clamped to the linear guide 1 m from the flat plate to keep twisted length constant as shown in the lower right part of Fig. 1. The twisting caused by the rotation of the motor is not generated on the weight side because this fixation restrains the rotation of the rope at the clamping point. Therefore, twisting occurs only in the 1 m section between the flat plate and the clamp. The rope is not fixed in the axial direction because a linear guide is used. The area where twisting is applied does not change because of the weight or twisting even if the length of the rope changes.

Experimental conditions for repetitive twisting are shown in Table I. The angle of twist is defined as the angle at which the rope is twisted with respect to 100 mm. As per this definition, the flat plate connected to the motor is rotated forward and backward by an angle equal to the angle of twist multiplied by 10 because the range of the rope to which twisting is applied is 1 m. The time required for the test is 12 h and 58 min when the torsion angle is 720 deg/100 mm and 70000 repetitions of twisting are performed.

After the repetitive twisting test, the tensile strength test of the rope is performed using the tensile testing machine (AG-1, SHIMADZU) shown in Fig. 2. The test is conducted by fixing the rope to the jigs at the top and bottom of the testing machine and then raising the upper jig at a speed



(a) Overview. (b) Jigs.

Fig. 2: The tensile testing machine.

of 300 mm/min. The value obtained when the rope breaks is considered the tensile strength. A $\phi 100$ mm fixed pulley is placed on the jig that holds the rope in place. The rope is wound around the fixed pulley several times so that the tension is sufficiently damped at the end as per Euler's belt theory. Then, a loop is formed at the end of the wrapped rope by tying a double figure-eight knot; the loop is fixed by hanging it on a pin [18]. The tensile strength is measured when the rope breaks in the straight section between the jigs.

III. Experiments

A. Tested ropes and measurement method

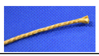
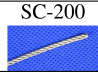
The $\phi 2$ mm and $\phi 3$ mm synthetic fiber ropes listed in Table II were used in the experiments. Dyneema2 and Dyneema3 ropes differ in the presence or absence of the heat-set, which is the process to give the rope heat and tension after braiding. Both 8- or 12-strand ropes were used to prevent the ropes from unraveling under torsion.

The repetitive twisting test was performed as follows:

1) A jack was raised at the bottom of the test apparatus after adjusting the mass of the weight to achieve the specified rope tension.
2) One end of the rope was fixed with a flat plate, and the other end was passed through a passive pulley and tied to the weight.
3) The rope was subjected to a predetermined tension decided based on the experimental conditions.
4) The rope was clamped at 1 m from the flat plate.
5) The motor was repeatedly rotated to satisfy the experimental conditions.
6) After repetitive twisting, the rope was unclamped to obtain a sample.

In this method, the temperature was controlled within the range $18-26$°C during the test. For the breaking test, the rope was fixed such that repetitive twisting was applied only between the jigs placed in the tensile testing machine and the tensile strength was measured accurately. The tensile strengths of three or four samples were measured under each experimental condition. The average value of these samples was determined as the tensile strength after repetitive twisting

TABLE II: Ropes tested in repetitive twisting experiments

Name	Model	Diameter [mm]	Supplier	Tensile strength [kN] Measured	Tensile strength [kN] Estimated	Fiber	Structure
Dyneema2	DB-96HSL 	2	Hayami Industry	4.93	7.81	Dyneema® SK-71 UHPE	2640 dtex × 8 strand braid
	DB-192HSL 	3	Hayami Industry	9.52	15.63	Dyneema® SK-71 UHPE	5280 dtex × 8 strand braid
Dyneema3	SK-99 Density Heat-set 	2	Armare	8.11	—	Dyneema® SK-99 UHPE	2200 dtex × 12 strand braid
Vectran2	VB-308 	2	Hayami Industry	4.63	6.41	Vectran® HT Polyarylate	3340 dtex × 8 strand braid
	VB-608 	3	Hayami Industry	9.11	12.83	Vectran® HT Polyarylate	6680 dtex × 8 strand braid
Zylon2	ZB-308 	2	Hayami Industry	6.33	9.89	Zylon® AS PBO	3340 dtex × 8 strand braid
	ZB-608 	3	Hayami Industry	13.39	19.77	Zylon® AS PBO	6680 dtex × 8 strand braid
Kevlar2	KB-308 	2	Hayami Industry	3.77	5.08	Kevlar® 49 Para-aramid	3340 dtex × 8 strand braid
Stainless1	SC-200 	2	SINYO	3.54	—	SUS304	7 × 19

$*$ Each estimated tensile strength was calculated based on the literature [19].

The strength efficiency was used to evaluate the decrease in strength with an increase in the number of repetitions or angle of twist; it was expressed as

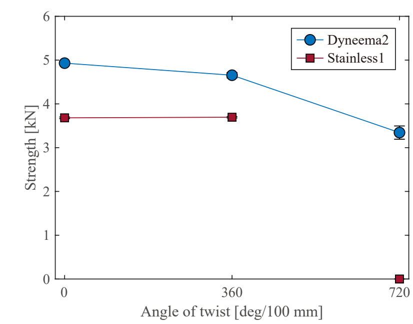
$$\text{Strength efficiency} = \frac{\text{Tensile strength after repetitive twisting}}{\text{Tensile strength before repetitive twisting}} \% \tag{1}$$

The pre-torsional tensile strength referred to in the calculation of strength efficiency is derived for each experimental condition.

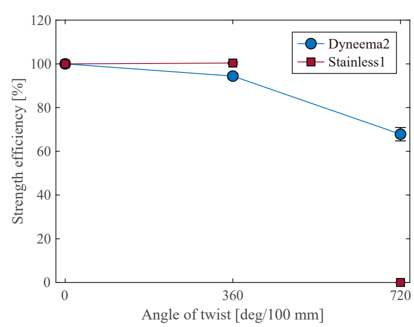
B. Comparison to stainless steel wire rope

The tensile strength of $\phi 2$ mm Dyneema2 and Stainless1 after repetitive twisting were compared. In this experiment, the angle of twist were $360, 720$ deg/100 mm and the number of repetitions was 70000. Fig. 3(a) and 3(b) show the relationships between the angle of twist and tensile strength, and between the angle of twist and strength efficiency calculated based on Fig. 3(a), respectively. For the case of breaking during the test, the tensile strength is set to 0 kN and strength efficiency is set to 0 % for convenience; the marker is not connected to other markers by lines.

Fig. 3(b) shows that the strength of Stainless1 decreased with twisting compared to that of Dyneema2; Stainless1 showed a slight increase in strength over the original strength when the angle of twist was 360 deg/100 mm. However, the rope broke during the test when the angle of twist was 720 deg/100 mm. Dyneema2 did not break even when the angle of twist was 720 deg/100 mm; they showed 70 %



(a)



(b)

Fig. 3: Relationship between angle of twist and tensile strength or strength efficiency of a single $\phi 2$ mm rope. The markers in these graphs show the average value and the error bars show the standard error.

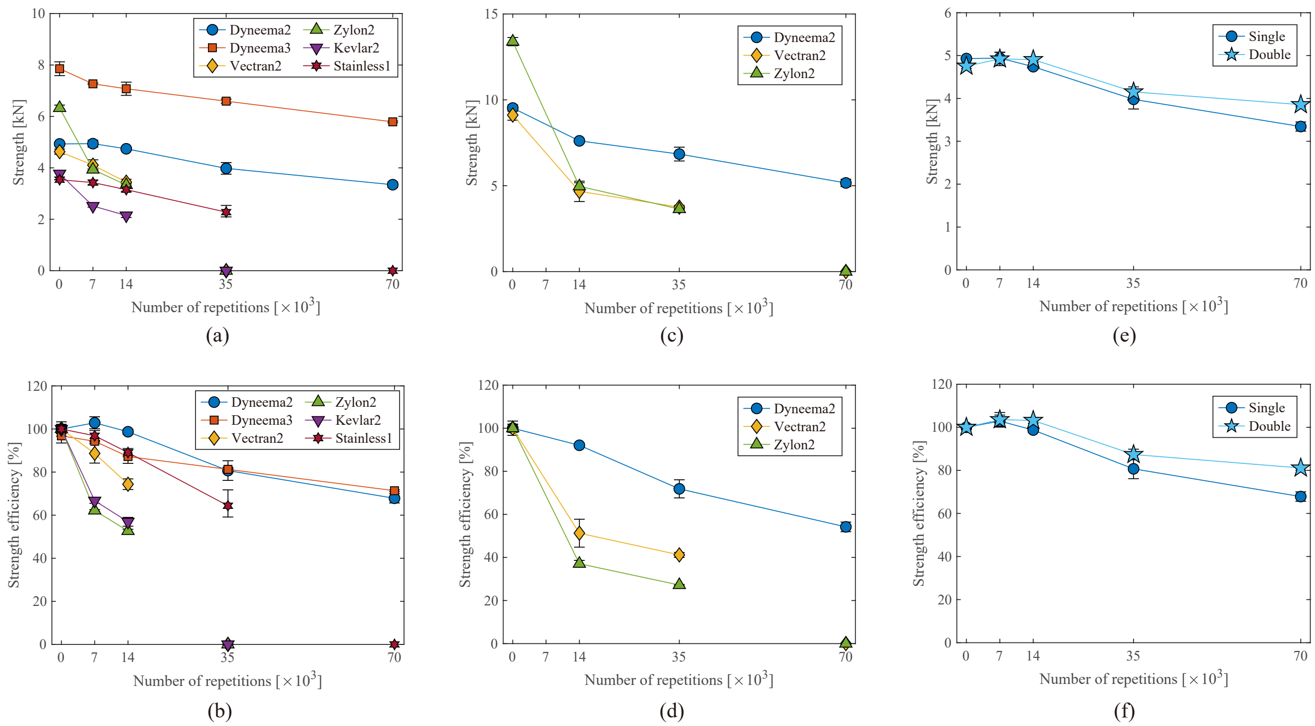


Fig. 4: Relationship between number of repetitions and tensile strength or strength efficiency. (a) and (b) show the result of a single $\phi 2$ mm rope, and (c) and (d) show the result of a single $\phi 3$ mm rope. (e) and (f) show the result of double $\phi 2$ mm Dyneema2 rope placed in parallel. The markers in these graphs show the average value and the error bars show the standard error.

tensile strength relative to the original one. These results suggest that Stainless1 has lower durability against torsion than Dyneema2.

C. Relationship between diameter and strength

The tensile strength of a $\phi 2$ mm synthetic fiber rope was measured after the repetitive twisting test. Six types of ropes (Dyneema2, Dyneema3, Vectran2, Zylon2, Kevlar2, and Stainless1) were used for this measurement. The angle of twist was 720 deg$/100$ mm, and the number of repetitions were $7000, 14000, 35000, 70000$. Fig. 4(a) and 4(b) show the relationships between the number of repetitions and tensile strength, and that between the number of repetitions and strength efficiency, respectively.

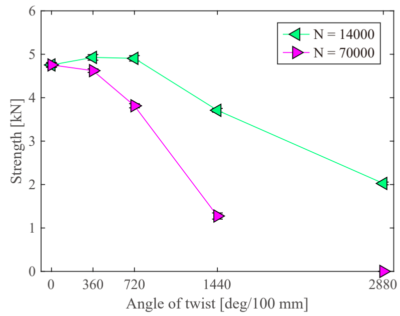
Fig. 4(b) shows that the tensile strength of all ropes decreased with an increase in the number of repetitions; Vectran2, Zylon2, and Kevlar2 showed a rapid decrease in strength because of twisting, and Stainless1 showed a gradual decrease in strength because of twisting. In contrast, Dyneema2 and Dyneema3 showed a slight decrease in tensile strength because of twisting; the presence or absence of the heat-set had negligible effect on strength efficiency.

In addition, in Fig. 4(b), Dyneema2 showed an increase in strength efficiency compared the original tensile strength when the number of repetitions was 7000. This increase is due to unintended pre-tension caused by the weight or small number of repetitions. The pre-tension not only removes the initial structural elongation of the rope but also improves the tensile strength by aligning the polymer orientation of the fibers. In this experiment, pre-tension fuctioned as the latter. It was possible to that pre-tension increased the strength efficiency of other fiber ropes as well as Dyneema2 at less than 7000, but it was not observed.

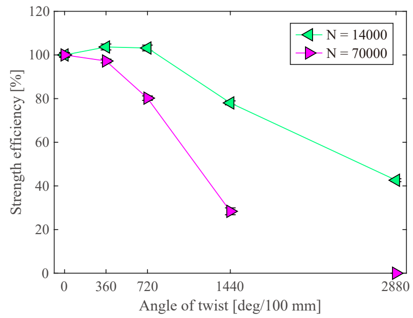
The tensile strength of $\phi 3$ mm synthetic fiber ropes after twisting was measured. Three types of ropes (Dyneema2, Vectran2, and Zylon2) were used in this measurement, and each was subjected to repetitive twisting. The relationship between number of repetitions and tensile strength obtained from these measurements is shown in Fig. 4(c); the relationship between number of repetitions and strength efficiency is shown in Fig. 4(d). The angle of twist was 720 deg$/100$ mm and the number of repetitions were $14000, 35000, 70000$ respectively.

Fig. 4(d) shows that the tensile strength decreased with an increase in the number of repetitions even at $\phi 3$ mm. Vectran2 and Zylon2 showed a rapid decrease in strength efficiency, whereas Dyneema2 showed a gradual decrease in strength with an increase in the number of repetitions. This trend is like that of $\phi 2$ mm, which suggests that Dyneema2 has high durability against torsion regardless of the diameter, and Vectran2 and Zylon2 have low durability.

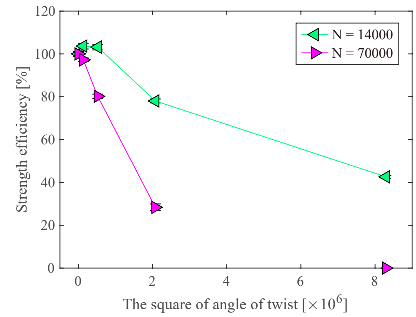
Fig. 4(b) and 4(d) show that the tensile strength of $\phi 3$ mm ropes decreased with an increase in the number of repetitions compared to $\phi 2$ mm ropes. This can be attributed to the damage of the rope caused by the linear contraction of the rope that occurs because of twisting as indicated in



(a)



(b)



(c)

Fig. 5: Relationship between angle of twist and tensile strength or strength efficiency when double $\phi 2$ mm ropes are placed in parallel. The markers in these graphs show the average value and the error bars show the standard error.

the relationship between linear contraction and lifecycle [16]. Based on the geometric model [17][20], the linear contraction ΔL of the rope due to torsion can be expressed as

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

where L, r and θ represent the length of the rope to which the tension caused by twisting is applied, radius of the rope, and angle of twist of the entire rope, respectively. The linear contraction of the rope attributed to twisting when the angle of twist is kept constant is considered; the Taylor expansion of (2) with respect to r can be expressed as

$$\Delta L \simeq \frac{\theta^2}{2L} r^2 + \mathcal{O}(r^4) \tag{3}$$

Equation (3) shows that the length of the linear contraction of the rope increases with the diameter of the rope for the same angle of twist. This contraction causes damage because of the friction between the fibers that make up the rope as discussed by Igor et al. [17]; the longer the length of contraction is, the greater the damage caused by friction is. Thus, the decrease in tensile strength in the initial stage of repetitive twisting was greater for the $\phi 3$ mm rope with a longer length of contraction. However, the number of repetitions that led to breaking during the test was greater for the $\phi 3$ mm rope because $\phi 3$ mm rope has larger original diameter. The linear contraction of the rope decreases with a decrease in the diameter of the rope caused by repetitive twisting damage; this results in a smaller degree of strength reduction with an increase in the number of repetitions. This smaller degree of strength reduction caused the long duration of $\phi 3$ mm rope.

D. Relationship between number of ropes and tensile strength

The tensile strength of two $\phi 2$ mm synthetic fiber ropes placed in parallel were measured after twisting the rope to compare the results with those of only one rope. Based on the results of the repetitive twisting test conducted on a single rope, only Dyneema2 was used in this experiment as its decrease in strength efficiency was small with an increase in the number of repetitions. The ropes were placed so that there were no gaps between the two ropes when they were placed adjacent to each other. The angle of twist was 720 deg/100 mm and the number of repetitions were $7000, 14000, 35000, 70000$. Since a 490 N weight was suspended by two ropes, the tension applied to one rope was approximately 245 N. The relationship between number of repetitions, tensile strength, and strength efficiency is shown in Fig. 4(e) and 4(f).

Fig. 4(f) shows that the decrease in strength efficiency when two ropes were placed in parallel was smaller than that when only one rope was placed. In this case, a double helix is formed with the central axis of twisting between the ropes when two ropes are lined up and twisting occurs. Therefore, there is an increase in the length of the linear contraction of the rope caused by twisting. However, the tension becomes halved by placing ropes in parallel. Based on the relationship between tension and lifecycle [20][21], it is implied that the effect of halved tension is more than the effect of linear contraction.

E. Relationship between angle of twist and strength

The tensile strength of two synthetic fiber ropes placed in parallel was measured with an increasing angle of twist. In this experiment, the angle of twist was varied from $360, 720, 1440, 2880$ deg/100 mm with the number of repetitions set to $N = 14000$ or 70000. The relationship between the number of repetitions, tensile strength, and strength efficiency is shown in Fig. 5(a) and 5(b), respectively.

Fig. 5(b) shows that the strength efficiency decreased with an increase in the angle of twist. The decrease in strength efficiency was more than twice as large when the angle of twist was doubled. Here, we consider the length of the linear contraction of the rope attributed to twisting when the diameter of the rope is kept constant. The Taylor expansion of (2) with respect to θ can be expressed as

$$\Delta L \simeq \frac{r^2}{2L} \theta^2 + \mathcal{O}(\theta^4) \tag{4}$$

Equation (4) indicates that the length of the linear contraction of the rope is proportional to the square of the angle of twist. Thus, the relationship between the strength efficiency and the square of the angle of twist can be derived as shown in Fig. 5(c), which confirms that the strength efficiency decreased linearly with an increase in linear contraction.

IV. DISCUSSION

Compared to metal ropes, synthetic fiber ropes are more flexible, and therefore, they are more durable against repetitive twisting. The experimental results obtained in this study confirmed that Dyneema rope was more durable against torsion compared to a stainless rope. Further, all synthetic fiber ropes showed strength loss because of twisting; the strength of Dyneema decreased more slowly than the other ropes, and the presence or absence of the heat-set had no effect on the strength of Dyneema.

The experimental conditions were changed to an environment similar to that of TSA to conduct additional tests because of the high durability of Dyneema against repetitive twisting. This verification confirmed that two Dyneema ropes placed in parallel had higher strength after twisting compared to a single rope. Further, the strength of the rope decreased drastically with an increase of the angle of twist even if Dyneema was used.

The results of this paper provide quantitative support to identify why Dyneema is selected for conventional TSA. However, the direct applicability of the conclusions of this paper to TSA requires focusing on end fixation. In general TSA, the end of a rope is fixed by drilling a hole in the motor shaft and passing the rope through the hole. In this method, contact between the rope and the shaft is always generated at the fixed point, and the friction at that point reduces the strength of the rope, which results in the rope breaking. In addition, as Giuanluca et al. [21] pointed, it is revealed that the lifecyle of ropes depends on the terminal fixation method. Therefore, a method for fixing the motor shaft that does not cause steep bending is required for TSA because the measurements in this paper are performed in an experimental system where such steep bending does not occur. This study was able to provide an upper limit in the strength of TSA itself by evaluating only simple torsion of the rope. Therefore, the terminal fixation method is needed to consider to evaluate the lifecycle of TSA.

Moreover, the results presented in this paper can provide a quantitative evaluation criterion for the number of movements of previously proposed robots. In our previous work [22], we have proposed a 3-DOF horizontally articulated robot arm (Fig. 6) based on ”bundled wire drive” using synthetic fiber ropes. This method is designed to simplify the mechanism by routing multiple ropes in a bundle because of the low friction coefficient of synthetic fiber ropes. Further details are provided in the literature [22]. A maximum of ± 174 deg of twist is applied at the joint axis via four ropes. The results reported in this paper corroborate the use of Dyneema in the robot arm, also suggest that at least 70000 deployment and retraction cycles are possible when Dyneema2 is used with a tension of 490 N; more operations can be performed because the actual tension is lower than this value. The experimental results presented in this paper provide quantitative criteria for evaluating the use of synthetic fiber ropes in robots.

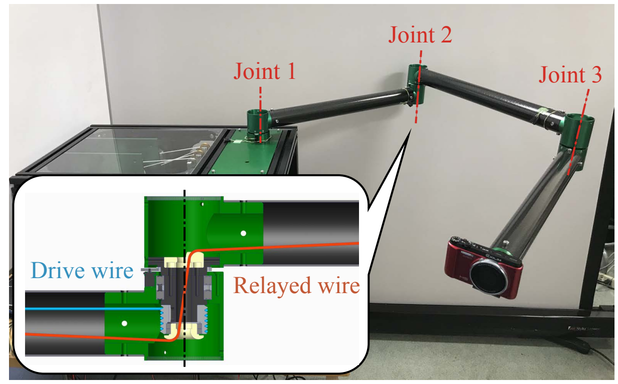


Fig. 6: Proposed 3-DOF horizontally articulated robot arm.

V. CONCLUSION

We measured the tensile strength of synthetic fiber ropes while varying the number of repetitions, number of ropes, and angle of twist and verified the strength loss of the ropes attributed to repetitive twisting. The following conclusions were obtained.

- The tensile strength of synthetic fiber ropes decreased with an increase in the number of repetitions, regardless of the type of rope.
- Dyneema showed the highest durability against repetitive twisting compared to those of Vectran, Zylon, and Kevlar.
- No difference in durability was observed between Dyneema with and without heat-set.
- The tensile strength of two Dyneema ropes placed in parallel showed less strength loss than that of only one Dyneema rope.
- The tensile strength decreased with an increase in the angle of twist for two Dyneema ropes.

This paper focused on the strength loss caused by repetitive twisting for using synthetic fiber ropes in robots. This basic information can help select appropriate ropes, and we plan to evaluate the durability under repetitive twisting when the tension is varied to various values considering actual applications.

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