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Controlled and scalable torsional actuation of twisted nylon 6 fiber

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Abstract

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Keywords

actuation, torsional, scalable, twisted, controlled, 6, nylon, fiber

Disciplines

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Controlled and Scalable Torsional Actuation of Twisted Nylon 6 Fiber

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ABSTRACT: Large scale torsional actuation occurs in twisted fibers and yarns as a result of volume change induced electrochemically, thermally, photonically and other means. A quantitative relationship between torsional actuation (stroke and torque) and volume change is here introduced. The analysis is based on experimental investigation of the effects of fiber diameter and inserted twists on the torsional stroke and torque measured when heating and cooling nylon 6 fibers over the temperature range of 26°C to 62°C. The results show that the torsional stroke depends only on the amount of twist inserted into the fiber and is independent of fiber diameter. The torque generated is larger in fibers with more inserted twist and with larger diameters. These results are successfully modelled using a single helix approximation of the twisted fiber structure.

KEYWORDS: fiber; yarn, actuator; torsion; artificial muscle

INTRODUCTION

Promising demonstrations of torsional actuators using lightweight, compact or inexpensive materials in highly twisted carbon nanotube, graphene and oriented polymer fibers and yarns have recently been described.[1-5] Generated rotations (or "torsional strokes") per actuator length of such twisted structures were 1000 times larger than previously reported torsional actuator systems.[6-8] Potential applications of these actuators include microfluidic mixing,[2] microsensors,[9] photonic displays[4] and energy harvesting devices.[8] Additionally, it was discovered that when the torsionally-actuating fibers and yarns were converted to coils, for example by extreme twist insertion or wrapping around a mandrel, the fiber untwist produces expansion or contraction along the coil axis.[5] Changes in length as high as 49% were reported for twisted and coiled nylon 6,6 fibers, delivering power densities over 5.3 kW/kg with 2.48 kJ/kg contractile work capacity[5] and greatly exceeding that produced by natural skeletal muscle (39 J/kg).[10,11]

Scalability of torsional actuation is an important practical issue that remains mostly unexplored. Important insights are provided by the study of Haines *et al.* [5] in which coils made by twisting nylon 6,6 monofilaments with diameters ranging from 0.15 mm to 2.45 mm and heated and cooled to induce tensile actuation showed tensile strokes and gravimetric work capacities that were essentially scale independent.[5] The authors suggested that the scale invariance of the tensile stroke was due to the similar twisted structures produced in all fibers and was interpreted through the known direct link[5] between fiber torsional stroke (ΔT in turns per fiber length) and fractional coil stroke (ΔL / L), which is the change in coiled fiber length (ΔL)

normalized to its length at room temperature (L):

$$\frac{\Delta L}{L} = \frac{l^2.\Delta T}{N.L} \qquad (1)$$

with l representing the twisted fiber length and N the number of turns in the coil. Observations of the coils made from the different diameter fibers showed all to have the same fiber twist bias angle (α_f) and identical coil bias angles (α_c) so that the reorganised equation (1) is the product of three scale invariant terms:

$$\frac{\Delta L}{L} = \left(\frac{l}{L}\right)\left(\frac{l}{d.N}\right)(d.\Delta T) \qquad (2)$$

The first term is simply the inverse of $\cos \alpha_c$ (= L/l) and the second term is proportional to $\sin \alpha_c$ (=$\pi ND/l$), since the coil diameter (D) is approximately double the fiber diameter (d). The final term is also scale invariant if it assumed that the degree of fiber untwist during actuation is proportional to the twist inserted per untwisted fiber length (T) during coil fabrication, since $\tan \alpha_f = \pi dT$. The untested assumption in this analysis is that the fiber untwist during actuation depends only on the amount of inserted twist and is otherwise independent of fiber diameter.

Treating the twisted fiber as a simple single helix of equivalent diameter and bias angle provides some basis for the torsional stroke being dependent on the inserted twist. Partial untwist of the fiber or yarn is known to result from a volume expansion (Figure 1), as has been experimentally demonstrated thermally, electrochemically, photonically, and chemically.[1,2,5] The volume (v) of the cylinder enclosed by a single helically wound string depends on the string length (l_s); the length (l) and diameter (d) of the cylinder; and the number of turns the string makes in forming the helix (n). A change in volume of the cylinder can be accommodated by changes in any of the above parameters so that the ratio of final to initial volume is described by the following expression, in which zero subscripts represent the initial values:

$$\frac{v}{v_o} = \left(\frac{n_o}{n}\right)^2\left(\frac{l}{l_o}\right)^2\left(\frac{{l_s}^2 - l^2}{{l_{s,o}}^2 - {l_o}^2}\right)^2 \qquad (3)$$

Rearranging equation (3) gives an expression representing the torsional actuation in terms of the ratio of final turns to initial turns:

$$\frac{n}{n_o} = \left(\frac{v_o}{v}\right)^{1/2}\left(\frac{l}{l_o}.\frac{{l_s}^2 - l^2}{{l_{s,o}}^2 - {l_o}^2}\right) \qquad (4)$$

Observations made by Haines *et al.*[5] of their twisted nylon 6,6 fibers indicated that the volumetric thermal expansion was mainly in the diameter direction with small axial contraction occurring upon heating. This asymmetry in thermal expansion has been long established in oriented, semi-crystalline polymer fibers.[12] Assuming that the cylinder length change is negligible and that the string length is constant, equation (4) simplifies to:

$$\frac{n}{n_o} \approx \left(\frac{v_o}{v}\right)^{1/2} = \frac{d_o}{d} \qquad (5)$$

Represented as the change in twist per cylinder length gives:

$$\Delta T = \frac{n}{l} - \frac{n_o}{l_o} \approx \frac{n_o}{l_o}\left(\frac{d_o}{d} - 1\right) \qquad (6)$$

The above expression suggests that the torsional stroke (ΔT) indeed depends on the inserted twist ($T_o = n_o/l_o$) and the diameter change from volume expansion, such as occurs during heating. If fiber twist has negligible effect on the asymmetric volume expansion of the fiber, then the above analysis suggests that the torsional stroke depends only on inserted twist and is independent of fiber diameter.

We here report further investigations of the scale dependency of torsional stroke and generated torque in twisted nylon 6 monofilaments. Twisted fibers were prepared from fibers with a two-fold difference in diameter and with different inserted twist. The key assumption that torsional stroke depends only on inserted twist is experimentally tested. Further, the single helix approximation of the twisted fiber structure is evaluated in terms of the quantitative prediction of the torsional stroke during fiber heating.

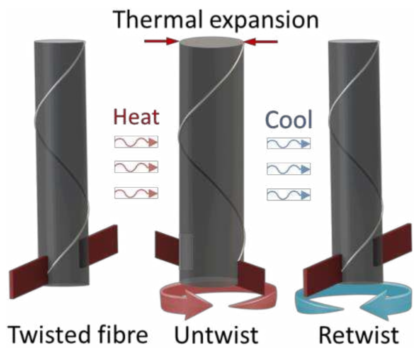

Figure 1 Schematic illustration of the thermally induced torsional actuation in a twisted fiber. Radial expansion results in untwist and rotation of the paddle attached to the fiber free end. The helically oriented polymer chains are assumed to be inextensible and are illustrated by a single helix at the fiber surface.

EXPERIMENTAL

Twist Insertion in Nylon 6 Fiber

Twist insertion into commercially available nylon 6 fiber (Sport Fisher monofilament fishing line) was conducted by an electrical DC motor as described previously.[13] All samples were suspended vertically from the DC motor and held under tension by a known weight that was free to move vertically, but prevented from rotating (Figure S1). After the desired twist was inserted into the fiber, it was removed from the motor without release of twist, clamped to a frame, annealed at 120°C for 30 minutes, cooled to room temperature and then removed from the frame at which time the twisted structure was permanently set.

Neat samples of different diameters (400, 500, 780, and 1000 µm) were chosen to be twisted under constant axial stress of 10 MPa (based on the cross-sectional area of the untwisted fiber). Initially, all the twisted samples were fabricated having similar twist directed bias angle (~30°) by calculating the amount of needed twist using the following geometric relation for a single helix:

$$\alpha_f = tan^{-1}(\pi d T) \quad (7)$$

Here, α_f is the bias angle relative to fiber axis, *d* is the fiber diameter and *T* is the amount of turns inserted per initial fiber length.

Next interest was the insertion of the same amount of twist (170 $T.m^{-1}$) in the different diameter fibers to give a range of different bias angles. Finally, different amounts of twist were inserted into a fiber of fixed diameter (780 µm). Overall fabrication variables are graphically illustrated in Figure S2.

Thermo-Physical Change in Fiber Dimensions

Thermally induced dimensional changes of twisted nylon 6 fiber were investigated by heating the sample in a silicone oil filled capillary tube. Silicone oil has high thermal stability and is particularly suitable as a high temperature heat-transfer liquid.[14] Fiber samples twisted in all experimental conditions were used, hence provided the detailed understanding of thermal expansion or contraction. Figure 2 shows the illustration of tests used to measure changes in length, diameter and volume of twisted fiber before and after heating. An optical microscope (ISSCO-OPTEK) was used to accurately measure the change in liquid level and fiber length.

Starting with the same initial volume of oil, the volume changes for the oil-only (ΔV_1) and fiber-in-oil cases (ΔV) can be written as:

$$\Delta V_1 = \pi . R^2 . (L_1{}' - L_1) \quad (8)$$

$$\Delta V = \pi . R^2 (L' - L) \quad (9)$$

The negligible change in capillary diameter over the temperature range used is ignored. Subtracting equation (8) from (9), gives the volume change of the twisted fiber (Δv):

$$\Delta v = \pi . R^2 [(L' - L) - (L_1{}' - L_1)] \quad (10)$$

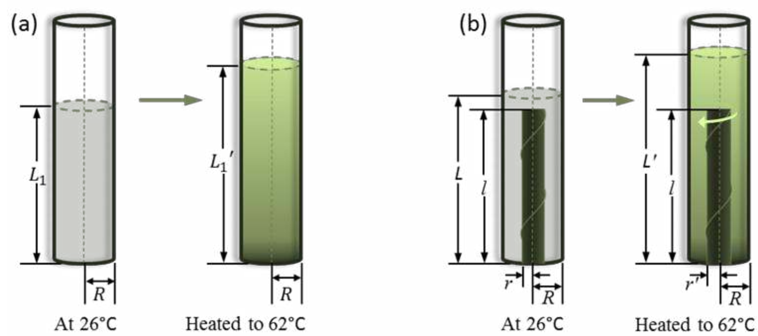

FIGURE 2 Experimental illustration of dimension change in twisted fiber operated in a silicone oil filled glass capillary (radius R); (a) calibration of oil thermal expansion having liquid height L_1 at 26°C, and $L_1{}'$at 62°C, (b) Combined thermal expansion of oil with immersed fiber from initial liquid level L raised to L' at 62°C. Fiber length (*l*) remained almost constant while radius changed from r to $r'$when heated.

Experimentally, it was observed that the fiber length change was negligible over the temperature range from 26°C to 62°C for all fibers, regardless of diameter and amount of inserted twist. The fiber volume change can be expressed solely as a change in radius (*r*):

$$\Delta v = \pi . l\left[r'^2 - r^2\right] \quad (11)$$

Combining equations (10) and (11) gives a general expression of change in radius of twisted fiber which was used to calculate the thermal expansion/contraction coefficients for further theoretical analysis:

$$r' = \sqrt{\frac{R^2\left[(L'-L)-(L_1{}'-L_1)\right]}{l} + r^2} \quad (12)$$

Thermally Induced Torsional Actuation Test

Torsional actuation tests were conducted in an in-house-built testing apparatus (Figure S3) described previously[13] and equipped with a DC power supply, programmable temperature controller and a dual mode lever arm force/distance transducer system (Aurora Scientific). Twisted nylon 6 fiber was thermally actuated by heating inside an electrical furnace. The fiber was fixed at one end and the other end attached to a shaft supported by two near frictionless air bearings. The rotation of the shaft caused by the torsional response of the fiber was measured continuously from the lever arm that was connected to the shaft by a fiber held at constant tension. All the isotonic tests (constant torque) reported herein were conducted under a constant small external torque (68 µN.m) applied by the lever arm and opposing the fiber untwisting. The effect of the applied torque on the rotation of the fiber attached to the shaft was negligible (Supporting Information). The same apparatus was also used to evaluate the torque generated during heating/cooling of the twisted nylon fiber. In this case, the lever arm was operated in the isometric (constant length) mode to prevent fiber rotation and provided a measure of the blocked torque. Unless otherwise stated, a constant twisted sample length (70 mm) and a constant temperature range (26-62°C) at average heating and cooling rates of 3.6°C/min and 1.8°C/min, respectively, were programmed and used for all the actuation tests.

Torsional Stiffness Measurements

Fiber torsional stiffness was measured using the same apparatus. Controlled rotation of the shaft attached to the free end of the fiber using the lever arm generated the torque – rotation relation. Previous studies of the same nylon 6 fibers have established that their torsional behavior is linear elastic over the range of rotations used here.[13] The torsional stiffness (*S*) were obtained from the slopes of these lines, as described previously.[13]

RESULTS

Characterisation of Twisted Fibers

Several fabrication parameters were considered while preparing twisted nylon 6 fibers for actuation testing. Firstly, fibers from four different diameters (400, 500, 780, and 1000 µm) were twisted to 428, 340, 221, and 170 $T.m^{-1}$, respectively, producing the same surface bias angle of ~30° (Figure 3). In a second set of samples, the four different diameter fibers were twisted to a constant twist (170 $T.m^{-1}$). Finally, a third set of samples was prepared by twisting fibers of constant diameter (780 µm) to 145, 170, 221, and 290 $T.m^{-1}$. The prepared fibers were examined using optical microscopy after fabrication to measure the surface bias angle and final fiber diameter. When twisted to a constant bias angle of 30°, the diameter of each fiber was increased by approximately 8% compared to their initial diameters (Figure 3). Fiber bias angle measurements show good agreement to the diameter/twist/bias angle relationship of equation (7).

Asymmetric Thermal Volume Expansion of Twisted Fibers

The twisted fibers were heated slowly in an oil-filled capillary to experimentally measure the length and volume change as described in Figure 2. In all cases, the fiber length change was negligible when heated from 26°C to 62°C and this observation is consistent with previously published results for the axial thermal expansion of oriented nylon 6 fibers over this temperature range.[12] In contrast, the

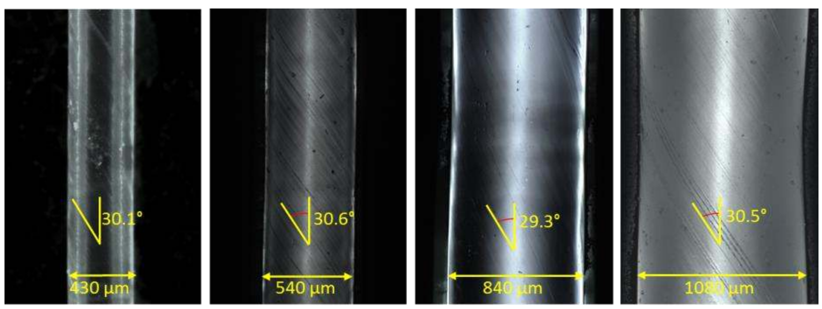

FIGURE 3 Photographs of different diameter fibers twisted to a constant bias angle by inserting twist of 428, 340, 221, and 170 $T.m^{-1}$ for fibers of starting diameters of 400, 500, 780, and 1000 µm and with a constant axial stress of 10 MPa applied during twist insertion. The obtained surface fiber twist bias angle and fiber diameter are as indicated.

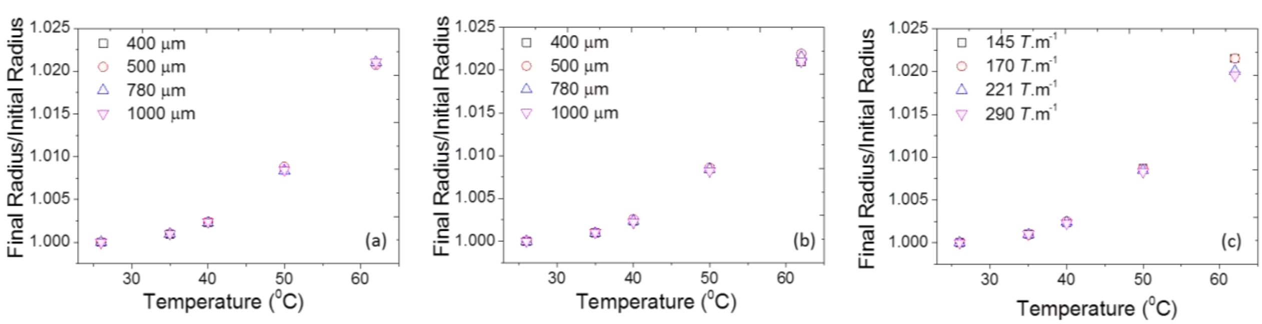

FIGURE 4 Thermally induced radial expansion of twisted nylon 6 fibers normalised to the diameter at 26°C: (a) different diameter fibers twisted to the same bias angle (30°); (b) different diameter fibers with the same amount of inserted twist (170 $T.m^{-1}$); and (c) different inserted twist in constant diameter fibers (780 µm).

thermal strain in the radial direction was considerably larger and almost identical for all of the twisted fibers prepared with different fabrication parameters (Figure 4).

Effect of Fiber Diameter and Inserted Twist on Torsional Actuation

Constant Bias Angle Fibers

The torsional stroke and torque generated from custom fabricated twisted fibers were found to be strongly influenced by the starting fiber diameter and amount of inserted twist. Figure 5(a) shows the thermally induced torsional stroke of different diameter nylon 6 fibers prepared with the same bias angle (~30°) achieved by inserting different amounts of twist.

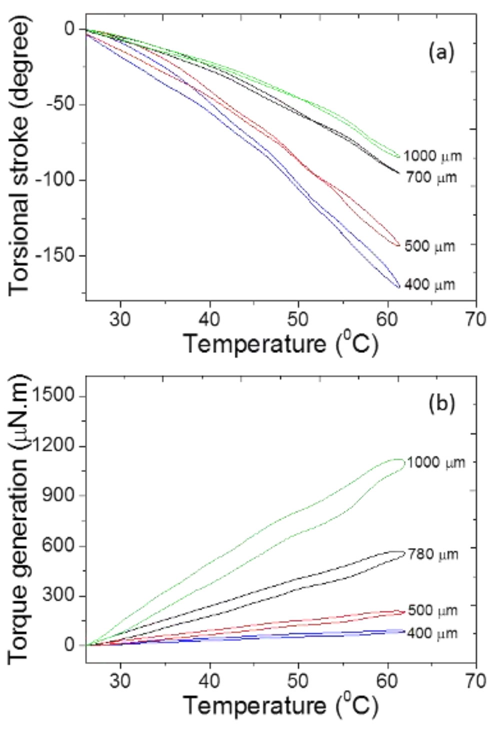

FIGURE 5 Torsional actuation test results of twisted nylon 6 fibers of different diameters and having the same bias angle (30^o): (a) isotonic torsional stroke; and (b) isometric torque generation.

The fiber rotation during both heating and cooling is shown to be fully reversible with a small hysteresis, which is at least partially related to the thermal lag between the recorded temperature of the furnace and the true fiber temperature. Slow heating and cooling rates minimized the magnitude of the observed hysteresis. It can be seen that the smallest considered diameter fiber has produced the largest stroke and the stroke at any given temperature decreased monotonically with increasing fiber diameter.

Figure 5(b) shows the isometric torque generation by these same different diameter fibers with constant bias angle. A steady increase of generated torque at any given temperature was noticed as fiber diameter increased. The torque generated during heating was fully relaxed during cooling with some hysteresis. In addition to the thermal lag, the hysteresis in torque was also increased by some stress relaxation that occurred during the short isothermal holding period between heating and cooling.

Constant Twist Insertion

Figure 6(a) shows the thermally induced torsional stroke of different diameter nylon 6 fibers prepared with the same amount of twist inserted per length of as-received fiber (~170 $T.m^{-1}$). All fibers generated remarkably similar torsional stroke-temperature curves during both heating and cooling. The results show that torsional stroke was clearly independent of the 2.5 fold difference in fiber diameter when fibers were prepared with the same inserted twist.

In contrast, the generated blocked torque of these same fibers increased significantly when larger diameter fibers were used [Figure 6(b)]. As described in more detail below, the generated torque is determined by the product of the torsional stroke and the fiber stiffness and the latter is strongly dependent on fiber diameter.

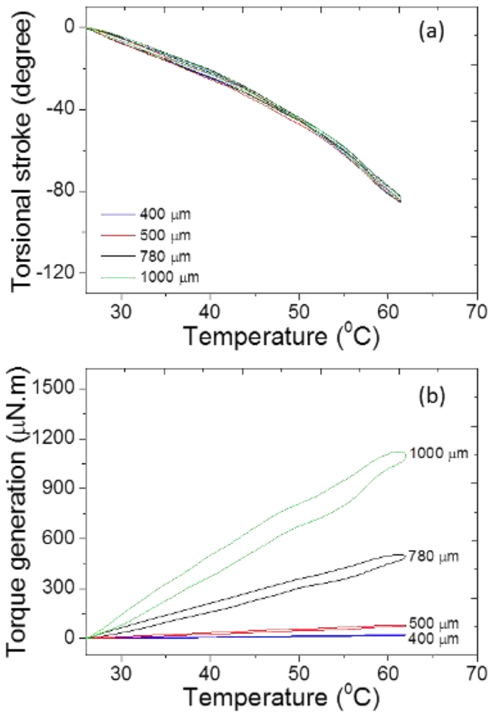

FIGURE 6 Torsional actuation test results of twisted nylon 6 fiber with different diameters and having the same twist inserted per initial fiber length (~170 $T.m^{-1}$): (a) isotonic torsional stroke; and (b) isometric torque generation.

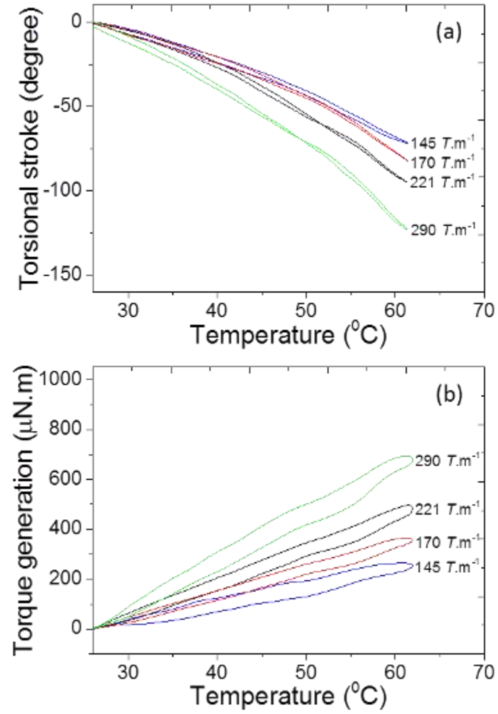

FIGURE 7 Torsional actuation test results of twisted nylon 6 fiber with a constant diameter and having variable twist inserted per initial fiber length: (a) isotonic torsional stroke; and (b) isometric torque generation.

Constant Fiber Diameter

The final experiment investigated the effect of inserted twist in fibers of constant diameter (780 µm). Figure 7(a) shows the torsional stroke increased monotonically with the amount of twist inserted. Similarly, Figure 7(b) shows blocked torque and the torque generation during heating was also seen to be dependent on the amount of twist inserted and increased with increasing amount of twist.

DISCUSSION

Theoretical Estimation of Torsional Rotation

Previous investigations of torsional actuation in twisted fibers and yarns have suggested that a single helix approximation can provide some insight into the actuation mechanism.[2,5]

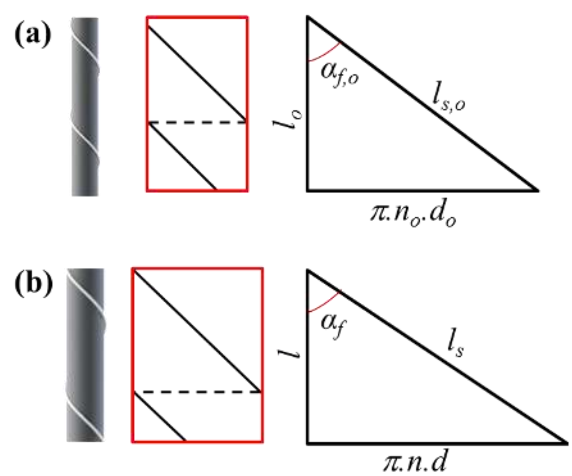

FIGURE 8 Illustration of a single helix fiber geometry, (a) before actuation, and (b) after actuation. l denotes fiber length, l_s is length of the helically wrapped string, *d* is fiber diameter, and n is the amount of twist, α_f denotes the helix bias angle. Zero subscripts represent the initial state.

Figure 8 illustrates two states of a helical string encompassing a cylinder of different volumes. The geometric analysis is facilitated by "opening up" the cylinder so that the string can be visualized as forming the hypotenuse of a right triangle. Derivation of equation (3) then follows. The expression has previously been applied to explain the possibility of fiber untwist during a volume expansion,[2,5] but has not been used to quantitatively predict the amount of untwist.

Combined torsional actuation measurements and volume expansion data allows the application of the single helix model to quantitatively predict the amount of torsional stroke. The starting assumption is that the "string length" in the single helix remains constant during the volume change. For the twisted nylon fibers the "string" can be thought of as the oriented polymer chains on the surface of the fiber. These molecules are likely highly extended and firmly connected through crystalline blocks. This topology exhibits a high axial stiffness and can be considered mechanically inextensible. However, previous work has shown a negative thermal expansion of oriented nylon fibers in the fiber direction.[12] In the present study, the temperature range for actuation tests has been chosen to minimise the axial length change and experiments confirm negligible changes in length of twisted fiber. This observation and the assumption that the string length is constant greatly simplifies equation (4) to equation (5) where the torsional actuation, in theory, depends only on the change in fiber diameter and the amount of twist inserted.

The torsional strokes have been calculated using equation (6) and from the measured diameter change. The results are shown in Figure 9 for each of the 3 series of prepared fibers. The measured torsional strokes are included for comparison and in all cases there is

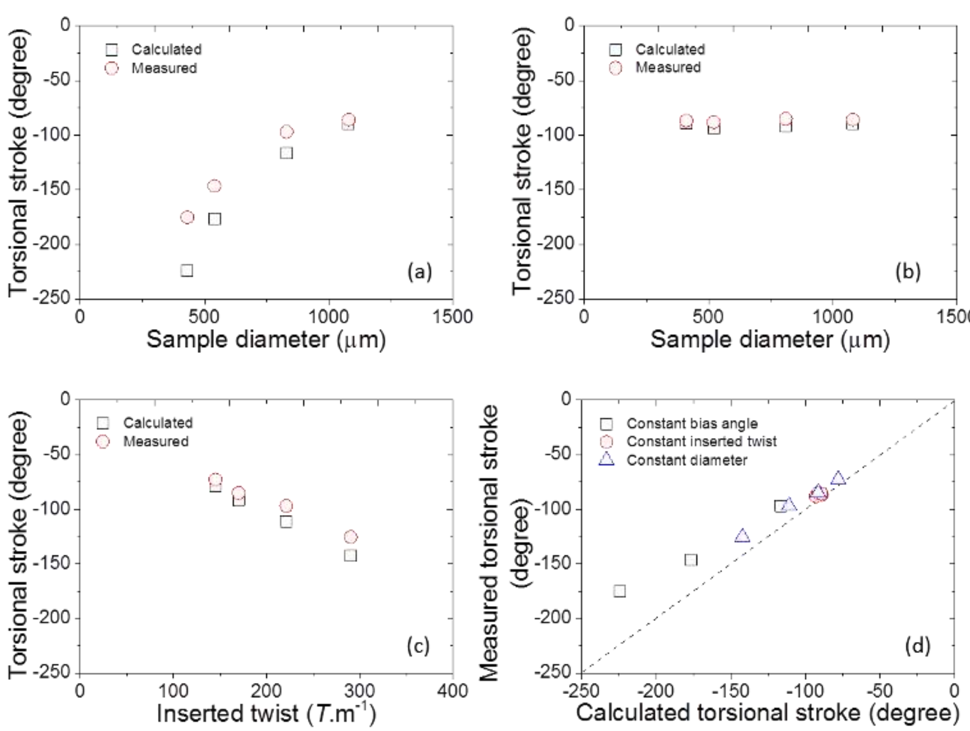

FIGURE 9 Comparison of experimentally measured and theoretically calculated torsional strokes for 70 mm long twisted nylon 6 fiber prepared with (a) similar bias angle (30^o to the fiber axis); (b) similar amount of twist (170 $T.m^{-1}$); (c) similar fiber diameter (780 μm). All calculated and measured torsional strokes are compared in part (d).

a very good agreement between the measured and calculated values. The single helix theory correctly predicts the dependence of torsional stroke on the diameter change and the amount of inserted twist. The theory also predicts the quantitative torsional strokes with high accuracy, giving support to the underlying assumption that the string length remains unchanged during heating. It is noted that the theory is slightly less accurate in quantitatively predicting torsional stroke for the most highly twisted fibers, for reasons that are not yet known. The overall degree of agreement between calculated and measured torsional strokes is especially good considering that the twisted fibers are not single helices encompassing a hollow cylindrical core as assumed in the model. A closer approximation to the actual fiber structure is described by a series of nested helices of different diameter and the same number of turns per length (and, hence, different bias angles). If all these helices displayed the same diameter expansion ratio and no change in length, then they would all produce equivalent torsional stroke.

The real fiber structure, however, likely involves entangled helices of oriented polymer chains joined by the crystalline blocks. The structure of the fiber, including crystal block size, defects and chain orientation, may be altered by the twist insertion and with possible variations in structure occurring along the radial direction. These molecular differences may affect the degree of "co-operation" between inner and outer layers in generating the torsional actuation. The data of the present study suggest that at smaller amounts of twist insertion the "co-operation" is good and all layers generate the predicted torsional stroke. However, at higher twist insertion some process slightly impedes the untwisting mechanism and further studies are needed to identify the cause(s).

Theoretical Estimation of Torque Generated

A quantitative analysis of torque generation from differently twisted fibers was also conducted. It has been shown previously that the maximum torque generated when the twisted fibers are heated occurs when the fibers ends are securely clamped.[13] This "blocked torque" ($\tau_{blocked}$) can be calculated using standard torsion mechanics and as verified previously [13]:

$$\tau_{blocked} = \Delta n.\frac{JG}{l} \quad (13)$$

Here, Δn represents the free rotation (in radians) of a fiber of length l that is clamped at one end and whose other end is free to rotate. G is the fiber shear modulus in the final state and J is the polar moment of inertia of fiber and formulated in terms of sample diameter (*d*) for a fiber of circular cross-section:

$$J = \frac{\pi d^4}{32} \quad (14)$$

Therefore, the general quantitative expression when combined with equation (5) can be written as:

$$\tau_{blocked} = \Delta n.\frac{\pi.d^4.G}{32.l} = \frac{\pi.d^4.G.n_o}{32.l}\left(\frac{d_o}{d} - 1\right) \quad (15)$$

Fiber shear moduli were determined from torsion tests at both the starting and finishing temperatures used in the actuation tests. The torsional stiffness ($S = \frac{JG}{l}$) of a 500 µm diameter nylon 6 fiber was experimentally evaluated and the stiffness of the other diameter fibers were calculated theoretically from equation (16) and verified previously [13]:

$$\frac{S_1.l}{S_2.l} = \left(\frac{d_1}{d_2}\right)^4 \quad (16)$$

Here, S_1 and S_2 are torsional stiffness of two different diameter fibers d_1 and d_2 of length l. Table 1 shows the torsional stiffness of different diameter fibers at two experimental conditions of 26°C and 62°C. The shear moduli are also included in Table 1 and it is seen that all fibers have nearly equivalent moduli of ~0.43 GPa and ~0.39 GPa at 26°C and 62°C, respectively.

TABLE 1 Torsional properties of twisted nylon 6 fibers having different diameter.

Fiber diameter (μm)	Torsional stiffness (N.m)		Shear modulus (GPa)	
	26°C	62°C	26°C	62°C
400	1.46×10^{-4}	1.31×10^{-4}	0.43	0.39
500	3.56×10^{-4}	3.19×10^{-4}	0.42	0.38
780	2.11×10^{-3}	1.89×10^{-3}	0.44	0.41
1000	5.70×10^{-3}	5.10×10^{-3}	0.43	0.38

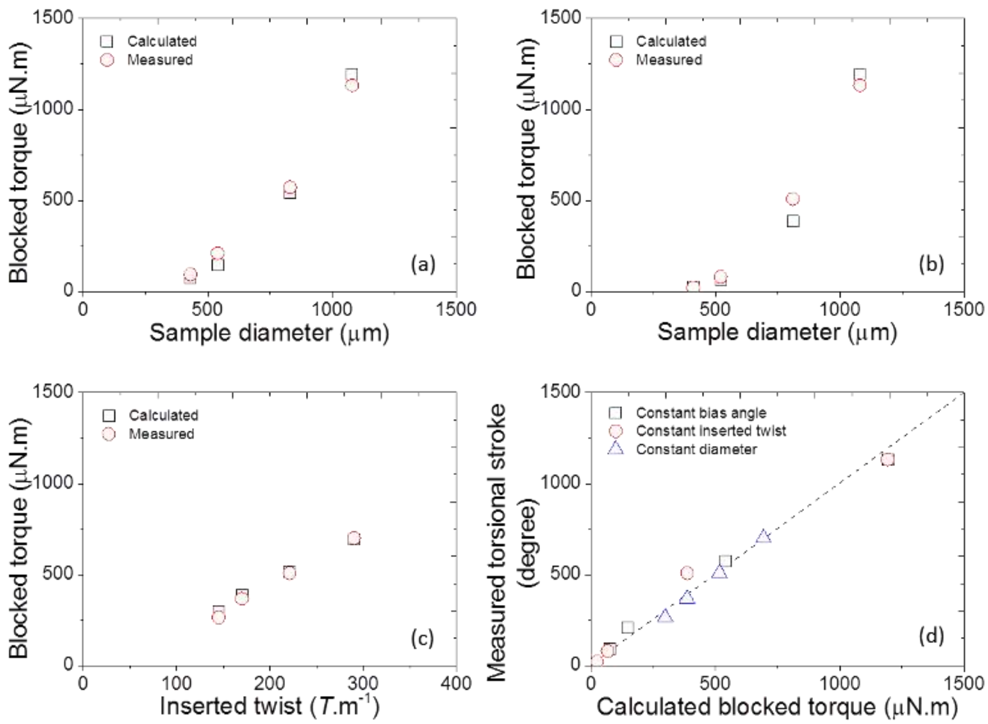

FIGURE 10 Comparison of experimentally measured and theoretically calculated blocked torque generated from 70 mm long twisted nylon 6 fiber of different fabrication parameters: (a) similar bias angle (30^{o} to the fiber axis); (b) similar amount of twist (170 *T*.m^{-1}); (c) similar fiber diameter (780 μm). All calculated and measured torsional strokes are compared in part (d).

Figure 10 shows the calculated blocked torques obtained from equation (15) and includes the measured torques for comparison. In all cases, there is an excellent agreement between the measured and calculated values, further supporting the analytical approach based on a single helix. Unlike the results of torsional stroke, the torque generation from the twisted fibers is strongly dependent on fiber diameter as indicated by the fourth power dependency of torque on fiber diameter in equation (15). Thus, for fibers having a constant amount of inserted twist [Figure 10(b)], the torque generated increases by a factor of 40 times for a 2.5 times increase in diameter. The generated torque also depends linearly on the amount of inserted twist, as shown in Figure 10(c) for fibers of constant diameter.

TABLE 2 Prediction of torque generation from induced twisted fiber.

Parameters			Theoretical prediction of blocked torque ($\boldsymbol{\tau_{blocked}}$)
Bias angle	Number of twist	Fiber diameter	
Constant	Variable	Variable	$\tau_{blocked} \sim D^3$
Variable	*Constant*	Variable	$\tau_{blocked} \sim D^4$
Variable	Variable	*Constant*	$\tau_{blocked} \sim \tan\alpha$ or, $\tau_{blocked} \sim T$

CONCLUSIONS

The aim of this study was to further investigate the scalability of torsional actuation in twisted monofilament fibers and to evaluate the single helix model for quantitatively predicting torsional stroke and torque. Nylon 6 monofilaments were prepared with different fiber diameters, amount of inserted twist and twist bias angle. Heating and cooling the samples over a ~30^{o}C range provided a measure of both torsional stroke and generated torque. The torsional stroke was dependent only on the amount of twist inserted into the fiber and was independent of fiber diameter and fiber bias angle. The single helix model accurately predicted the torsional stroke based on the measured fiber diameter change during heating. Generated torques were also accurately predicted by the single helix model when combined with the measured fiber torsional stiffness. Torque was strongly dependent on fiber diameter, along with the amount of inserted twist. A summary of the dependencies of stroke and torque on diameter for each of the three types of fibers prepared is given in Table 2.

The degree of agreement between the measured torsional actuation parameters and those calculated from the single helix model was impressive. There were some small discrepancies between the calculated and measured torsional strokes obtained from the most highly twisted fibers, and possible causes for these differences are being investigated. The success of the single helix model indicates that the solid twisted fiber behaves co-operatively, with the mechanism of fiber untwist operating consistently throughout the fiber thickness. In the example studied, it was found that the fiber length change was negligible and this observation greatly simplified the application of the single helix model. Further work will consider fibers in which significant fiber length changes occur during heating and then evaluate whether the single helix approximation remains valid.

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