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A Study on the Elongation Behaviour of Synthetic Fibre Ropes under Cyclic Loading

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***Abstract*— Synthetic fibre ropes have high tensile strength, a lower friction coefficient and are more flexible than steel ropes, and are therefore increasingly used in robotics. However, their characteristics are not well studied. In particular, previous work investigated the long-term behaviour only under static loading. In this paper, we investigate the elongation behaviour of synthetic fibre ropes under cyclic loading. In particular, we use ropes made from Dyneema DM20 (UHMWPE) and Zylon AS (PBO), which according to prior work have low creep. While Dyneema is more widely used, Zylon has higher tensile strength. We could show that under cyclic loading the Dyneema DM20 rope elongated more than 9% and kept on extending even after 500 cycles. Zylon exhibited a more stable and lower elongation of less than 3%.**

I. INTRODUCTION

Tendons are a popular option for actuation in robots. They can be used to place the actuator apart from the actuated joint. For example, in multi-fingered robot hands, which have a lot of actuated joints in limited space, there is typically not enough space to place the motors in the fingers, and a common solution is to place the actuators in the forearm instead and connect the actuators with tendons to the joints [1][2][3]. Even if there is enough space to place the actuator in the link, tendons can be used to place the actuator closer to the base of the robot, which reduces the moving mass of the robot, which has benefits for safety and reduces the required power by the actuators for robotic arms [4]. Robots that try to replicate the human musculoskeletal system also use tendons [5]. Tendons have been also used in twisted string actuators [6][7], where the tendon also acts as a form of speed reducer, or for passive gravity compensation mechanisms [8].

Steel tendons are most commonly used. However, synthetic fibre ropes have benefits compared to steel tendons, in particular, they have high tensile strength (breaking strength), a lower friction coefficient (1/3 to 1/5 than that of steel ropes [9]), and high flexibility. Due to their advantages, synthetic ropes are increasingly used in robots [5] [10] [11] [12] [13] [14].

However, the properties of synthetic fibre ropes, especially of the low creep ones used in this paper, have not been well studied. Horigame and Endo [9] studied the repetitive bending durability of synthetic fibres. They also showed that the ratio of pulley diameter D and wire diameter d determines the strength reduction. Horigame et al. [15] studied different terminal fixation methods for synthetic fibre ropes. Summers investigated several factors relevant for robotic applications, but not the elongation of the ropes [16].

One characteristic of particular importance is the elongation behaviour of tendons when loaded. Compared to steel tendons, synthetic fibre ropes exhibit substantial strain as a result of stress. Indeed, this is one of the major downsides of synthetic fibre ropes and should be investigated. Several papers studied the elongation behaviour of synthetic ropes, especially for the use as marine ropes [17][18][19][20][21][22][23]. However, the required characteristics of marine ropes are different from those of tendons in robots. Werff et. al [24] studied the creep behaviour of several Dyneema ropes and concluded that DM20 has low creep even after 6 months. Sry et. al [25] studied the effect of impact loading. Kirchhoff et. al [26] studied the elongation behaviour of several ropes, with the intended use in robotic applications. However, in none of these studies the effect of cyclic loading was investigated. For robotic applications, cyclic loading is crucial.

This paper studies the elongation behaviour under cyclic loading of two synthetic fibres, which in previous works exhibited low creep, i.e. Dyneema DM20 and Zylon (PBO).

II. MATERIALS

In this paper, based on the related studies, we used Dyneema and Zylon, two of the most well-known synthetic fibres in robotic applications which are reported to have negligible creep. Two ropes made from Dyneema DM20 fibres and Zylon AS (As Spun) fibres are compared based on the testing data acquired from the experiments.

Dyneema DM20 falls under the Ultra-High-Molecular-Weight-Polyethylene (UHMWPE) category of synthetic fibres. Dyneema DM20 fibre is available in the market in the form of ropes, sheets or only fibres and is manufactured by various companies. As stated in the previous section, Dyneema DM20 is said to exhibit low creep. Furthermore, it has high resistance to abrasion and UV light, but a low tolerance to temperature. Different sources list different temperature limits for Dyneema, with 50°C being the temperature at which the material starts decomposing due to temperature alone.

Zylon is a trademarked name for a material made from liquid-crystalline poly-phenylene benzobisoxazole (PBO) fibres, which has a rigid and very linear molecular structure. Compared to Dyneema, Zylon has a considerably higher tolerance to high temperatures, as stated in [27]. Zylon is manufactured by Toyobo Co. LTD, Japan and is also

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available in the form of ropes, sheets, etc. or fibres. Liu et. al [28] also found that PBO fibre is more resistant to heat than Dyneema, but has a weak resistance to UV light. Previous work found that Zylon experiences significant loss of tensile strength during repeated bending [9]. Moreover, Zylon is somewhat stiffer than Dyneema. Specifications of the Dyneema fibre and the Zylon AS fibre are stated in Table I.

TABLE I: Specification of materials used.

Material	Dyneema DM20	Zylon AS
Tensile Modulus (cN/dtex)	920	1150
Elongation at break (%)	3.6	3.5
Melting Point (°C)	150	650
Distributor	DSM	Toyobo Co, LTD

III. Experiments

A. Test Samples

Ropes made from Dyneema DM20 and Zylon AS were used in the experiments. A ∅4 mm Dyneema tendon was selected for our experiments. The Dyneema rope that we used in the experiments was purchased from LIROS GmbH. Upon consulting with DSM technical support, the creep of ∅3 mm and ∅4 mm Dyneema ropes at 30°C and 70°C with a maximum load of 2 kN was calculated using a creep prediction calculator developed by DSM. The ∅4 mm model showed far better resistance to creep than the ∅3 mm rope, especially at 70°C, which is a temperature that is easily attained in robotic actuator modules. Furthermore, ropes with diameters above 4 mm were estimated to have lesser flexibility, which was not desirable for our intended application as a tendon in a robot. The Dyneema tendon had an eye loop on both ends with splicing as the end terminal fixation technique. As advised on page 38 of [29], the spliced eye loop of the Dyneema tendon was 4 times the diameter of the shaft on which it was to be mounted on. The end loops of the Dyneema tendon were spliced by Sake Robotics, USA and they also pre-stretched it with high load for a short time.

A special custom tendon (hereafter, referred to as ZylonDM), made from Zylon AS as the core and Dyneema SK-series (referred to as IZANAS by Toyobo Co. LTD) as the sleeve, was made. The core of the ZylonDM rope was 2 mm in diameter and the total diameter of the rope was 2.8 mm. In a compound structure, the core material is said to bear most of the load while the sleeve takes fairly less load and just acts as a cover. Hayami Industry Co, LTD, Japan manufactured the ZylonDM tendon for us and pre-stretched the ZylonDM tendon using a universal testing machine with 5.5 kN load with a stroke-controlled rate of 200mm/min and the tendon experienced an initial elongation of 13.43 mm. The ZylonDM too had eye loops on both ends and used sewing using polyester threads as the end terminal fixation technique. As study [15] suggests, sown loops result in a better overall performance of the rope in loaded conditions, especially with Zylon ropes. Fig. 1 shows the ZylonDM

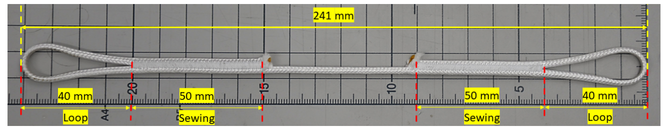


Fig. 1: ∅2.8 mm proposed ZylonDM tendon made from ∅2 mm Zylon AS as the core and Dyneema as the sleeve with 50 mm sewing end termination and 40 mm of loops on both ends with a total length of ∼241 mm.

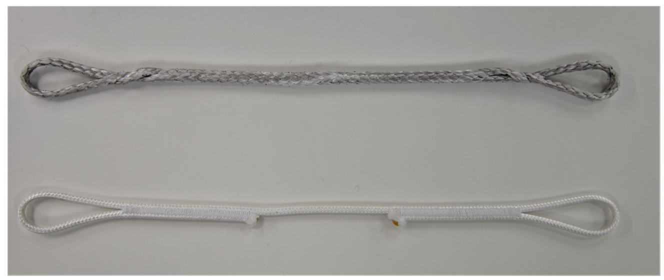


Fig. 2: Dyneema (top) with spliced eye loops and ZylonDM (bottom) with sown eye loops test samples used in the experiments.

tendon with sown lopes of 40 mm in length which is 4 times the diameter of the mounting shaft and with 50 mm of sewing.

The total length of the tendons used in the experiments was 240 mm for the Dyneema rope and 241 mm for the ZylonDM before the tests. Fig. 2 shows a picture of the test samples used in the experiments. Both terminal fixation methods used in this paper (splicing and sewing), according to previous works, support far higher loads than the 2 kN used in our experiments.

B. Tests and Experimental Setup

In robotic applications of a tendon rope, one of the most important factors is the strain behaviour of the rope. To analyse the strain behaviour, we used a universal testing machine. In particular, we utilized a SHIMADZU Autograph AG-X plus which had a maximum tensile loading capacity of 250 kN. The load cell in the testing machine also had a maximum rated capacity of 250 kN. The machine uses a direct, high-precision, constant-rate strain control using non-backlash precision ball-screw drive and is equipped with a high precision load cell. The machine has 3 basic testing modes, Single, Control and Cycle, and for the experiments we used Control mode for the tensile test, which forms the bedding-in process, and Cycle mode for the cyclic test. Each tendon went through the tensile test first and the same tendon was used in the cyclic test afterwards. A maximum tensile load of 2 kN was used for the experiments and ’Force control’ technique was used to control and limit the applied load and monitor the stroke which corresponds to the elongation of the rope. Based on our experience and after a few trial tests, we used two load acting speeds (v), 1 N/sec and 50 N/sec and the data sampling rate was set to 50 ms for the bedding-in process and 0.5 s for the cyclic test. The tests were programmed as depicted in Fig. 3.

Even though the manufacturers already performed a bedding-in process, we ran our own bedding-in cycle to check it in a controlled environment. The bedding-in process was carried out using a controlled tensile test with a slow increase in load till 70 N, then the load was kept at 70N for 15 s, which was followed by a rapid increase in load until 2 kN. The tendons were held at 2 kN for 10 min to observe the behaviour at constant load and the load was then released down to 70 N and held for another 10 min to monitor the elongation and recovery. While controlling the tensile force that was applied by the machine, the stroke was monitored which is the displacement of the mount in the longitudinal direction. After mounting each tendon on the machine, the stroke was set to 0 mm when the force in the tendon was 0 N without any slack in the tendon. Hence, the stroke directly resembled the amount of elongation experienced by the tendon during the experiment. As the tendons had loops on both ends, it was not necessary to use a special apparatus for testing the ropes in either test. 2 kN is used as the applied load because it was calculated to be the required strength in our application in a robot arm. The rated tensile strength of both ropes far exceeds 2 kN.

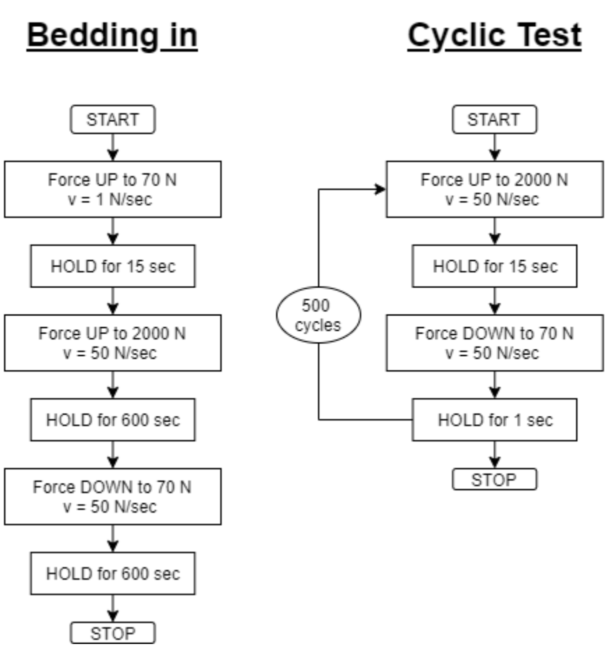


Fig. 3: Sequential flow of actions set up in the machine for the bedding-in process (left) and cyclic test (right).

IV. Results and Discussions

A. Bedding-in Process

The bedding-in process was carried out using a tensile test on each of the tendons and the results were noted. Fig. 4 shows the elongation curves obtained based on the data acquired from the first tensile test. The elongation trend of the Dyneema tendon against time is shown by the red curve and the blue curve shows the elongation trend of the ZylonDM tendon whereas the black curve shows the force applied over time. The Dyneema tendon extended by a maximum of 2.87% and the ZylonDM tendon by 2.27%. The data tips in the graph show the elongation (from left to right) when the force first reached 2 kN, after a constant load of 2 kN for 10 min, when the force was dropped to 70 N and after the force was held at 70 N for 10 min. It can be seen that the ZylonDM tendon has a flatter curve at constant load than Dyneema and extends by 0.18% only as opposed to 0.46% with Dyneema. The immediate recovery of both the tendons is similar, i.e. the ZylonDM tendon recovers immediately by 0.87% and Dyneema recovers by 0.75%. Furthermore, the overtime or slow recovery of the ZylonDM tendon is 0.12% and that of Dyneema is 0.29%. From Fig. 4, it is also evident that both the tendons do not recover the elongation as soon as the load is reduced. Fig. 5 gives us a clear illustration of the elongation curves where ZylonDM outperforms Dyneema.

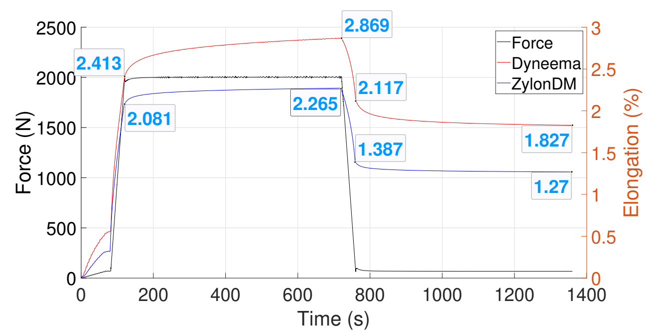


Fig. 4: Results of the tensile test with force in Newtons and tendon elongation in percentage.

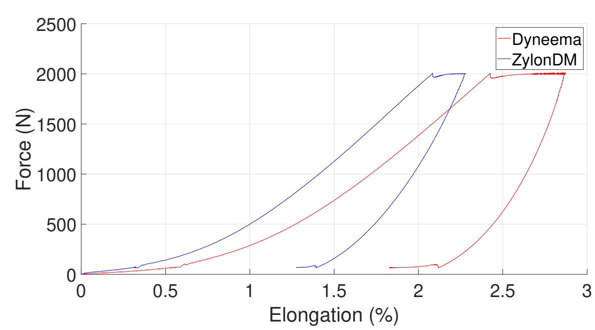


Fig. 5: Force vs elongation graph illustrating the results of the bedding-in process of Dyneema and ZylonDM.

B. Cyclic Test

A cyclic test was performed on both the tendons to evaluate the behaviour of the tendons when subjected to varying loads to mimic the movement of a robot arm. In this experiment, the main criterion of evaluation was the creep property more than the strength of the rope. The tendons were rested for more 24 hours at no load before undergoing the cyclic test. After performing 500 cycles with each tendon, the results of the test of the Dyneema tendon and the ZylonDM tendon were noted. Fig. 6 shows the elongation of Dyneema as the red curve and the blue curve denotes the elongation of ZylonDM with respect to time. Dyneema exhibited an elongation of more than 9%, while ZylonDM exhibited only 2.7% by the end of 500 cycles. For robotic applications with no length adjustment mechanisms, 9% of elongation could mean immense loss of position accuracy. The data tips show the final elongation after 500 cycles and the time taken to complete the test.

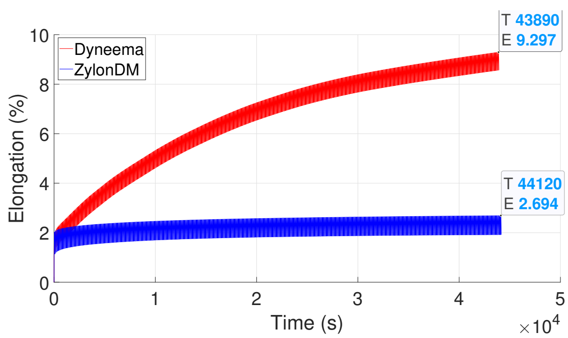


Fig. 6: Graph showing the results of the cyclic test of Dyneema and ZylonDM tendons. The data tips in the graph show the maximum final elongation (E) of the tendons at the end of 500 cycles which took approximately 12 hours for Dyneema and 12.5 hours for ZylonDM. T in the data tips denotes the time taken in seconds.

Fig. 7 and 8 show the elongation trend of the tendons with each cycle. If we compare both the graphs in Fig. 7 and 8, it is evident that the Dyneema tendon did not reach its saturation point of elongation until the 500th cycle. However, the elongation per cycle in the Dyneema tendon reduced overtime. On the other hand, the ZylonDM tendon only elongated by 2.69% as compared to 9.30% of the Dyneema tendon. Furthermore, after the initial elongation of 2% of the ZylonDM tendon in the first cycle, it only further elongated by 0.69% till the 500th cycle which is considerably lower than the 7.37% in the Dyneema tendon. Though it still cannot be concluded that the ZylonDM tendon reached its saturation point by the 500th cycle, it can be concluded that the elongation per cycle decreased quicker than the Dyneema tendon. The data tips in the graphs indicate the elongation on the first cycle and last cycle (500th) respectively. The zoomed-in graphs of the first 10 cycles of the Dyneema and the ZylonDM tendon are shown in Fig. 9 and 10, respectively. The data tips also indicate that the rate of elongation of each cycle is higher for Dyneema than for

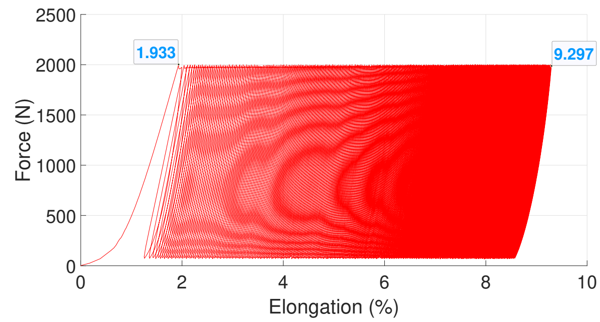


Fig. 7: Force vs elongation graph of the cyclic test of the Dyneema tendon. The data tip on the left shows the elongation on the 1st cycle (1.93%) and the right shows the elongation on the 500th cycle (9.30%).

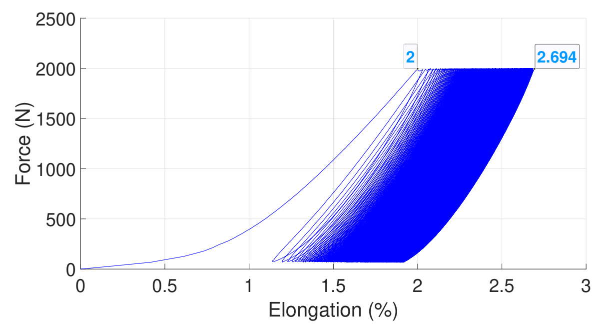


Fig. 8: Force vs elongation graph of the cyclic test of the ZylonDM tendon. The data tip on the left shows the elongation on the 1st cycle (2%) and the right shows the elongation on the 500th cycle (2.69%).

ZylonDM. Additionally, it can be noticed that the elongation shows a linear behaviour when the force increases, whereas when the force is released, the elongation recovery is non-linear. It is also important to note that even if the recovery time was known, the tendon may not be allowed that much time in a real-case application in robots.

After finishing the experiments, the length of the tested tendons was compared to the virgin tendons of their respective specification. A virgin tendon, in this case, is the tendon that did not undergo any test other than the pre-stretching that was done by the manufacturers. Fig. 11 shows the change in length of both the tendons. The end loops of the tendons in Fig. 11 were closed to reduce the chances of errors while depicting the lengths. The change of approximately 20 mm in the Dyneema is considerably higher than expected. One possible reason for this large elongation could have been the end termination method which was splicing for Dyneema. However, from Fig. 11 it can be seen that the loops did not change their length (~40 mm) and if splicing was the cause of the elongation of around 20 mm, the loops would have extended considerably.

V. Conclusion and Future Work

In this paper, we evaluated two synthetic ropes which are available in the market. Their properties make them an

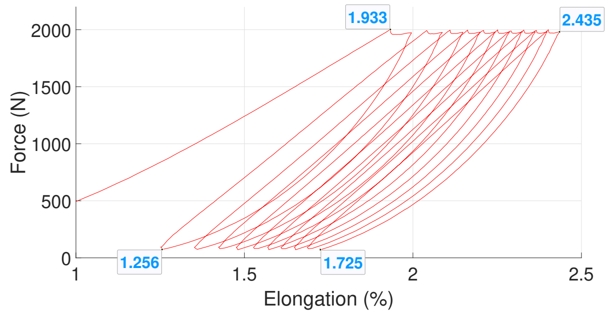


Fig. 9: Force vs elongation graph showing a zoomed plot of the first 10 cycles of the cyclic test of the Dyneema tendon. The data tip on the top-left shows the elongation on the 1st cycle (1.93%) whereas the data tip on the top-right shows the elongation at the 10th cycle (2.44%) and the bottom-left shows the elongation at the end of the 1st cycle (1.26%) and bottom-right tip shows the elongation at the end of the 10th cycle (%1.73).

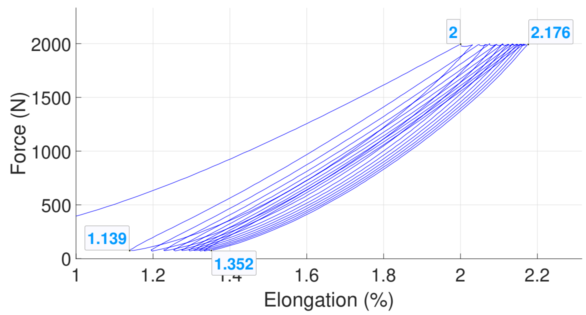
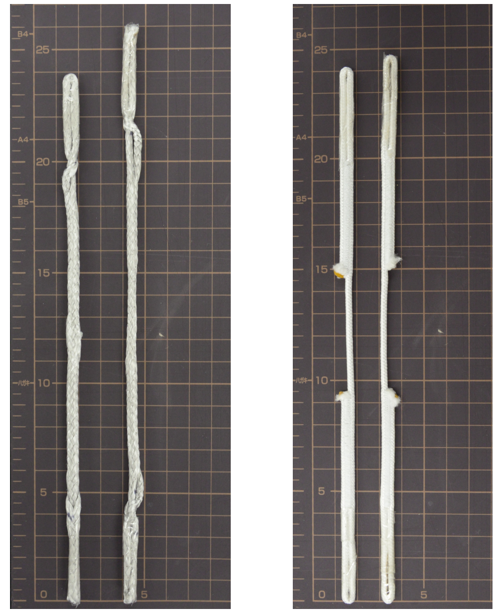


Fig. 10: Force vs elongation graph showing a zoomed plot of the first 10 cycles of the cyclic test of the ZylonDM tendon. The data tip on the top-left shows the elongation on the 1st cycle (2%) whereas the data tip on the top-right shows the elongation at the 10th cycle (2.18%) and the bottom-left shows the elongation at the end of the 1st cycle (1.14%) and bottom-right tip shows the elongation at the end of the 10th cycle (%1.35).

interesting choice for many applications, including robotics. Both tested materials claim to exhibit negligible creep, and we investigated their elongation behaviour under cyclic loading.

A Dyneema DM20 rope and a rope made from Zylon AS (PBO) as the core and Dyneema (SK, IZANAS) as the sleeve, which we named ZylonDM, were tested. For the terminal fixation method, the ZylonDM used sewing instead of splicing. A tensile test was performed to bed-in the tendons and a cyclic test was performed to test the strain behaviour of the tendons against load and time. It was deduced that the ZylonDM tendon showed better resistance to all forms of creep regimes than Dyneema. It was also verified from the results that the cause of the unexpected elongation of ∼20 mm in the Dyneema tendon was not due to the different end terminal fixation technique.



(a) Virgin (Left) & Post-experiment (Right) Dyneema Tendon

(b) Virgin (Left) & Post-experiment (Right) ZylonDM Tendon

Fig. 11: Comparison of lengths of tendons after all the experiments to a virgin tendon. The Dyneema tendon shows a plastic elongation of almost ∼20 mm whereas ZylonDM only extended by ∼4 mm.

Overall, while both tendons exhibited noteworthy elongation behaviour, the ZylonDM tendon exhibited lower and more stable elongation.

However, it should also be mentioned that previous work found that Zylon experiences significant loss of tensile strength during repeated bending [9]. Moreover, Zylon is somewhat stiffer than Dyneema. Therefore, it depends on the application which synthetic fibre is better.

The areas of application for both tendons can be widened by including a length adjustment mechanism in the system.

In the future, we plan to study the visco-elasticity regime in further detail and mainly, the recovery time of this regime. Also, further tests to analyse the behaviour of the tendon after it has reached an elongation saturation point are planned.

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